

THE IMPACT OF FISSION GAS ON URANIUM–MOLYBDENUM FUEL

A Dissertation

presented to

the Faculty of the Graduate School

at the University of Missouri

In Partial Fulfillment

of the Requirements for the Degree

Doctor of Philosophy

by

ABU RAFI MOHAMMAD IASIR

Dr. Karl Hammond, Dissertation Supervisor

MAY 2021

© Copyright by Abu Rafi Mohammad Iasir 2021

All Rights Reserved

The undersigned, appointed by the dean of the Graduate School, have examined the dissertation entitled

THE IMPACT OF FISSION GAS ON URANIUM–MOLYBDENUM
FUEL

presented by Abu Rafi Mohammad Iasir,
a candidate for the degree of Doctor of Philosophy,
and hereby certify that, in their opinion, it is worthy of acceptance.

Professor Karl Hammond, chair

Professor Scott Kovalaski, member

Professor Robert Winholtz, member

Professor Nickie Peters, member

To my parents Ismail and Halima

*“Do you think that I know what I am doing?
That for one breath or half-breath I belong to myself?
As much as a pen knows what it’s writing,
Or the ball can guess where it’s going next.”*

—Rumi

ACKNOWLEDGMENTS

TABLE OF CONTENTS

ACKNOWLEDGMENTS	ii
LIST OF TABLES	vi
LIST OF FIGURES	vii
LIST OF SYMBOLS	x

Chapter

1. INTRODUCTION	1
1.1 Metallic Uranium and Alloys	3
1.2 Fission Gas	7
References	8
2. BACKGROUND	11
2.1 First Principles Method	11
2.1.1 The Many-Body Hamiltonian	11
2.1.2 Hartree–Fock Approach	14
2.1.3 Density Functional Theory	17
2.1.4 Kohn–Sham Equations	21
2.1.5 Kohn–Sham problem for an isolated atom	22
2.1.6 Theory of Pseudopotential	24
2.1.7 Basic Phillips–Kleinman Construction	24
2.1.8 Norm-Conserving Pseudopotentials	28
2.1.9 Ultrasoft Pseudopotentials	29
2.1.10 Projector Augmented-Wave Method (PAW)	29
References	30

3. EFFECT OF XENON ON THE OVERALL THERMAL CONDUCTIVITY OF U-10Mo	31
3.1 Introduction	31
3.2 Methods	33
3.2.1 Effective Thermal Conductivity Calculation	36
3.3 Results and Discussion	38
3.3.1 Effect of Xenon Gas Bubbles on the Thermal Conductivity	38
3.3.2 Effect of Xenon Pressure on the Overall Thermal Conductivity	41
3.3.3 Effect of Bubble Arrangement on Thermal Conductivity	42
3.4 Conclusions	46
References	47
4. FIRST-PRINCIPLES STUDY OF METALLIC URANIUM	50
4.1 Introduction	50
4.2 Computational Details	52
4.3 Results	54
4.3.1 α -Uranium	54
4.3.2 γ -U: Crystal Structure and Elastic Moduli	57
4.3.3 Body-centered Tetragonal Uranium	59
4.3.4 Face-centered Cubic Uranium	60
4.3.5 Electronic Density of States	61
4.4 Conclusion	63
Appendices	65
.1 Calculation of Elastic Parameters of α -uranium	66
.2 Elastic Parameter Calculation for γ -uranium	68
References	72
5. XENON MOBILITY IN U-Mo FUEL	79
5.1 Introduction	79
5.2 Theory	82
5.3 Methodology	85
5.4 Results and Discussion	86
5.4.1 Vacancy Formation and Impurity–Vacancy Binding Energies	86
5.4.2 Xenon and Molybdenum Diffusion	87

5.5	Conclusions	90
	References	94
6.	CONCLUSIONS AND FUTURE WORK	99
 Appendix		
A.	ATOMIC UNITS	100
B.	HELIUM INTERACTION WITH BCC LITHIUM	103
C.	ORTHOGONAL PLANE WAVE.....	112
D.	PROJECTOR AUGMENTED WAVE	116
E.	FINITE ELEMENT METHOD IN MOOSE	122
F.	INPUT FILES	124
	BIBLIOGRAPHY	148
	VITA	161

LIST OF TABLES

Table	Page
4.1 Parameters used to generate the pseudopotential in atompaw	54
4.2 Comparison of ground-state properties and elastic moduli of α -U with previous work	57
4.3 Comparison of ground-state properties and elastic moduli of γ -U with previous work	58
4.4 Comparison of ground-state properties and elastic moduli of bcc uranium with previous work	59
4.5 Comparison of ground-state properties and elastic parameters of fcc uranium	60
5.1 Probability of having different numbers of molybdenum atoms in the nearest-neighbour (NN) location for a bcc uranium–molybdenum alloy. We have used Eq. (5.5) to calculate the probabilities.....	85
5.2 Vacancy formation energy (eV) of γ -U compared with previously-published results.	87
5.3 Solute–vacancy binding energies in γ -uranium for various solutes near a vacancy. Positive energies indicate energetically-favourable binding.....	88
5.4 Xenon migration energy (E_m) for different configurations.....	92
B.1 Defect formation energies in bcc lithium	105
B.2 Formation energy of helium in lithium	106
B.3 He–He dumbbell formation energy in lithium	106

LIST OF FIGURES

Figure	Page
1.1 Orthorhombic crystal structure of α -uranium	5
1.2 U–Mo phase diagram	5
1.3 U–Al phase diagram	6
2.1 Schematic representation of the self-consistent loop solution of Kohn-Sham equations.	23
2.2 Radial distribution function of Hydrogenic 1s, 2s and 3s electron. It shows higher kinetic energy near the nucleus.	25
2.3 Schematic diagram of the replacement of all-electron wave function and core potential by a pseudo-wavefunction and pseudopotential.	25
3.1 Discretized domain of intra-granular xenon bubbles	34
3.2 SEM image of the fission gas bubbles along the grain boundary	36
3.3 Thermal conductivity of xenon as a function of pressure and temperature	37
3.4 Comparision between the thermal conductivities	38
3.5 Comparison of thermal conductivities with theoretical models	40
3.6 Comparing thermal conductivities between the inclusion of GB xenon and withouth xenon	41
3.7 Overall thermal conductivity of U-10Mo using the thermal conductivity of xenon at two extremes of pressure (1 bar and 1000 bar)	42
3.8 Different bubble arrangements in which the area of each bubble and the number of bubbles are the same	43

3.9	Comparison of the calculated thermal conductivity of different bubble arrangements (constant bubble area and diameter)	44
3.10	Different bubble arrangements where the area is the same but the bubbles have different diameters.	45
3.11	Comparison of thermal conductivity between different bubble diameters at constant total bubble area with bubble-free U-10Mo.	45
4.1	Energy vs volume plot for α -uranium	56
4.2	Total electronic densities of states of α , γ , bct, and fcc uranium near the Fermi level.	61
4.3	The partial electronic densities of states of α , γ , bct, and fcc uranium near the Fermi level.	62
4	Changes in strain energy in D_1 , D_2 and D_3	69
5	Changes in strain energy in D_4 , D_5 and D_6	70
6	Changes in strain energy in D_7 , D_8 and D_9	71
7	Energy as a function of lattice parameters for γ -uranium.	73
8	Changes in the strain energy as a function of strain (δ) for monoclinic distortions of γ -uranium	74
9	Changes in the strain energy as a function of strain (δ) for orthorhombic distortions of γ -uranium	75
5.1	(a) Diagram of a xenon jump from the centre site to a nearest-neighbour vacancy in γ -uranium. (a) All eight jumps are symmetrically equivalent with no molybdenum present; (b) with one molybdenum atom in the nearest neighbour shell, there are three unique solute jumps (1, 2, and 3).	90
5.2	The three sets of symmetrically-inequivalent hops of xenon from the centre with two molybdenum atoms in the nearest-neighbour shell. The numbers denote symmetrically distinct pathways.	91
5.3	The three sets of symmetrically-distinct hops from the centre site with three molybdenum atoms in the nearest-neighbour shell. The numbers denote symmetrically distinct pathways.	91

B.1	Different dumbbell configuration in bcc lithium	108
B.2	Interstitial atom location in 2D for bcc crystal	109
B.3	He binding energy	109

LIST OF SYMBOLS

$E_{\text{bind}}^{X-\square}$	binding energy between solute (X) and vacancy (\square)
ℓ	angular quantum number
λ	thermal conductivity
λ_0	thermal conductivity of 100% dense material
λ_p	thermal conductivity of dispersed phase
λ_s	thermal conductivity of continuous phase (U–10Mo)
\mathcal{H}	many body hamiltonian
\mathcal{P}	probability of having different numbers of molybdenum atoms in nearest-neighbor locations in bcc crystal
ν	porosity
ν_p	volume fraction of xenon in U–10Mo
$\Psi(t)$	time dependent wave function
ψ_{AE}	all electron wave function
ψ_{ps}	pseudo wave function
ν^{EX}	exchange potential
\mathbf{R}_a	position of a -th nucleus
\mathbf{r}_j	position of j -th electron
D	diffusion coefficient
D_0	pre-exponential factor
E	energy of the system
$E_{\text{U}_{N-1}}^{\square_1}$	energy of a system with one vacancy
E_f^{\square}	vacancy formation energy
$E_{\text{U}_{N-2}}^{X_1\square_1}$	energy of a system with a solute–vacancy pair

$E_{U_{N-1}}^{X_1}$	energy of a system with one solute atom
$E_f^{\text{He}-\square-\text{He}}$	helium–helium dumbbell formation energy around a vacancy
E_f^{oct}	helium formation energy in a octahedral position
E_f^{subs}	helium formation energy in a substitutional position
E_f^{tetr}	helium formation energy in a tetrahedral position
E_m	migration energy
E_{U_N}	energy of a system with N uranium atoms
$E_{\text{He}_{\text{isolated}}}$	energy of an isolated helium atom
E_{xc}	exchange-correlation energy
K	thermal conductivity tensor
K_{eff}	effective thermal conductivity
m	spin
m_e	mass of a single electron
N	number of atoms in a supercell
N	number of electrons
n	principle quantum number
$n(\mathbf{r})$	electron density
q''	heat flux
Q_{IS}	vibrational partition function of the initial state
Q_{TS}	vibration partition function of transition state
r_{core}	core radius
r_{shape}	shape function cutoff
r_{PAW}	augmentation radius
T	absolute temperature
V_{ext}	external potential
x_{Mo}	mole fraction of molybdenum

CHAPTER 1

INTRODUCTION

Since the discovery of fission in 1938, the world has experienced the impact of nuclear power on modern society. The primary fuel for fission is ^{235}U . Naturally occurring uranium consists of a combination of different isotopes; about 99.3% ^{238}U , 0.7% ^{235}U and trace amounts of ^{234}U isotope. Uranium can be “enriched” in the ^{235}U isotope by using various complicated processes that mainly uses the difference in masses and/or other physical properties. A typical power generating reactor requires less than 5% enriched uranium. Research reactors needs a higher percentage of enriched uranium. The primary purpose of a research reactor is to produce neutron. The neutron produced by a research reactor are used for neuttrion scattering, testing and analysis of materials, production of radioisotopes, and training. They are also referred as non-power reactors.

After the Manhattan project, the highly enriched uranium ($> 90\%$ ^{235}U) has been used peaceful in scientific research and radioisotope production. Nuclear fuels are characterized by a unique combination of physics, engineering, safety requirements, social and environmental factors, and international concerns. The purpose of nuclear safety is to prohibit the uncontrolled release of the radioactive isotopes to the environment and ensuring safe use of the fissile material. Highly enriched uranium (HEU) fuel is also a proliferation concern. All enrichments above 20% ^{235}U are considered HEU [1].

HEU can be used to make simple nuclear explosives, such as the one used in Hiroshima by the United States. That weapon code named “little boy”, contained about 50 kilograms of ^{235}U with an average enrichment of about 80% [2]. The neutron production in 60 kg

of metallic enriched uranium (from both fission and (α, n) reactions on oxygen) is about 100 per second. This low rate and combined with a neutron reflector can be made into simple highly-enriched uranium weapon. Although there are counter arguments about the likelihood of acquiring necessary technical capabilities to make an implosion design, there is little argument that it is much easier to design a so called gun-type weapon that could in theory work without testing. Stocks of HEU fuel at research reactors and in their nuclear fuel cycles are particularly vulnerable to theft.

Proliferation concerns about HEU resulted in a global effort, led by the USA, to eliminate the civil uses of HEU in research and test reactors. One of the important HEU reduction programmes is known as the Reduced Enrichment for Research and Test Reactors (RERTR). The RERTR program was initiated in the USA in the late 1970s to develop new nuclear fission fuels to replace high-enriched uranium (HEU) [3, 4]. The RERTR program is now managed by the U. S. National Nuclear Security Administration's (NNSA) Office of Material Management and Minimization [5]. The development of low-enrichment uranium (LEU) fuels for high-performance reactors is an important nonproliferation initiative.

This initiative has completed a total of 69 reactor conversions to use LEU fuel, and 26 HEU-based reactor facilities have been verified to have been shut down [6]. The conversion of six domestic high performance research reactors¹ that still use highly enriched uranium fuel is yet to be achieved. Due to their unique operating conditions, converting these six reactors will not be easy and a plethora of nuclear engineering challenges are associated with their conversion. These conversion process may take longer time periods, but developing a new LEU fuel is essential to ensure better performance and limiting nuclear proliferation. The timeline for the conversion is currently estimated to be 10–16 years [7–9].

Research reactors operate at relatively low peak fuel temperatures, but are required to meet fuel performance requirements at high burnup. A typical peak fuel centerline temper-

¹Advance Test Reactor (ATR) at INL, Idaho; Advanced Test Reactor Critical (ATRC) Assembly at INL, Idaho; High Flux Isotope Reactor (HFIR) at ORNL, Tennessee; Massachusetts Institute of Technology Reactor (MITR), Massachusetts; National Bureau of Standards Reactor in Gaithersburg, Maryland; University of Missouri Research Reactor (MURR) in Columbia, Missouri.

ature in a research reactor is around 250°C [10]. For a research reactor, fission densities are usually in the range of 3×10^{21} to 6×10^{21} fissions/cm³. In some cases, peak fuel fission density exceeds 7×10^{21} fissions/cm³, requiring a higher density of ²³⁵U atoms. Consequently, one of the main requirements of LEU fuels is increased uranium density, such as that found in metallic uranium, to offset the decrease in ²³⁵U enrichment.

1.1 Metallic Uranium and Alloys

Uranium has three allotropic forms: orthorhombic (α -phase), stable from below room temperature to 662°C; tetragonal (β -phase), stable from 662 to 774°C; and body-centered cubic (γ -phase), stable from 772°C to the melting point, 1132°C [9]. Metallic uranium at standard temperature is thought to have sufficient density (19.05 ± 0.02 g/cm³). α -U belongs to the orthorhombic system, in which the three axes are mutually perpendicular ($a \perp b \perp c$) but are unequal length ($a \neq b \neq c$). This orientation of crystal is considered *anisotropic*. As a result, a great deal of work has gone into studying the textures of alpha uranium. Different heat treatment, corrosion studies, grain size analysis, mechanical and elastic property studies and post irradiation analysis indicate that α -uranium has poor properties to be considered as nuclear fuel [11–13].

Alloying uranium to obtain certain properties was extensively studied in the early stages of nuclear fuel development. Some of the reasons being 1) to achieve a finer grain size, 2) to improve mechanical properties, 3) to improve corrosion resistance, 4) to increase irradiation performance etc. Aluminum is the material for choice for many components of low-temperature research reactors. The irradiation behavior of Al at low temperature (<100°C) shows favorable behavior, which retains significant ductility and metallic property [14]. The uranium-aluminum system has three compounds (Fig. 1.3) – UAl_2 , UAl_3 and UAl_4 . UAl_2 solidifies at temperature of 1615°C; UAl_3 forms at 1355°C by a peritectic reaction between the solid phase of UAl_2 and liquid phase of Al–60wt%U. UAl_4 forms at 740°C by a peritectic reaction between the solid phase UAl_3 and the liquid phase of Al–18wt%U.

Uranium–aluminum alloys in which the matrix is either primary aluminum or Al+UAl₄ eutectic are widely being as research reactor fuel. This type of fuel is called *dispersion*² fuel.

Uranium-aluminum alloys can have density as high as 4.522 gU/cm³ [16], for LEU the required density exceeds 8.5 gU/cm³ [17]. There are only a few fuel phases with both a high uranium density and stable irradiation properties. The two types of fuels that meet the density requirements are γ -stable uranium and U₆Me (Me=transition metal) type compounds. The U₆Me type fuels showed very poor irradiation performance at low fission density (3×10^{21} fissions/cm³) [18–20]. The γ -phase of uranium can be stabilized by alloying it with suitable elements. Several transition metals stabilizes γ -U. Elements such as molybdenum (Mo), niobium (Nb), titanium (Ti), and zirconium (Zr) have been tried as alloying elements because of their solubility in γ -uranium [21–23]. The U–Mo phase (Fig. 1.2) has a eutectoid decomposition of γ -phase at 11.1 wt% Mo and 555 °C. If the U–Mo γ -phase contains more than 5–7 wt% Mo, the γ -phase is retained at room temperature by rapid cooling [24, 25]. To take advantage of this, uranium alloyed with 10 wt% molybdenum (U-10Mo) is currently being developed as a potential high-density LEU fuel for high-performance research reactors [10, 26, 27].

Before the current interest in U–Mo metallic fuel, some of the early nuclear reactors used metallic fuel because of the combination of high uranium density and metallic properties. The Godiva IV pulsed reactors at Los Alamos (initially known as *Lady Godiva*) used U–Mo alloys, which date back to 1960. The Fast Burst Reactor (FBR) at White Sands, the Army Pulsed Radiation Facility (Aberdeen, MD), and the Sandia Pulsed Reactor II also used U–Mo alloys. All of these reactors utilized the γ phase of uranium, but because of the short irradiation time, the impacts of fuel burnup were minimal [29]. The Dounreay Fast Reactor used a number of metal-fuel-based designs, which includes U–9.1Mo (9.1 wt% Mo) and U–7Mo clad in niobium. The highly alloyed fuel cracked more, even though the

²A dispersion type fuel is one in which the fissile material is contained as a compound dispersed in a nonfissile matrix [15]

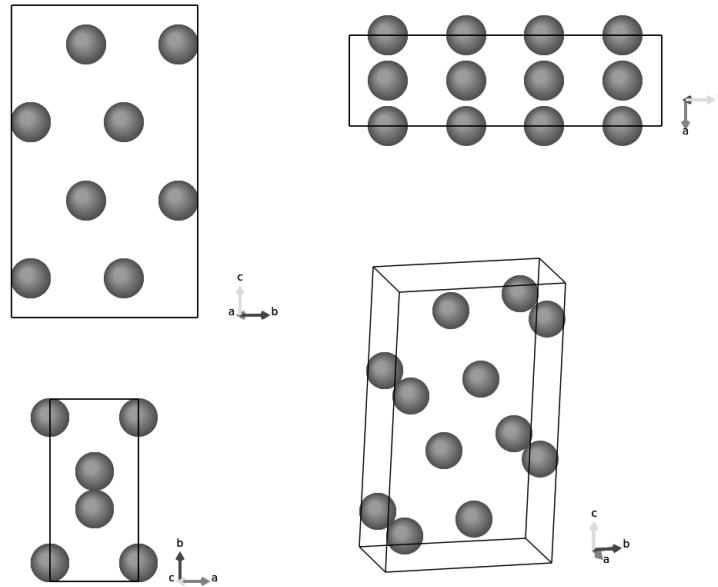


Figure 1.1. Orthorhombic crystal structure of α -uranium

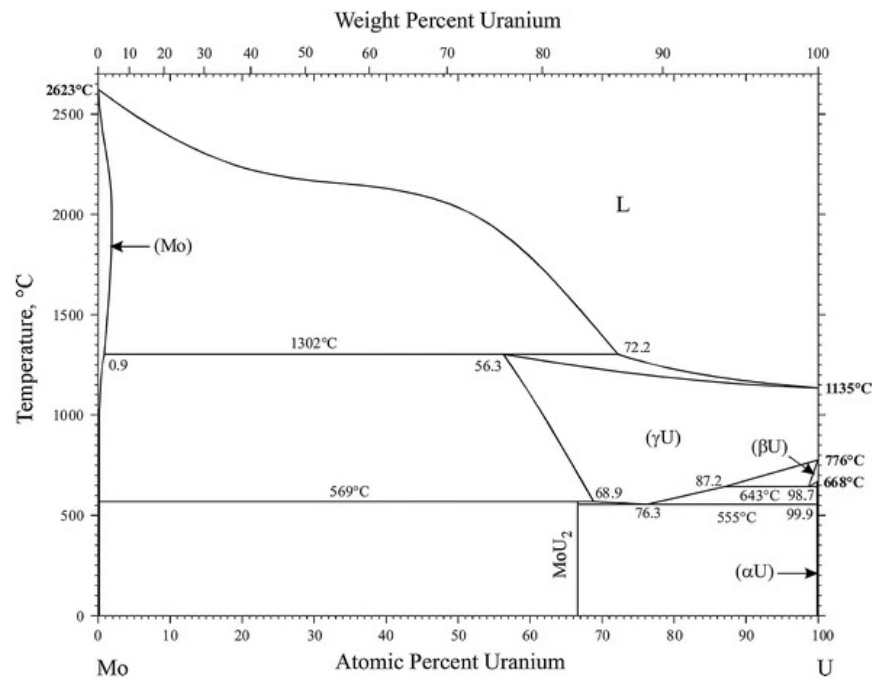


Figure 1.2. Uranium–Molybdenum phase diagram. Image reprinted with permission from Okamoto [28]

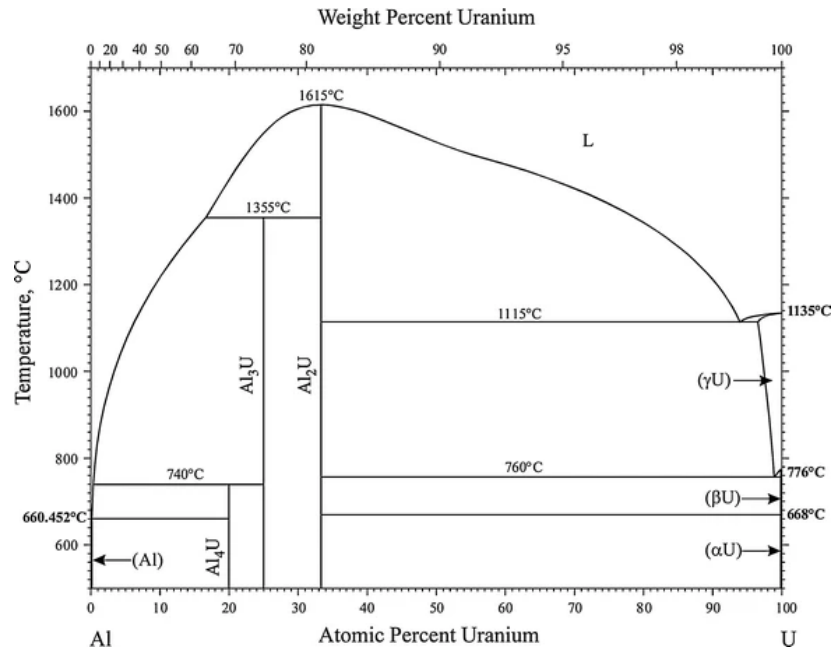


Figure 1.3. Uranium–Aluminum phase diagram. Image reprinted with permission from Okamoto [28]

U–9.1Mo fuel swelled slightly less than U–7Mo alloy [30]. In U.S. the Enrico Fermi Fast Breeder Reactor (EFFBR) was the first commercial fast reactor that used U–10Mo fuel.

The primary concern was to ensure that the fuel would remain in the γ -phase during the operating condition. A series of experiments have been performed to map the fission rate and temperature dependence of the γ -phase’s stability [31]. Two types of U–Mo alloy fuel have been designed and tested. One is monolithic fuel, in which a thin layer of U–Mo foil is bonded to aluminum cladding. The other is a dispersion fuel in which of U–Mo fuel particles are dispersed in an Al matrix.

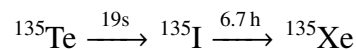
For five decades, dispersion fuels have powered many test and research reactors world-wide. The manufacturing process and operating conditions are well established for these types of fuels. High-burnup testing of dispersion fuels showed a pattern of breakaway swelling³ behavior at intermediate burnup. The post-irradiation examination of the U–Mo dispersion fuel revealed that this phenomenon is related to the formation of ternary aluminide phase. Reaction between the U–Mo fuel kernels and aluminum cladding occurs

during irradiation and forms a ternary [(U–Mo)Al_x] phase which releases the fission gas at the boundary between the interaction phase and the aluminum matrix [32–35]. These gas bubbles have a tendency to aggregate into the gas pockets, which weakens the fuel meat by exerting internal pressure. The result is mechanical failure and increase in fuel volume. To eliminate the fuel–matrix interaction, a ‘monolithic’ U–Mo fuel was suggested. In monolithic fuels, a zirconium foil is used as a diffusion barrier between the fuel and the cladding (aluminum) to prevent diffusion of molybdenum into the cladding [33].

1.2 Fission Gas

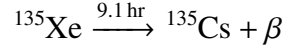
The behavior of fission products xenon and krypton has perplexed and fascinated both the experimentalists and theorists more than many processes simultaneously occur in a nuclear fuel element during irradiation. These inert gases are insoluble in fuel matrix, causing them to form small gas bubbles. If the gas is released from the fuel, the pressure within the fuel pin rises and that ultimately results in failure. If the fission gases are retained in the fuel, however, they almost always precipitates as bubbles and causes swelling in the fuel matrix. Swelling adversely impact the fuel efficiency. It impacts the thermal conductivity of the fuel thereby disrupts the efficient heat extraction from the fuel. One particular xenon isotope, ¹³⁵Xe has a large neutron absorption cross section which can lead a reactor poisoning. As a result the basic aspects of inert gas behavior were studied for fuel such as UO₂.

Xenon is produced directly from fission. 0.3% of the fission products are ¹³⁵Xe. It is also produced by the decay of ¹³⁵I via the following scheme:



³*Breakaway* is defined as “the limiting exposure, beyond which there will be a marked increase in the rate of swelling as a function of burnup [36]”

^{135}I constitutes almost 6.1% of fission products. Thus, 95% of the total xenon production is due to the decay of iodine. Xenon is removed from the reactor by a beta decay or by neutron absorption:



In U–Mo fuel fission gas forms bubbles both inside the grain and in to the grain boundary. In side the grains fission gas forms superlattices [37, 38].

This dissertation investigates how fission gas (xenon and krypton) impacts the transport properties of U–Mo fuel. Chapter 2 summarizes theoretical methods used in this work. In Chapter 3, We discuss the reduction of thermal conductivity due to the presence of fission gas. We have used finite element method to approximate the overall thermal conductivity. In Chapter 4, we introduce a new pseudopotential for metallic uranium to study the properties using density functional theory (DFT). In Chapter 5 we look into the diffusion mechanism of xenon in γ -uranium and U–Mo alloy. In Chapter 6, we discuss the conclusions and potential future work.

References

1. IAEA, *Management of High Enriched Uranium for Peaceful Purposes: Status and Trends*, TECDOC Series No. 1452 (INTERNATIONAL ATOMIC ENERGY AGENCY, Vienna, 2005).
2. R. Serber, *The Los Alamos primer: The first lectures on how to build an atomic bomb* (Univ of California Press, 1992).
3. A. Travelli, *Current status of the RERTR program*, Tech. Rep. (Argonne National Lab., IL (USA), 1980).
4. J. L. Snelgrove, G. L. Hofman, M. K. Meyer, C. L. Trybus, and T. C. Wiencek, Nucl. Eng. Des. **178**, 119 (1997).
5. D. E. Burkes, I. J. Schwerdt, T. K. Huber, H. Breitzkreutz, C. Reiter, W. Petry, J. L. Schulthess, A. M. Casella, A. J. Casella, E. C. Buck, *et al.*, J. Nucl. Mater. **547**, 152823 (2021).

6. E. Wilson, A. Bergeron, J. Stillman, T. Heltemes, D. Jaluvka, and L. Jamison, in *Proceedings of the 2017 European Research Reactor Conference* (RRFM Rotterdam, Netherlands, 2017).
7. National Academies of Sciences, Engineering, and Medicine, *Reducing the Use of Highly Enriched Uranium in Civilian Research Reactors* (National Academies Press, Washington, DC, 2016).
8. National Research Council, *Progress, Challenges, and Opportunities for Converting U.S. and Russian Research Reactors: A Workshop Report* (National Academies Press, Washington, DC, 2012).
9. A. R. Kaufmann, *Nuclear Reactor Fuel Elements: Metallurgy and Fabrication* (Interscience Publishers, New York, 1962).
10. M. K. Meyer, J. Gan, J. F. Jue, D. D. Keiser, E. Perez, A. Robinson, D. M. Wachs, N. Woolstenhulme, G. L. Hofman, and Y. S. Kim, *Nucl. Eng. Technol.* **46**, 169 (2014).
11. S. Pugh, *Journal of Nuclear Materials* **4**, 177 (1961).
12. B. Loomis and D. Pracht, *Swelling of uranium and uranium alloys on postirradiation annealing*, Tech. Rep. (Argonne National Lab., Ill., 1962).
13. H. H. Chiswik, A. E. Dwight, L. T. Lloyd, M. V. Nevitt, and S. T. Zegler, *Second Un. Nat. In. Conf. on the Peaceful Uses of Atomic Energy* (1958), 10.2172/4322509.
14. K. Farrell, in *Comprehensive Nuclear Materials*, edited by R. J. Konings (Elsevier, Oxford, 2012) pp. 143–175.
15. D. W. White, A. P. Beard, and A. H. Willis (General Electric Company, 1957).
16. H. A. Saller, R. F. Dickerson, F. A. Rough, E. L. Foster, A. A. Bauer, and J. R. Lulay, *A Study of Aluminum-Uranium Alloys*, Tech. Rep. (Battelle Memorial Inst., Columbus, Ohio, 1956).
17. L. Sannen, S. van den Berghe, and A. Leenaers, in *6th Forum on New Materials - Part B*, *Advances in Science and Technology*, Vol. 94 (Trans Tech Publications Ltd, 2014) pp. 43–54.
18. M. K. Meyer, T. C. Wiencek, S. L. Hayes, and G. L. Hofman, *J. Nucl. Mater.* **278**, 358 (2000).
19. G. L. Hofman, R. F. Domagala, and G. L. Copeland, *J. Nucl. Mater.* **150**, 238 (1987).
20. S. van den Berghe, A. Leenaers, E. Koonen, and L. Sannen, in *5th FORUM ON NEW MATERIALS PART B*, *Advances in Science and Technology*, Vol. 73 (Trans Tech Publications Ltd, 2011) pp. 78–90.
21. G. Donzé and G. Cabane, *J. Nucl. Mater.* **1**, 364 (1959).

22. F. Giraud-Heraud and J. Guillaumin, *Acta Metall.* **21**, 1243 (1973).
23. D. A. Lopes, T. A. G. Restivo, and A. F. Padilha, *J. Nucl. Mater.* **440**, 304 (2013).
24. H. A. Saller, F. Rough, and A. Bauer, *Transformation kinetics of uranium-molybdenum alloys*, Tech. Rep. (Battelle Memorial Inst., Columbus, Ohio, 1954).
25. W. A. Bostrom and E. K. Halteman, *THE METASTABLE GAMMA PHASE IN URANIUM BASE MOLYBDENUM ALLOYS*, Tech. Rep. (Westinghouse Electric Corp. Bettis Plant, Pittsburgh, 1956).
26. R. Prabhakaran, *JOM* **69**, 2529 (2017).
27. W. Williams, A. Robinson, and B. Rabin, *JOM* **69**, 2546 (2017).
28. H. Okamoto, *Journal of Phase Equilibria and Diffusion* **33**, 497 (2012).
29. J. A. Horak, J. A. Reuscher, and D. J. Sasmor, *Operating experience with uranium-molybdenum fuel in pulsed reactors*, Tech. Rep. (Sandia Labs., Albuquerque, N. Mex.(USA), 1973).
30. S. A. Cottrell, E. Edmonds, P. Higginson, and W. Oldfield, *Development and performance of Dounreay fast reactor metal fuel*, Tech. Rep. (United Kingdom Atomic Energy Authority. Industrial Group. Dounreay, 1964).
31. I. A. E. Agency, *Nuclear Fuel Cycle and Material Section* (2003).
32. A. Leenaers, S. Van den Berghe, E. Koonen, C. Jarousse, F. Huet, M. Troabas, M. Boyard, S. Guillot, L. Sannen, and M. Verwerft, *J. Nucl. Mater.* **335**, 39 (2004).
33. J.-F. Jue, D. D. Keiser, C. R. Breckenridge, G. A. Moore, and M. K. Meyer, *J. Nucl. Mater.* **448**, 250 (2014).
34. S. Van den Berghe, W. Van Renterghem, and A. Leenaers, *J. Nucl. Mater.* **375**, 340 (2008).
35. D. Olander, *J. Nucl. Mater.* **383**, 201 (2009).
36. A. E. Guay, "Uranium swelling in N-Reactor (PT-NR-4, Sup. A, Report No. 1)," United States. <https://www.osti.gov/biblio/10163384> (1965).
37. B. D. Miller, J. Gan, J. Madden, J.-F. Jue, A. Robinson, and D. D. Keiser, *J. Nucl. Mater.* **424**, 38 (2012).
38. J. Gan, D. D. Keiser, D. M. Wachs, A. B. Robinson, B. D. Miller, and T. R. Allen, *J. Nucl. Mater.* **396**, 234 (2010).

CHAPTER 2

BACKGROUND

2.1 First Principles Method

First principles or *ab initio* methods has become an essential tool in material science over the last three decades. Any relevant physical property of real materials can in principle be described by the law of quantum mechanics. The foundation of this method is computational solution of electronic many-body Schrödinger equation. With the proper description of the positions of the atomic nuclei, and the total number of electrons in the system; the energy and other relevant properties can be approximated. The ability to obtain a solution that is good enough, requires well efficient description of electronic system and considerable computational power.

2.1.1 The Many-Body Hamiltonian

The quantum theory of electrons and nuclei controls the characteristics of matter over wide ranges in temperature and pressure. One of the most fundamental qualities of solid is that it has a variety of properties which are not featured by a single atom. Electric conductivity as well as magnetism arise as collective properties of the particle in the system. The particles of a solid can be described by the Schrödinger's equation

$$\mathcal{H}|\Psi(t)\rangle = i\hbar\frac{\partial}{\partial t}|\Psi(t)\rangle, \quad (2.1)$$

The time-independent Schrödinger equation is as follows:

$$\mathcal{H}|\psi_j\rangle = E_j|\psi_j\rangle \quad (2.2)$$

where the Hamiltonian expresses the motion of the particles:

$$\begin{aligned} \mathcal{H} &= - \sum_j \frac{\hbar^2}{2m_e} \nabla_j^2 - \sum_a \frac{\hbar^2}{2M_a} \nabla_a^2 \\ &\quad - \sum_{j,a} \frac{Z_a e^2}{|\mathbf{r}_j - \mathbf{R}_a|} + \frac{1}{2} \sum_{j,k}^{j \neq k} \frac{e^2}{|\mathbf{r}_j - \mathbf{r}_k|} + \frac{1}{2} \sum_{a,b}^{a \neq b} \frac{Z_a Z_b e^2}{|\mathbf{R}_a - \mathbf{R}_b|} \\ \mathcal{H}^{Htr. \text{ units}} &= - \sum_j \frac{1}{2} \nabla_j^2 - \sum_a \frac{1}{2\tilde{M}_a} \nabla_a^2 \\ &\quad - \sum_{j,a} \frac{Z_a}{|\mathbf{r}_j - \mathbf{R}_a|} + \frac{1}{2} \sum_{j,k}^{j \neq k} \frac{1}{|\mathbf{r}_j - \mathbf{r}_k|} + \frac{1}{2} \sum_{a,b}^{a \neq b} \frac{Z_a Z_b}{|\mathbf{R}_a - \mathbf{R}_b|} \\ &= T_e + T_N \\ &\quad + V_{Ne}(\mathbf{r}, \mathbf{R}) + V_{ee}(\mathbf{r}) + V_{NN}(\mathbf{r}) \end{aligned} \quad (2.3)$$

The second part of the equation is expressed in Hatree units (see Appendix A), which will be used for the remainder of the discussion. In these units, the electron mass m_e as well as the elementary charge e , the reduced Planck's constant \hbar and Coulomb's constant $1/4\pi\epsilon_0$ are set to unity, leaving $\tilde{M}_a = M_a/m_e$ as the relative atomic mass of the nucleus of atom a . \mathbf{r}_j denotes the position of the j -th electron, while \mathbf{R}_a is the position of the nucleus of atom a . Z_a is that nucleus' charge number. A solution of the Schrödinger equation (2.2) would be a function dependent on the spatial coordinates of all particles in the system and is as such only obtainable for very small systems. The Schrödinger equation with the above Hamiltonian is impossible to solve exactly for most of systems of interest. A series of approximations and methods were therefore developed to reduce the complexity of the problem. With the help of Eqn (2.3) the Schrödinger equation (2.2) becomes

$$[T_e + T_N + V_{Ne}(\mathbf{r}, \mathbf{R}) + V_{ee}(\mathbf{r}) + V_{NN}(\mathbf{r})]\Phi(\mathbf{r}, \mathbf{R}) = E\Phi(\mathbf{r}, \mathbf{R}) \quad (2.4)$$

In order to simplify the equations, the electronic coordinates and spin indices are combined into a vector $\mathbf{r} = (\vec{r}, s)$ and \mathbf{R} denotes the nuclear coordinates. The wave function here is a regular function of the atomic positions but a quantum state $|\Phi(x, t)\rangle$ in the Hilbert space for the electrons and nuclei, so that $\Phi(\vec{r}) = \langle \vec{r} | \Phi(\mathbf{r}, \mathbf{R}) \rangle$. The nuclear mass exceeds the electron mass by more than three orders of magnitude, and so both move on different time scales. Thus the wave function $\Phi(\mathbf{r}, \mathbf{R})$ can be separated into an electronic part $\Psi(\mathbf{r}, \mathbf{R})$ and a nuclear wave function $\chi(\mathbf{R})$

$$\Phi(\mathbf{r}, \mathbf{R}) = \Psi(\mathbf{r}, \mathbf{R})\chi(\mathbf{R}) \quad (2.5)$$

The nuclear wave function is much more localized, which is why the Schrödinger equation can be separated into two parts:

$$[T_e + V_{ee}(\mathbf{r}) + V_{Ne}(\mathbf{r}, \mathbf{R})]\Psi(\mathbf{r}, \mathbf{R}) = \epsilon_n(\mathbf{R})\Psi(\mathbf{r}, \mathbf{R}) \quad (2.6)$$

$$[T_N + V_{NN}(\mathbf{R}) + \epsilon_n(\mathbf{R})]\chi(\mathbf{R}) = E\chi(\mathbf{R}) \quad (2.7)$$

The nuclear positions (\mathbf{R}) in the equation (2.6) serves only as a parameter and it is possible to use the *adiabatic* or *Born-Oppenheimer* approximation. On the timescale of the nuclear motion the electrons follow the ions adiabatically. As a further approximation, the quantum effects on the motion of the nuclei are neglected and the time dependent Schrödinger equation is replaced by Newton's equation of motion:

$$\frac{\partial P_I}{\partial t} = -\nabla_I E_0(\mathbf{R}) \quad (2.8)$$

$$\text{with } E_0(\mathbf{R}) = \epsilon_0(\mathbf{R}) + V_{NN}(\mathbf{R}) \quad (2.9)$$

This refers to the so called *ab-initio* molecular dynamics, where the forces around a nuclei are calculated from the electronic ground state.

Equation 2.6 and 2.7 are not generally applicable. However, for several physical systems, the Born-Oppenheimer approximation works and Eqn. 2.6, 2.7 produces meaningful results. In solid state physics, Eqn (2.7) usually written in a classical form and Eqn (2.6) becomes the problem to be solved. It is still a very complicated equation, where the term describing the interaction between electrons would require the knowledge of 3^N variables for a system of N electrons. Such a large number of variables make the problem computationally not tractable and several approximated methods have been introduced. Some of those important methods will be discussed.

These approximation methods are based on the *independent particle* approximation, in which the Hamiltonian takes the form

$$\mathcal{H}' = \sum_j \mathcal{H}_j \quad (2.10)$$

The electrons wave function can be written as products of single particle wave functions. This leads to a further simplification of the Hamiltonian.

$$\begin{aligned} \mathcal{H}' \stackrel{\text{eqn.2.6}}{=} & - \sum_j^N \frac{1}{2} \nabla_j^2 - \sum_j^N \sum_a^M \frac{Z_a}{|\mathbf{r}_j - \mathbf{R}_a|} + \frac{1}{2} \sum_{j \neq k}^N \sum_k^N \frac{1}{|\mathbf{r}_j - \mathbf{r}_k|} \\ & = T_e + V^{\text{ext}} + \frac{1}{2} \sum_{j \neq k} v_{jk}(|\mathbf{r}_j - \mathbf{r}_k|) \end{aligned} \quad (2.11)$$

2.1.2 Hartree–Fock Approach

A very simple way to write many-electron wavefunction is as a product of single-particle wavefunction:

$$\Psi(r_1, r_2, \dots, r_N) = \prod_j^N \psi_j(r_j) \quad (2.12)$$

The Hamiltonian (2.11) is not just a sum of single-particle Hamiltonians, the true wavefunctions cannot be written in the product of the form (2.12), furthermore, it does not have the *antisymmetry* property required for fermions.

The fermionic nature of the electrons imposes the Pauli exclusion principle as an additional constraint. One can achieve that by constructing a many-body wave function in an antisymmetric manner. This is achieved by writing the electronic wave function as a Slater determinant of single-particle wave functions:

$$\Psi(r_1, r_2, \dots, r_N) = \frac{1}{\sqrt{N!}} \begin{vmatrix} \psi_1(\mathbf{r}_1) & \psi_1(\mathbf{r}_2) & \dots & \psi_1(\mathbf{r}_N) \\ \psi_2(\mathbf{r}_1) & \psi_2(\mathbf{r}_2) & \dots & \\ \vdots & & \ddots & \\ \psi_N(\mathbf{r}_1) & \dots & & \psi_N(\mathbf{r}_N) \end{vmatrix} \quad (2.13)$$

The expectation value of the Hamiltonian (2.11) can be calculated using the newly introduced wave function, which leads to an energy functional that can be minimised variationally (2.14). Additional constraints for the single particle orbitals is to be normalized (2.15).

$$E \leq E' \equiv \frac{\langle \Psi | H | \Psi \rangle}{\langle \Psi | \Psi \rangle} = \quad (2.14)$$

Here, for any state $|\Psi\rangle$ provides an upper bound E' for the exact ground-state energy E . The orthonormalization conditions,

$$\langle \psi_i(\mathbf{r}_i) | \psi_j(\mathbf{r}_j) \rangle = \int d\mathbf{r} \psi_i(\mathbf{r})^* \psi_j(\mathbf{r}) = \delta_{ij} \quad (2.15)$$

The many-particle wave function (2.13) and the Hamiltonian (2.11) give the single particle Hartree-Fock¹(HF) Equations:

$$\begin{aligned} \mathcal{H}_i^{\text{HF}} \psi_i(\mathbf{r}_i) &= \left[-\frac{\nabla^2}{2} + v^{\text{ext}}(\mathbf{r}_i) + v^{\text{H}}(\mathbf{r}_i) + v^{\text{EX}}(\mathbf{r}_i) \right] \psi_i(\mathbf{r}_i) \\ &= \epsilon_i \psi_i(\mathbf{r}_i) \end{aligned} \quad (2.16)$$

where the kinetic energy term T_e and the external potential V^{ext} are unchanged from Eqn (2.11), are divided into the single particle contributions, with $V^{\text{ext}} = \sum_{i=1}^N v^{\text{ext}}(\mathbf{r}_i)$. The third term

in Eqn (2.11), the interaction between the electrons, produces two additional operators v^H and v^{EX} . The first term is called the *Hartree potential* and has the following form:

$$\begin{aligned} v^H(\mathbf{r}_i) &= \sum_{j=1}^N \int \frac{|\psi_j(\mathbf{r}_j)|^2}{|\mathbf{r}_i - \mathbf{r}_j|} d\mathbf{r}_j \\ &= \int \frac{n(\mathbf{r}_j)}{|\mathbf{r}_i - \mathbf{r}_j|} d\mathbf{r}_j \end{aligned} \quad (2.17)$$

where

$$n(\mathbf{r}) = N \int d\mathbf{r}_1, \dots, d\mathbf{r}_N |\Psi^0(\mathbf{r}_1, \dots, \mathbf{r}_N)|^2 \quad (2.18)$$

It takes account of the mean-field Coulomb interaction between the i th electron and the total electron density $n(\mathbf{r})$ as defined in Eqn (2.17). The second term in Eqn (2.16) can be written in its integral form

$$v^{EX}\psi_i(\mathbf{r}_i) = \sum_{j=1}^N \int d\mathbf{r}_j \psi_j^*(\mathbf{r}_j) \frac{1}{|\mathbf{r}_i - \mathbf{r}_j|} \psi_j(\mathbf{r}_i) \psi_i(\mathbf{r}_j) \quad (2.19)$$

It is known as *exchange potential* and takes account the antisymmetric nature of the total wave function. When the two particles have same coordinates the Hartree and exchange potential cancel each other.

The solution of the Hartree-Fock equation are the HF orbitals. Since the orbitals are also part of the equation the problem needs to be solved self-consistently. The exchange operator v^{EX} is usually referred to as a non-local operator, which makes it impossible to carry out full HF calculations for condensed matter system without introducing the local approximations. Evaluating v^{EX} is already a non trivial task, but the HF equation approximates the full many-body problem in a way that leaves out important contributions. What is not considered is usually referred to as *correlation* which adds an extra term in the Hamiltonian form (2.16). This contribution is small compared to the total energy of the system, but it is crucial for many solid systems. The *correlation* contribution to the Hamiltonian takes mainly account of the fact that one electron is screened by others from the interaction with

the nuclei and more distant electrons. The HF method usually works for systems in which the particles do not “see” each other. HF performs badly for systems with large number of electrons in metals.

2.1.3 Density Functional Theory

In the Hartree-Fock approach where we used wave-functions to solve many-body problems which are solved self-consistently. The density $n(\mathbf{r})$ plays a prominent role in self-consistent calculations. This evokes the query as to whether there exists an *exact* theory for the ground state electronic system of the density $n(\mathbf{r})$. This question leads to the *density functional theory* (DFT). The simplest and oldest version of the DFT formalism is the Thomas-Fermi model [3, 4].

2.1.3.1 Density

The idea to shift focus from wavefunction ($\Psi(\mathbf{r})$) to density ($n(\mathbf{r})$) to solve many-body Schrödinger equation is very important. For many particle systems the density, $n(\mathbf{r})$, is calculated by the expectation value of the single-particle density operator for many-body wavefunction.

$$\hat{n}(\mathbf{r}) = \sum_i^N \delta(\mathbf{r} - \mathbf{r}_i) \quad (2.20)$$

The density can be calculated as follows:

$$\begin{aligned} n(\mathbf{r}) &= \langle \Psi | \hat{n}(\mathbf{r}) | \Psi \rangle = \sum_i^N \int \delta(\mathbf{r} - \mathbf{r}_i) |\Psi(\mathbf{r}_1, \dots, \mathbf{r}_N)|^2 \\ &= N \int |\Psi(\mathbf{r}_2, \dots, \mathbf{r}_N)|^2 \end{aligned} \quad (2.21)$$

where \mathbf{r}_i are the variables associated with each of the electrons. Assuming the wavefunction is normalised to unity, the above integration over all the space yields the total number of

¹From Hartree [1], who first postulated the factorization of the wave function in single particle states in 1928, and Fock [2], who redefined the method by including Slater determinant.

electrons.

$$\int d\mathbf{r} n(\mathbf{r}) = N \quad (2.22)$$

2.1.3.2 Energy in Terms of the Density

It is necessary to represent all the energy in terms of density to eliminate wavefunction dependency. This is necessary because the electronic energy needs to be minimized with respect to density to obtain the ground state energy and corresponding electronic density. This is one of the foundations of DFT that was proposed by Hohenberg and Kohn in 1964 [5].

As we have discussed earlier (HF theory), once the wavefunction is obtained by solving the Hamiltonian the observable of other operator can be calculated by calculating the expectation value of the operator. This allows to calculate the separate the energy terms associated to the potential operator given in the Hamiltonian (2.11). For the sake of completeness lets reproduce the Hamiltonian in a simplest form

$$\begin{aligned} \hat{\mathcal{H}}_e &= \hat{T} + \hat{V}_{en} + \hat{V}_{ee} \\ &\stackrel{\text{eqn. 2.11}}{=} - \sum_j^N \frac{1}{2} \nabla_j^2 - \sum_j^N \sum_a^M \frac{Z_a}{|\mathbf{r}_j - \mathbf{R}_a|} + \frac{1}{2} \sum_{j \neq k}^N \sum_k^N \frac{1}{|\mathbf{r}_j - \mathbf{r}_k|} \end{aligned} \quad (2.23)$$

Lets assume we have managed to solve many-body problem and obtained the wavefunction.

The expectation value of the nuclei-electron interaction operator is given by

$$\begin{aligned} \langle \Psi(\mathbf{r}_1, \dots, \mathbf{r}_N) | \hat{V}_{ne} | \Psi(\mathbf{r}_1, \dots, \mathbf{r}_N) \rangle &= - \sum_j^N \sum_a^M \Psi^*(\mathbf{r}_1, \dots, \mathbf{r}_N) \frac{Z_a}{|\mathbf{r}_j - \mathbf{R}_a|} \Psi(\mathbf{r}_1, \dots, \mathbf{r}_N) \\ E_{ne} &= - \sum_a^{M=Nn} \int n(\mathbf{r}) \frac{Z_a}{|\mathbf{r} - \mathbf{R}_a|} d\mathbf{r} \\ &= \int n(\mathbf{r}) V_{ne}(\mathbf{r}) d\mathbf{r} \end{aligned} \quad (2.24)$$

The equivalent derivation for electron-electron term is not trivial. This is because the electron-electron terms require two-particle density instead of single-particle density.

$$E_{ee} = \frac{1}{2} \int \int d\mathbf{r} d\mathbf{r}' \frac{n^{(2)}(\mathbf{r}, \mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|} \quad (2.25)$$

where $n^{(2)}$ can be interpreted as the probability of finding an electron at location \mathbf{r} given that a second electron exists at location \mathbf{r}' . Eqn. (2.25) makes the many-particle problem so hard to solve. It is required to know the conditional probability $n^{(2)}$ to solve the above equation exactly. However, to make approximation single-particle density is preferred. If the two electrons were complete uncorrelated then two-particle density can be written as the product of one-particle density.

$$n^{(2)} = n(\mathbf{r})n(\mathbf{r}') + \Delta n^{(2)}(\mathbf{r}, \mathbf{r}') \quad (2.26)$$

Where $n^{(2)}$ is a correction term. The electron-electron energy can be written as

$$E_{ee} = \frac{1}{2} \int \int d\mathbf{r} d\mathbf{r}' \frac{n(\mathbf{r})n(\mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|} + \Delta E_{ee} \quad (2.27)$$

where the ΔE_{ee} term comes from the correction term in Eqn. (2.26). The kinetic energy operator has a derivative term, which creates a problem to calculate the expectation value. This is because of the derivative, it is not possible to collect wavefunction and its conjugate as a single norm square.

$$T = -\frac{1}{2} \int d\mathbf{r} \Psi^*(\mathbf{r}_1, \dots, \mathbf{r}_N) \nabla^2 \Psi(\mathbf{r}_1, \dots, \mathbf{r}_N) \quad (2.28)$$

In order to calculate kinetic energy the key assumptions of DFT is to expand the density as the sum of squares of single-particle orbitals

$$n(\mathbf{r}) = \sum_j^{N_e} |\phi_j(\mathbf{r})|^2 \quad (2.29)$$

These orbitals are called *Kohn-Sham* orbitals. Now the kinetic energy term can be written as single-particle kinetic energy plus a correction

$$T = -\frac{1}{2} \sum_j^{N_e} \int d\mathbf{r} \phi_j^*(\mathbf{r}) \nabla^2 \phi_j(\mathbf{r}) + \Delta T \quad (2.30)$$

The total ground state energy can be written as

$$\begin{aligned} E &= -\frac{1}{2} \sum_j^{N_e} \int d\mathbf{r} \phi_j^*(\mathbf{r}) \nabla^2 \phi_j(\mathbf{r}) + \int n(\mathbf{r}) V_{ne}(\mathbf{r}) d\mathbf{r} + \frac{1}{2} \int \int d\mathbf{r} d\mathbf{r}' \frac{n(\mathbf{r})n(\mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|} + \Delta E_{ee} + \Delta T \\ &= -\frac{1}{2} \sum_j^{N_e} \int d\mathbf{r} \phi_j^*(\mathbf{r}) \nabla^2 \phi_j(\mathbf{r}) + \int n(\mathbf{r}) V_{ne}(\mathbf{r}) d\mathbf{r} + \frac{1}{2} \int \int d\mathbf{r} d\mathbf{r}' \frac{n(\mathbf{r})n(\mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|} + E_{xc} \end{aligned} \quad (2.31)$$

Here the two correction terms are replaced with E_{xc} , called the *exchange-correlation* energy. The origin of this term is the difference between N interacting and noninteracting particles. Several well-developed approximations exist for exchange-correlation, and one of them is called local approximation

$$E_{xc} = \int d\mathbf{r} n(\mathbf{r}) \epsilon_{xc}([n], \mathbf{r}) \quad (2.32)$$

where ϵ_{xc} is an energy per electron at point \mathbf{r} that depends only on the density $n(\mathbf{r})$. Thus, within the local density approximation the total energy can be written as

$$E = -\frac{1}{2} \sum_j^{N_e} \int d\mathbf{r} \phi_j^*(\mathbf{r}) \nabla^2 \phi_j(\mathbf{r}) + \int d\mathbf{r} n(\mathbf{r}) V_{ne}(\mathbf{r}) + \frac{1}{2} \int \int d\mathbf{r} d\mathbf{r}' \frac{n(\mathbf{r})n(\mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|} + \int d\mathbf{r} n(\mathbf{r}) \epsilon_{xc}([n], \mathbf{r}) \quad (2.33)$$

The above equation is used to derive to obtain Kohn-Sham equation which makes DFT applicable in practice. The functional form of the above equation can be written as follows:

$$E_{KS}[n] = T_s[n] + \int d\mathbf{r} V_{ext} n(\mathbf{r}) + E_H[n] + E_{xc}[n] \quad (2.34)$$

Here V_{ext} is the external potential due to the nuclei and other external field.

2.1.4 Kohn–Sham Equations

The previous section addressed the formation of K-S equation and the idea of self-consistency. In DFT based calculation, methods are classified based on the representation of the density, potential and especially KS orbitals. The choice of representation is made to increase the computational efficiency, while maintaining the accuracy. For a choice of basis, the coefficients are the only variable to be determined (density depends on KS orbitals). The total energy of DFT becomes variational, then the solution of the self-consistent KS equations requires to determine occupied orbitals that provides a minima of the total energy.

According to the second theorem of Hohenberg and Kohn, all properties such as kinetic energy, etc. are uniquely determined if $n(\mathbf{r})$ is specified. Eqn (2.33) shows the relationship. To minimize the total energy with respect of KS orbitals, the variational principle is usually used. While performing the minimization, it is prefer to minimize with $\phi^*(\mathbf{r})$ (both yield the same result). Using the chain rule for functional derivatives, the equations becomes:

$$\frac{\delta E}{\delta \phi_i^*(\mathbf{r})} = \frac{\delta T_s}{\delta \phi_i^*(\mathbf{r})} + \left[\frac{\delta E_{ext}}{\delta n(\mathbf{r})} + \frac{\delta E_H}{\delta n(\mathbf{r})} + \frac{E_{xc}}{\delta n(\mathbf{r})} \right] \frac{\delta n(\mathbf{r})}{\delta \phi_i^*(\mathbf{r})} = 0 \quad (2.35)$$

The kinetic energy may be differentiated separately with respect to orbital. In the above equation the E_{ei} is replaced with E_{ext} which means potential due to nuclei and any other external fields.

$$-\frac{1}{2}\nabla^2\phi_i^*(\mathbf{r}) + \left[V_{\text{ext}}(\mathbf{r}) + \int d(\mathbf{r}') \frac{n(\mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|} + \epsilon_{xc}(n) + n(\mathbf{r}) \frac{\delta\epsilon_{xc}[n]}{\delta n(\mathbf{r})} \right] \phi_i(\mathbf{r}) = \epsilon_i \phi_i(\mathbf{r}) \quad (2.36)$$

Eqn 2.36 is a system of equations, represent the many-particle system in terms of single-particle orbitals. Each of these equations resemble a Schrödinger equation.

$$\left[\hat{T} + V_{\text{eff}} \right] \phi_i(\mathbf{r}) = \epsilon_i \phi_i(\mathbf{r}) \quad (2.37)$$

Here the V_{eff} is the sum of the V_H , V_{xc} and V_{ext} , which depends on the density and indirectly depends on orbitals. Now we have an equation where any change in the orbitals effect also the potential on which they in turn depend on orbital. This problem is resolved by solving Kohn-Sham system of equations self-consistently.

2.1.5 Kohn–Sham problem for an isolated atom

For an one-electron atom, the Coulombic potential, $V(\mathbf{r}) = V(r) = -Z/r$ is spherically symmetric, the solution can be split into a radial and an angular part

$$\psi_{n\ell m}(\mathbf{r}) = \psi_{n\ell}(r) Y_{\ell m}(\theta, \phi) = r^{-1} \phi_{n\ell}(r) Y_{\ell m}(\theta, \phi) \quad (2.38)$$

The above equation sometime is referred to as spherically symmetric Schrödinger equation and $Y_{\ell m}(\theta, \phi)$ are normalized spherical harmonics. Using the Laplacian in the spherical coordinates the wave equation can be reduced to the radial equation for principle quantum number n

$$-\frac{1}{2} \frac{d^2}{dr^2} \psi_{n\ell} + \left[\frac{\ell(\ell+1)}{2r^2} + V_{\text{ext}}(r) - \epsilon_{n\ell} \right] \psi_{n\ell} = 0 \quad (2.39)$$

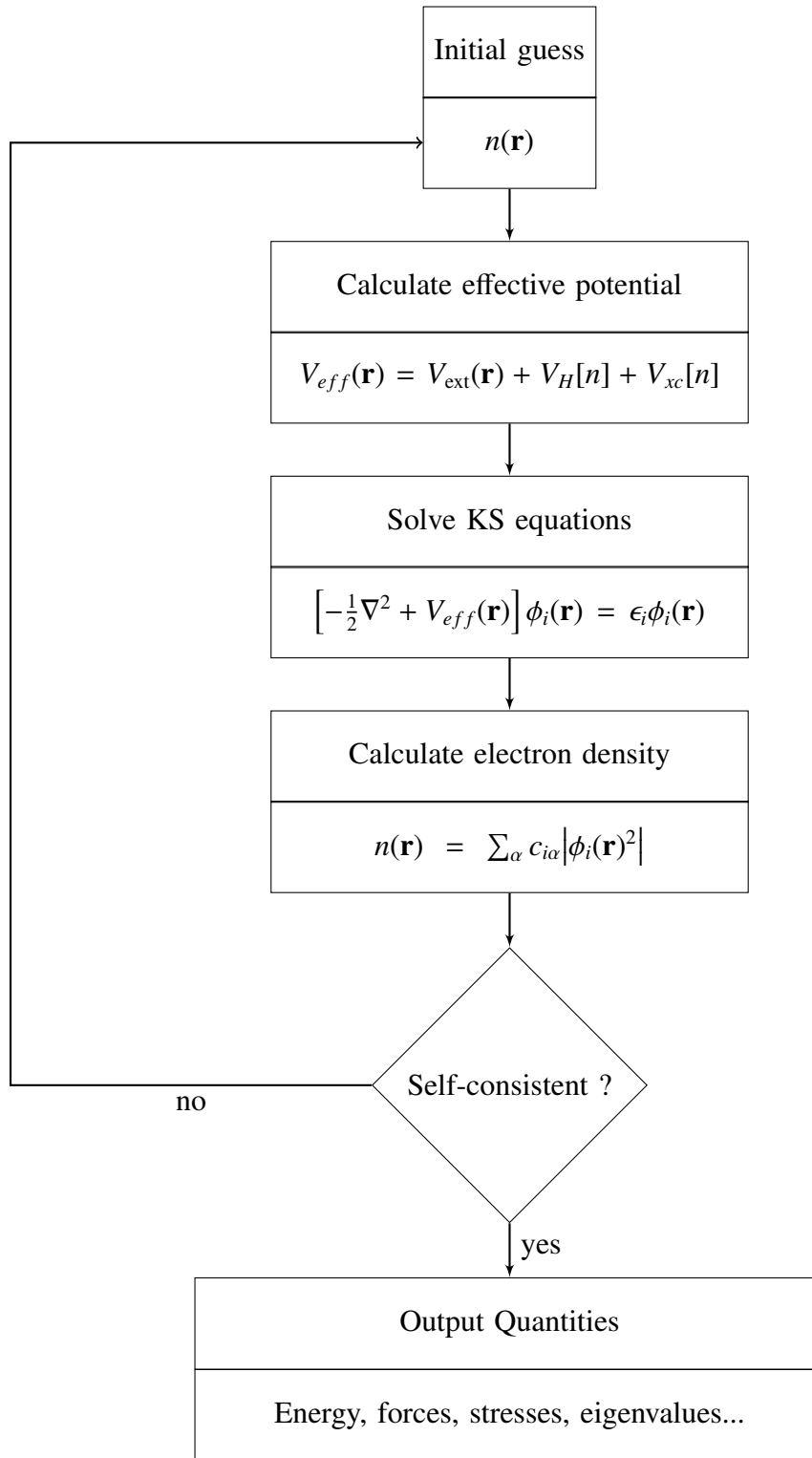


Figure 2.1. Schematic representation of the self-consistent loop solution of Kohn-Sham equations.

In the Kohn-Sham approach to the many-particle system, the form of the single-particle equations are identical to the above radial Schrödinger equation with an effective potential V_{eff} replacing the Coulomb potential. The effective potential ($V_{eff} = V_{ext}(r) + V_H(r) + V_{xc}(r)$) is spherically symmetric in the Kohn-Sham approach. The independent-particle Kohn-Sham states may be classified by the angular quantum numbers $L = \{\ell, m\}$, and the one particle equations becomes analogous to the Schrödinger equation for one-electron atom.

$$-\frac{1}{2} \frac{d^2}{dr^2} \psi_{n\ell} + \left[\frac{\ell(\ell+1)}{2r^2} + V_{eff}(r) - \epsilon_{n\ell} \right] \psi_{n\ell} = 0 \quad (2.40)$$

2.1.6 Theory of Pseudopotential

In Solids, the electrons and nuclei interact strongly through the Coulomb potential. However, according to the Fermi Liquid theory (FLT) the electronic excitation near the Fermi energy in metals behave as if they were independent particles. This leaves the strong interactions with the core electrons and the nuclei. In most cases, the core electrons are quite strongly bound, and do not respond effectively to the motions of the valence electrons. Hence, they can be regarded as essentially fixed. This is the essence of the pseudopotential approximation, the strong core potential is replaced by a pseudopotential, whose ground state wave function resembles the all electron wavefunction outside a selected core radius. In this way both the core states and the wiggles (Fig. 2.2) in the valence wavefunctions are removed. For many metals the pseudowavefunctions can be represented by lower number of planewaves. Thus making planewaves a simple and reasonable efficient basis for the pseudo wavefunctions.

2.1.7 Basic Phillips–Kleinman Construction

For a given many electron Hamiltonian, $\hat{H} = \hat{T} + \hat{U}$, where \hat{T} is the kinetic energy operator and \hat{U} is the potential energy operator, the core electron wave functions are defined

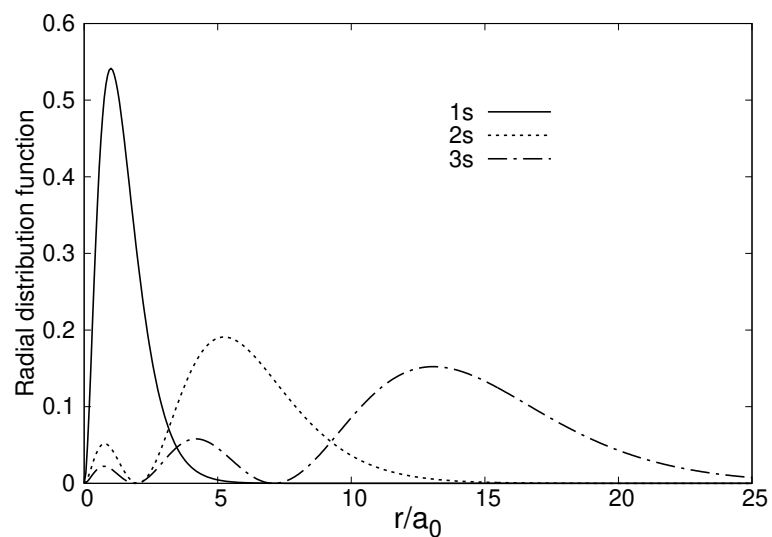


Figure 2.2. Radial distribution function of Hydrogenic 1s, 2s and 3s electron. It shows higher kinetic energy near the nucleus.

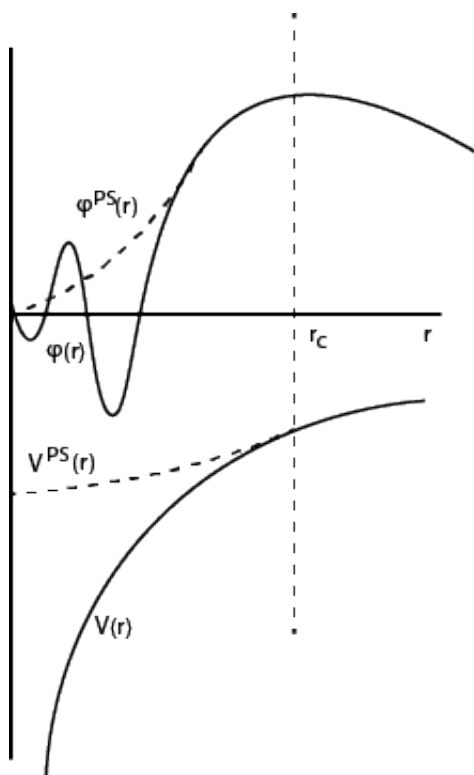


Figure 2.3. Schematic diagram of the replacement of all-electron wave function and core potential by a pseudo-wavefunction and pseudopotential.

by the Schrödinger equation

$$\hat{H} |\psi_i\rangle = \epsilon_i |\psi_i\rangle \quad (i = 1, ncore) \quad (2.41)$$

The valance electron wave function similarly can be found by the Hamiltonian

$$\hat{H} |\psi_v\rangle = \epsilon_v |\psi_v\rangle \quad (2.42)$$

The valence electron wave function is orthogonal to the core electron wave function ($\langle \psi_v | \psi_i \rangle = 0$), this orthogonality always has to be preserved, even if the core electrons are not treated explicitly. One way to preserve this orthogonality is to write valence electron wave function in a basis set that is priori orthogonal to the core electrons. The simple Gram-Schmidt orthogonalization technique can be used. Herring [6] was the first one to use Orthogonalized plane waves (OPWs)(Appendix C) as basis for the first quantitative calculations of bands. Using this idea, we can orthogonalize any arbitrary basis set $\{|\chi_n\rangle\}$ to the core electron wave functions by defining a new basis set $\{|\varrho_n\rangle\}$

$$|\varrho_n\rangle = |\chi_n\rangle - \sum_{i=1}^{ncore} \langle \psi_i | \chi_n \rangle |\psi_i\rangle \quad (2.43)$$

Here each of the new basis set, $\{|\varrho_n\rangle\}$, satisfies $\langle \chi_n | \psi_i \rangle = 0$ for each $|\psi_i\rangle$. Now we can express the valance electron wave function as a linear combination of the new basis sets,

$$|\psi_v\rangle = \sum_n C_n |\varrho_n\rangle \quad (2.44)$$

Using Eqn 2.43 into the Eqn 2.44, the valence electron can be expressed in the following way. The orthogonality condition with the core electron still valid.

$$|\psi_v\rangle = \sum_n C_n \left[|\chi_n\rangle - \sum_{i=1}^{ncore} |\psi_i\rangle \langle \psi_i | \chi_n \rangle \right] = |\phi\rangle - \hat{\Omega} |\phi\rangle \quad (2.45)$$

Here, $\hat{\Omega}$ is a projection operator for core electron wave function

$$\hat{\Omega} = \sum_{i=n}^{ncore} |\psi_i\rangle\langle\psi_i| \quad (2.46)$$

and a new wave function which is a linear combination of $|\chi_n\rangle$, sometime designated as pseudo-orbital,

$$|\phi\rangle = \sum_n C_n |\chi_n\rangle \quad (2.47)$$

This technique of representing the valance electron wave function in preorthogonalized basis set has been studied and used as a computational tool [6]. It took the insight of the Phillips and Kleinman [7]. The new pseudoorbitals satisfies the orthogonality condition, but it also change the Hamiltonian so that the eigen values are same with the valance electrons. Mathematically, it can be obtained by replacing original valance electron Hamiltonian equation (Eqn 2.42) with newly obtained pseudo wave function.

$$\hat{H} |\psi_v\rangle = \hat{H} \left[|\phi\rangle - \sum_n |\psi_i\rangle \langle\psi_i|\phi\rangle \right] = \epsilon_v \left[|\phi\rangle - \sum_n |\psi_i\rangle \langle\psi_i|\phi\rangle \right] \quad (2.48)$$

Rearranging the above equation provides a new Hamiltonian,

$$\left[\hat{H} + \sum_n^{ncore} (\epsilon_v - \epsilon_i) |\psi_i\rangle \langle\psi_i| \right] |\phi\rangle = \epsilon_v |\phi\rangle \quad (2.49)$$

The above equation has the form of the original valance electron eigenequation (2.42), but with an extra term for preorthogonalization. This extra potential ($V_{nl} = \sum_n^{core} |\psi_i\rangle\langle\psi_i|$), is a nonlocal operator, and the pseudo orbital ($|\phi\rangle$) is an eigenstate of the new effective Hamiltonian, $\hat{H} + V_{nl}$. The new Hamiltonian has an extra potential V_{nl} , which depends on the angular momentum l due to the spherical symmetry. Because of its spherical symmetry, each angular momentum l, m can be treated separately. The dependence on l means that, a

pseudopotential is an non-local operator, can be written in “semilocal” (SL) form

$$\hat{V}_{SL} = \sum_{\ell m} |Y_{\ell m}\rangle V_{\ell}(r) \langle Y_{\ell m}| \quad (2.50)$$

Where $Y_{\ell m}(\theta, \phi) = P_{\ell}(\cos(\theta))e^{im\theta}$. It is semi-local because it is non local on the angular variables but local in the radial variable.²

The sophistication and accuracy have evolved considerably since the Phillips-Kleinman construction. This development produces many methods of generating pseudopotentials. All of these methods follow these goals: (1) Pseudopotential should be as soft as possible, so that it can allow representation of pseudo-wavefunction with fewer planewaves. (2) Transferability has to be maintained (it means a generated pseudopotential with a configuration should produce other properties accurately) (3) the pseudo-charge density should produce the valance charge density as accurately as possible.

2.1.8 Norm-Conserving Pseudopotentials

Hamann, Schlüter and Chiang [8] developed the concept of norm-conservation, which was a first step to fulfill all the above requirements. As the exchange-correlation energy of the electronic system depends on the electron density, it is necessary that outside the core region the real and pseudo wavefunctions be identical. In the outer region ($r > r_c$), both functions coincide. Therefore, the total charge density created in the core region ($r < r_c$) must be the same after pseudisation:

$$\int_0^{r_c} \psi_{AE}^*(r) \psi_{AE}(r) dr = \int_0^{r_c} \psi_{ps}^*(r) \psi_{ps}(r) dr \quad (2.51)$$

Where $\psi_{ae}(r)$ is the all electron wavefunction and ψ_{ps} is the pseudo wavefunction. The logarithmic derivatives of the real and pseudo wave function and their energy derivative agree in the outer region. These types of pseudopotentials are the most transferable

² P_l is the Legendre polynomials

since they are able to reproduce the scattering properties of an ion in different chemical environments[8]. The downside of Norm-Conserving pseudopotential is a higher cutoff radius and thus increased memory and CPU requirements. Troullier and Martins [9] developed a more effective method to generate norm-conserving pseudopotentials for practical calculations.

2.1.9 Ultrasoft Pseudopotentials

The norm conservation requirement produces a very high requirement of cutoff energy for the plane-wave basis set. Particularly the tightly bound orbitals that have a substantial fraction of their weight inside the core region of the atom. There are some important cases where it was impossible to construct a pseudopotential that allows a significant reduction of the cutoff energy. Vanderbilt [10] suggested to relax the norm conservation criteria in favor of a smoother (i.e. softer) potential. The ultrasoft pseudopotentials are difficult to construct and require extensive testing [11].

2.1.10 Projector Augmented-Wave Method (PAW)

The electronic wave functions oscillate wildly near the nuclei (Fig. 2.2) than the bonding area between the atoms. Expanding these region using plane-wave creates computational challenges. Augmented-wave methods uses the separation of the wave functions in two regions to address this issue. The first part is partial wave expansion inside an atom-centered sphere called the augmentation region and a plane wave expansion outside. Both expansions are continuously differentiable at the boundary.

Blöchl [12] suggested that there is a linear transformation from the all-electron to the pseudo wave functions. The transformation is as follows:

$$|\Psi\rangle = |\tilde{\Psi}\rangle + \sum_i (|\phi_i\rangle - |\tilde{\phi}_i\rangle) \langle \tilde{p}_i | \tilde{\Psi} \rangle \quad (2.52)$$

Here ϕ_i are the partial waves within the augmentation regions, and $\langle \tilde{p}_i |$ is a projector with a condition of $\langle \tilde{p}_i | \tilde{\phi}_i \rangle = \delta_{ij}$. The tilde quantities are related the pseudo representation. Kresse and Joubert [11] showed a connection between PAW and US-pp and how the PAW method can be implemented into existing code.

References

1. D. R. Hartree, Mat. Proc. Cambridge Philos. Soc. **24**, 89 (1928).
2. V. Fock, Zeitschrift für Physik **61**, 126 (1930).
3. L. H. Thomas, in *Mathematical Proceedings of the Cambridge Philosophical Society*, Vol. 23 (Cambridge University Press, 1927) pp. 542–548.
4. E. Fermi, Rend. Accad. Naz. Lincei **6**, 32 (1927).
5. P. Hohenberg and W. Kohn, Phys. Rev. **136**, B864 (1964).
6. C. Herring, Phys. Rev. **57**, 1169 (1940).
7. J. C. Phillips and L. Kleinman, Phys. Rev. **116**, 287 (1959).
8. D. R. Hamann, M. Schlüter, and C. Chiang, Phys. Rev. Lett. **43**, 1494 (1979).
9. N. Troullier and J. L. Martins, Phys. Rev. B **43**, 1993 (1991).
10. D. Vanderbilt, Phys. Rev. B **41**, 7892 (1990).
11. G. Kresse and D. Joubert, Phys. Rev. B **59**, 1758 (1999).
12. P. E. Blöchl, Phys. Rev. B **50**, 17953 (1994).

CHAPTER 3

EFFECT OF XENON ON THE OVERALL THERMAL CONDUCTIVITY OF U-10Mo

This chapter was largely published as an article in Journal of Nuclear Materials. The authors of that paper are A. Rafi M. Iasir and Karl D. Hammond of the University of Missouri and Nickie J. Peters of the University of Missouri Research Reactor.

3.1 Introduction

Thermal conductivity is an important property of any nuclear fuel, since most of the important physical properties are temperature-dependent. In the case of high-performance reactors, fuels must undergo high fission density at relatively low temperatures. For this reason, research reactor fuels are designed for efficient heat rejection. During test operations, Burkes and coworkers [1] observed that the thermal conductivity in monolithic fuels decrease significantly with increased burnup. For a fission density of $3.30 \times 10^{21} \text{ cm}^{-3}$ at 200 °C, thermal conductivity decreased by approximately 30%; at $4.53 \times 10^{21} \text{ cm}^{-3}$, conductivity decreased by 45% [1].

Fission also creates a variety of fission products, which result in gas bubbles, metallic precipitates, and solutes in the fuel matrix [2]. These fission products, in addition to radiation damage in reactor environments, result in complex microstructural evolution that restructures the nuclear fuel over time. Fission gas bubbles are particularly problematic, as they cause changes in thermal conductivity and swelling of the fuel. In addition, ^{135}Xe is a potent neutron absorber.

For every four fission events, an average of one inert gas atom (xenon or krypton) is produced. The dominant gaseous species is xenon, accounting for almost 85% of fission gas [3, 4]. Xenon atoms in U–Mo alloy fuels have a strong tendency to precipitate into small bubbles due to their low solubility. The formation and growth of gas bubbles inside irradiated nuclear fuels has technical importance, as bubbles influence the microstructure of the material [5]. Recent TEM and SEM images show that fission bubbles in U-10Mo distribute themselves in both inter-granular and intra-granular formations [6–9]. High-fission-density fuels show randomly-distributed, micrometer-sized fission gas bubbles distributed throughout the grains [9]. Inter-granular bubble density increases with burnup.

Inside the micrometer-sized grains, fission gas forms superlattices [6, 7, 9], similar to those seen in ion-irradiated materials [10–19]. Typical bubble sizes are 2–6 nm in diameter, and the distance between the bubbles is typically in the 4–12 nm range. The superlattice usually has the same crystal structure as the host material, but an exception exists: the superlattice in U-10Mo shows a face-centered cubic structure in a body-centered cubic matrix. An ion-irradiated bubble superlattice has a lattice parameter of tens of nanometers [6]; that of fission gas bubbles is typically similar [20].

The thermal conductivity of a monolithic U–Mo fuel plate is at a maximum prior to irradiation [1]. Inclusions and porosity change the thermal and the electrical conductivity of many materials [21]. Solid fission products usually have minimal impact on overall thermal conductivity, as their conductivities are similar to the conductivity of the fuel. Gases, on the other hand, have much lower thermal conductivity than the matrix, and typically have much lower densities and heat capacities as well. Various models, both empirical and theoretical, have been proposed to describe the changes in conductivity due to gas bubbles. Maxwell [22] was among the first to derive an expression for the effective thermal conductivity of heterogenic media; his model assumed uniform distribution of spherical particles in a matrix. A few other empirical models also exist [23–25]; unfortunately, the large diversity of pore shape, pore size, and type of included material inside nuclear fuel make it

impossible to describe heat transfer with a single equation. Several theoretical models have been proposed to describe the influence of porosity and inclusions on the thermal conductivity [22, 26–29]. These theoretical models usually assume pores with regular geometric shapes, and that the pore arrangement is sufficiently dilute so as to neglect interaction between inclusions.

The microstructure of irradiated nuclear fuels is very complicated due to the lack of consistency between bubbles. The intra-granular gas bubbles are two or three order of magnitude smaller than the inter-granular gas bubbles [30]. The shapes of the bubbles are also highly variable: the intra-granular gas bubbles are approximately spherical, whereas inter-granular gas bubbles do not have consistent shapes. In this work, we assess contributions to the thermal conductivity of U-10Mo from both inter- and intra-granular gas bubbles. The impact of xenon bubble pressure on the overall thermal conductivity is also estimated. At the end, we present a study of the influence of different bubble arrangements on the overall thermal conductivity.

3.2 Methods

A finite element model was used to solve the steady-state heat conduction equation in the presence of various microstructures. Two types of microstructures containing xenon gas bubbles were used: a xenon bubble superlattice structure representing intra-granular bubbles, and a grain boundary structure representing inter-granular bubbles. Figure 3.1 shows an example of an intra-granular bubble distribution, while Figure 3.2 shows the inter-granular bubble distribution. In the intra-granular bubble case, xenon gas bubbles were placed in a variety of spatial configurations, including configurations consistent with a gas bubble superlattice. All simulations were performed in a two-dimensional domain. The gas bubble superlattice structure was created based on data from Miller et al. [6]. According to Miller et al. [6], the bubble size inside the grain boundary superlattice structure is normally distributed. Based on their experimental values, we chose four bubble diame-

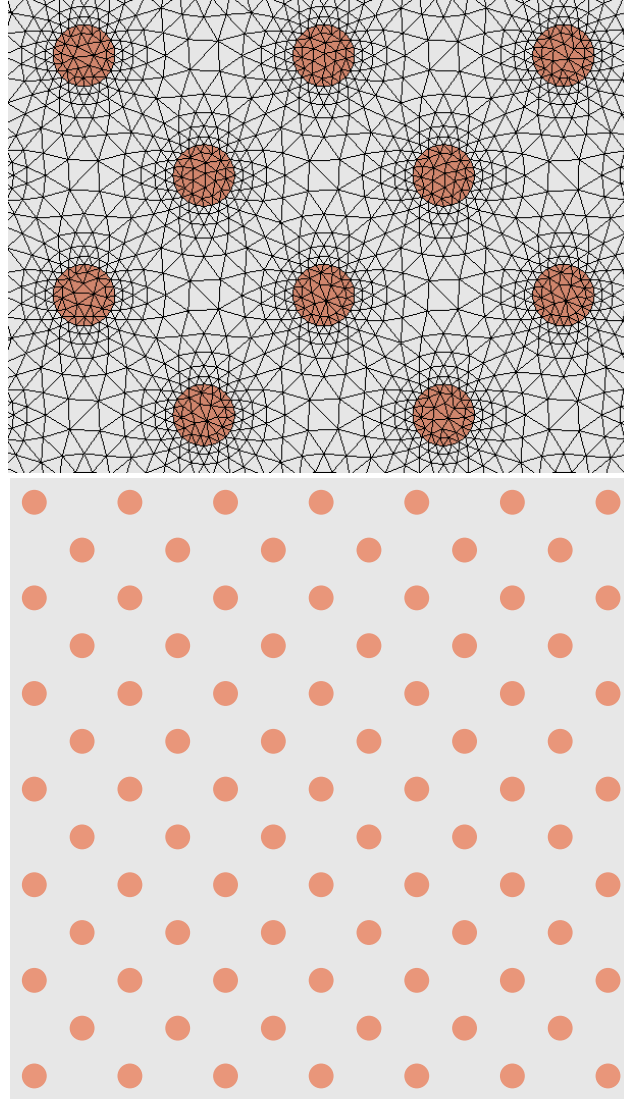


Figure 3.1. (a) Discretized domain of intra-granular xenon bubbles inside a U-10Mo matrix; (b) Example two-dimensional bubble distribution used for intra-granular xenon gas, consisting of bubbles with 3.1, 3.6, 3.75, and 4.0 nm diameters, consistent with the work of Miller and coworkers [6]. The lattice parameter for the gas bubble superlattice is 12.0 nm.

ters to create our simulation. Since the superlattice in U-10Mo is FCC, the two-dimensional structure of bubbles was created based on the FCC structure with a 12 nm lattice parameter, which was also taken from Miller et al. [6]. The bubble sizes were randomly sampled from this distribution using the discrete values of 3.1, 3.6, 3.75, and 4.0 nm in diameter. The square domain's dimensions were 80 nm \times 80 nm, which results in 85 bubbles with a lattice constant of 12 nm. Triangular elements were used to create the mesh using the Trelis Pro software package [31].

In the inter-granular bubble case, the grain boundary structure of U-10Mo was created based on images from Miller et al. [7]. Their SEM (Scanning Electron Micrograph) of a Focused Ion Beam (FIB) cross-section showed fission gas bubbles populating the grain boundaries, as shown in Figure 3.2. This domain was also discretized with triangular elements. The top and bottom boundaries of the domain of the FEM domain were assumed to be adiabatic. The left and right boundary have fixed-temperature boundary conditions applied. This temperature difference drives the heat flow.

The thermal conductivity of U-10Mo was estimated from a linear fit of thermal conductivity as a function of temperature between 298 K and 1073 K from Kaufmann [33]. Burkes et al. [34] also provided a linear fit of the U-10Mo thermal conductivity as a function of temperature up to 873 K; their results were in good agreement with Kaufmann's [33]. The thermal conductivity of xenon depends on both temperature and pressure [32], as shown in Figure 3.3. The pressure inside a bubble depends on the radius of the bubble, the surface tension, the magnitude of the Burgers vector, and the shear modulus of the host material [35, 36]. According to Xiao et al. [37], the pressure inside a xenon bubble can be as high as 120 kbar. Such high pressures suggest the possibility of forming solid xenon bubbles inside the fuel [38–40]. Unfortunately, thermal conductivity data for xenon above 1000 bar are not available, so we chose two limiting sets of thermal conductivity data: 1 bar and 1000 bar. For each set of data, a polynomial fit (fifth order) was used to interpolate the conductivity over the temperature range.

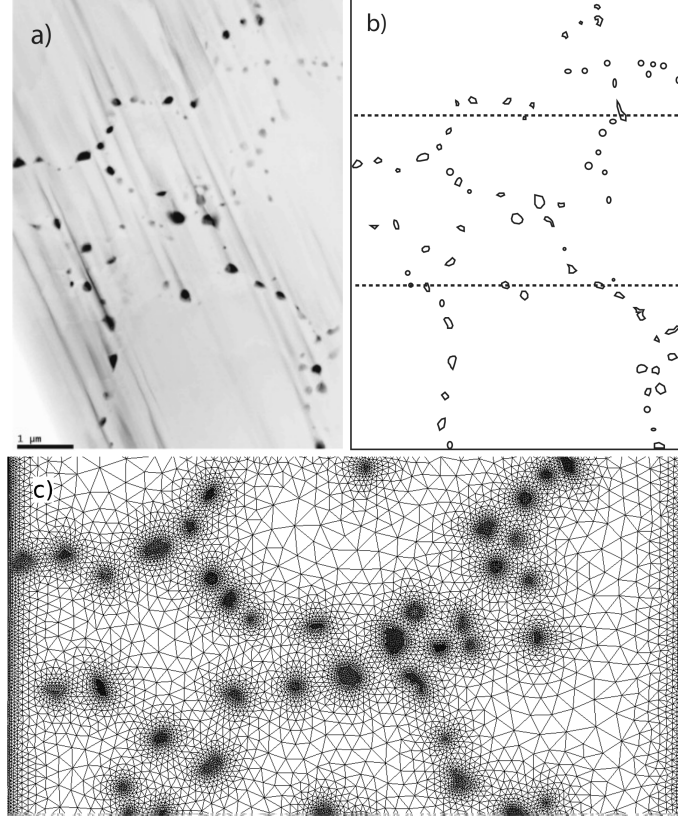


Figure 3.2. (a) SEM image of the fission gas bubbles along the grain boundaries from Miller et al. [7] used for FEM calculations [7] (b) Geometry created based on the grain boundary fission gas image in (a) (c) FEM mesh with grain boundary fission gas of the region between the dotted line in (b)

3.2.1 Effective Thermal Conductivity Calculation

The temperature in a composite material in the absence of heat source is described by the heat equation:

$$\nabla \cdot (K \nabla T) = 0 \quad (3.1)$$

where $K(x, y) = \chi_1(x, y)K_1 + \chi_2(x, y)K_2$ is the thermal conductivity tensor, T is the temperature, K_i ($i = 1$ for the matrix and 2 for the bubble) is the thermal conductivity tensor, and $\chi_i(x, y)$ is the indicator function of phase i . Local heat flux can be calculated using the equation

$$q''(x, y) = -K(x, y) \cdot \nabla T(x, y) \quad (3.2)$$

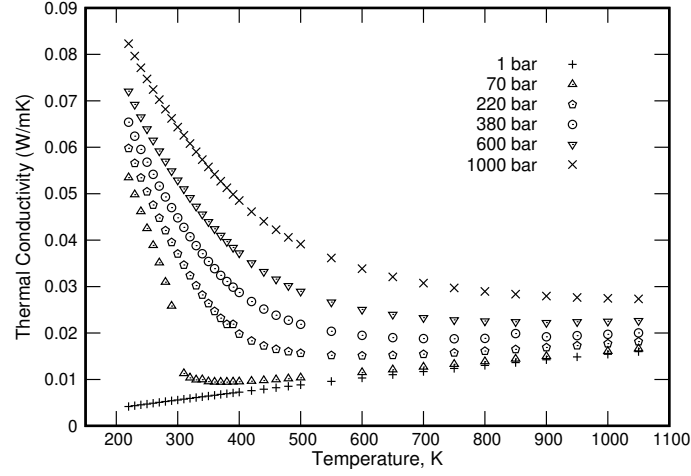


Figure 3.3. Thermal conductivity of xenon as a function of pressure and temperature based on the measurements of Rabinovich et al. [32]. Note that the critical point of xenon is 289.733 K and 58.42 bar; this is why there is such a drastic change in conductivity at low temperature between the 1 bar and 70 bar isobars.

where $q''(x, y)$ is the local heat flux vector and $\nabla T(x, y)$ is the local temperature gradient. Local temperature and heat flux are calculated by solving Equation (3.1) and (3.2). The components of the effective thermal conductivity tensors are calculated via

$$K_{\text{eff}}^x = -q''_x \left\langle \frac{\partial x}{\partial T} \right\rangle \quad (3.3)$$

Where q''_x is the mean heat flux in the x direction, and $\left\langle \frac{\partial x}{\partial T} \right\rangle$ is the average inverse temperature gradient in the x direction. The MOOSE Framework [41] was used to solve Equation (3.1) with Dirichlet boundary conditions at $x = 0$ and $x = L$ and Neumann (adiabatic) boundary conditions at $y = 0$ and $y = L$. The effective thermal conductivity was calculated using Equation (3.3).

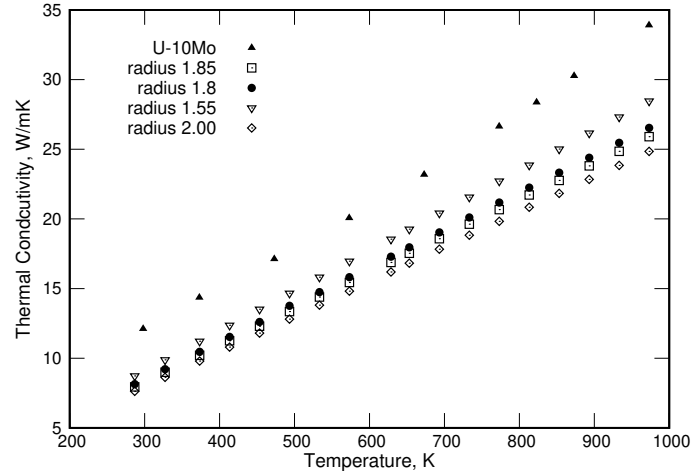


Figure 3.4. Comparison between the thermal conductivity of U-10Mo (from Kaufmann [33]) to the effective thermal conductivity of U-10Mo with intra-granular xenon bubbles of different diameters as arranged in Figure 3.1b.

3.3 Results and Discussion

3.3.1 Effect of Xenon Gas Bubbles on the Thermal Conductivity

We examined two broad categories of bubbles: inter-granular bubbles (i.e., bubbles that collect at grain boundaries), and intra-granular bubbles. The intra-granular case is intended to represent the effect of a gas bubble superlattice (GBS) on the conductivity. We will discuss each case in turn.

3.3.1.1 Intra-Granular Bubbles

A two-dimensional representation of a gas bubble superlattice, as shown in Figure 3.1, was used to simulate the effect of intra-granular bubbles on the thermal conductivity. Five different bubble sizes were used, each with the same superlattice constant (resulting in the same center-center distance between bubbles). Figure 3.4 shows the effective thermal conductivity due to the xenon bubble distribution in the intra-granular region. As is clear from Figure 3.4, the thermal conductivity decreases with increasing bubble size, and is 20–40 percent lower in all cases than it is for bubble-free U-10Mo. In these simulations, the thermal conductivity of xenon was assumed constant at its 1 bar value (it is still a

function of temperature). Figure 3.5 shows the result of the finite element method solution compared with the theoretical solution for porous materials' thermal conductivity from the Maxwell–Eucken equation [22],

$$\lambda = \lambda_s \frac{\lambda_p + 2\lambda_s + 2\nu_p(\lambda_p - \lambda_s)}{\lambda_p + 2\lambda_s - \nu_p(\lambda_p - \lambda_s)}, \quad (3.4)$$

where λ is the effective thermal conductivity of the fuel, λ_s is the thermal conductivity of the continuous phase (U-10Mo), λ_p is the thermal conductivity of the dispersed phase (xenon bubble), ν_p is the volume fraction of the dispersed phase (i.e., the volume fraction of xenon in U-10Mo). Equation (3.4) assumes the pore volume fraction is less than 15 percent, that the pores are dispersed uniformly in the solid, and that the distance between the pores is large enough that they do not interact [42, 43]. The result is also compared with the Hashin–Shtrikman upper bound, which is based on a theoretical expression derived for the magnetic permeability of a multiphase material [44],

$$\lambda = \frac{1}{4} \left[\lambda_p(3\nu_p - 1) + \lambda_s(2 - 3\nu_p) + \left(\left[\lambda_p(3\nu_p - 1) + \lambda_s(2 - 3\nu_p) \right]^2 + 8\lambda_s\lambda_p \right)^{\frac{1}{2}} \right]. \quad (3.5)$$

Figure 3.5 shows the effect of distributed gas bubbles in the intra-granular region (grain boundary bubbles were not included). Both theoretical models over-predict the conductivity by 5–10 percent, and the absolute error increases with temperature.

3.3.1.2 Inter-Granular Bubbles

Inter-granular fission gas bubbles are associated with bubbles that collect on or near grain boundaries. Bubbles are naturally drawn to grain boundaries because of the excess volume that accompanies grain boundaries, as well as the decreased energy associated with void formation at grain boundaries relative to the bulk.

To evaluate the effect of inter-granular fission gas on the overall thermal conductivity, Figure 3.2b was used as the simulation domain. As can be seen in Figure 3.2, fission gas

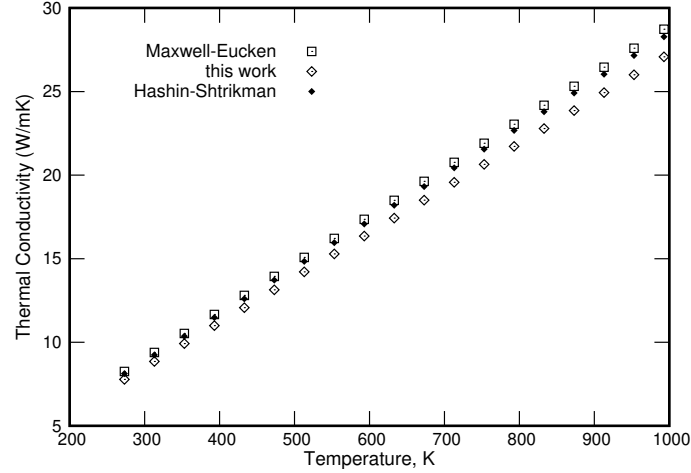


Figure 3.5. Comparison of the calculated effective thermal conductivity of U-10Mo with intra-granular xenon bubble (radius 1.55 nm, 10% porosity) with the Maxwell–Eucken [22] and Hashin–Shtrikman [44] models. In all cases, we find that the two theoretical models over-predict the thermal conductivity by about 5–10 percent compared with the numerical solution.

bubbles trapped on grain boundaries do not have consistent shapes. Note that this is only a snapshot in time of the grain structure: as burnup increases, the stress in the fuel changes, more fission gas is evolved, and the grains can rotate and change shape. For simplicity, the thermal conductivity values at 1 bar were used for xenon.

The presence of these (intra- and inter-granular) xenon bubbles decreased the thermal conductivity by more than 25 percent, as shown in Figure 3.6. According to Miller et al. [7], their sample (on which our simulations are based) went through a fission density of $3.46 \times 10^{21} \text{ cm}^{-3}$. At this fission density, Burkes and coworkers [1] found that the experimental thermal conductivity of U-10Mo reduced to almost 33 percent of its unirradiated value at 473 K. It should be noted that the real material has a three-dimensional grain boundary structure with varying levels of fission gas at each cross section, meaning our estimates of the thermal conductivity (which effectively assume rod-like inclusions rather than spheres) will be too low. Past studies [21, 45] have indicated that conductivity in the presence of inclusions is underestimated in two-dimensional models. This suggests that the measured conductivity (33% of the conductivity of the unirradiated material) may be

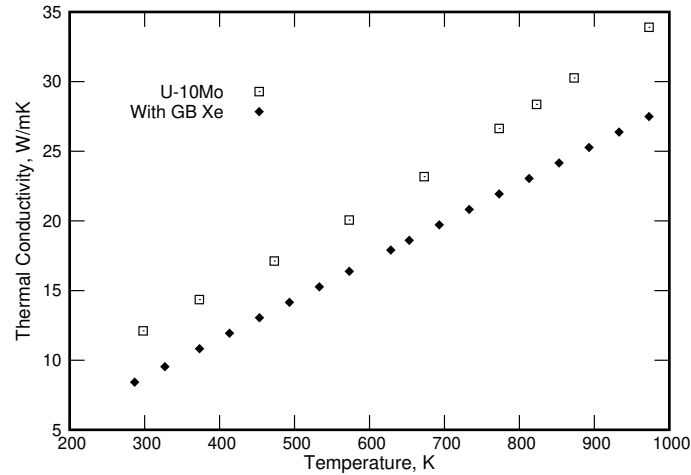


Figure 3.6. Comparison between the thermal conductivity of bubble-free U-10Mo with that of U-10Mo that has xenon bubbles decorating the grain boundaries according to the distribution in Figure 3.2. A 4% drop is observed, increasing with temperature.

reasonably consistent with the conductivity estimated here (i.e., 25% of the conductivity of the unirradiated material).

3.3.2 Effect of Xenon Pressure on the Overall Thermal Conductivity

To evaluate the impact of the pressure of the xenon bubbles on the overall thermal conductivity, we performed a study of the overall conductivity as a function of temperature for five different xenon bubble pressures given a fixed bubble distribution (Figure 3.1b). Each pressure has a distinct thermal conductivity (Figure 3.3) as a function of temperature. In this part of the study, a constant bubble size was used (radius 1.55 nm). The results are shown in Figure 3.7. The results show little to no change of the overall thermal conductivity of the fuel due to the bubbles' pressure over the range studied. However, though xenon has a wide range of thermal conductivities at different pressures (see Figure 3.3), the effect is negligible relative to the thermal conductivity of the fuel.

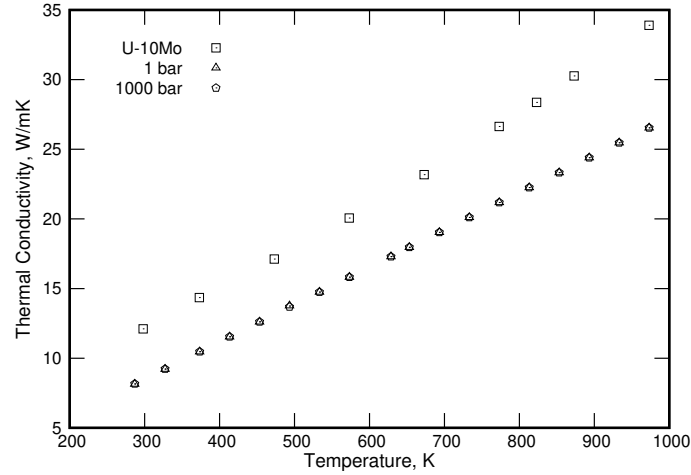


Figure 3.7. Overall thermal conductivity of U-10Mo using the thermal conductivity of xenon at two extremes of pressure (1 bar and 1000 bar), compared to that of pure (bubble-free) U-10Mo. Bubbles are distributed as in Figure 3.1b with radii of 1.55 nm.

3.3.3 Effect of Bubble Arrangement on Thermal Conductivity

We performed a series of simulations to determine whether bubble distribution has a significant influence on the overall thermal conductivity. Two cases were considered. In the first case, we used same number (16) of bubbles of the same diameter (1 nm) and organized them into five different arrangements. The arrangements are arbitrary, but each has the same area fraction of bubbles (xenon gas). In the first arrangement (Figure 3.8a), the bubbles are dispersed uniformly throughout the domain. In Figure 3.8b, the bubbles are arranged in a denser pattern with bubble-free portions near the high-temperature side. In Figure 3.8c, the bubbles are arranged in one corner. In Figure 3.8d, the bubbles are tightly clustered near the center of the domain, creating significant bubble-free regions at the top and bottom. The overall thermal conductivities for these arrangements are presented in Figure 3.9. In these simulations, heat is flowing from left to right, whereas the top and bottom boundaries are insulating (adiabatic).

Based on the results from Figure 3.8, arrangement (d) shows a minor deviation, particularly at high temperatures, compared to the other arrangements. The other four bubble

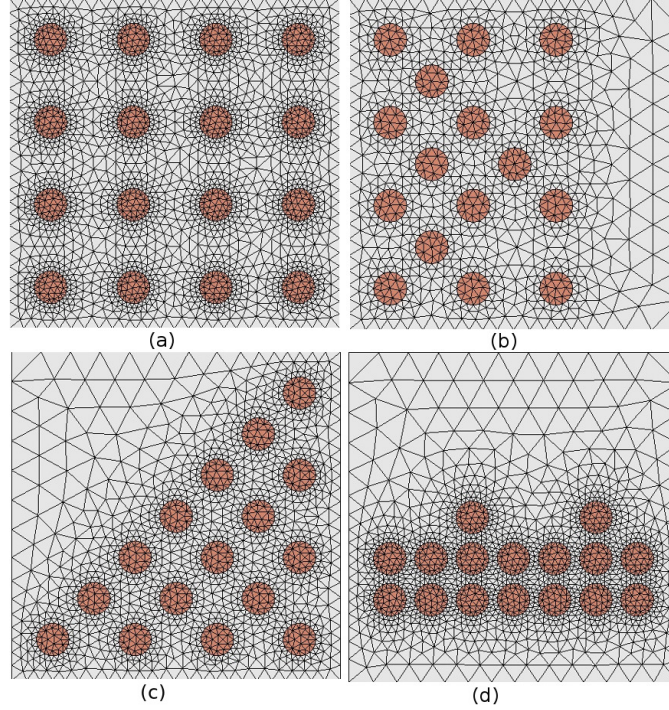


Figure 3.8. Different bubble arrangements in which the area of each bubble and the number of bubbles are the same. Heat flows from left to right in these simulations; only arrangement (d), with its uninterrupted “heat channel” in the top half of the domain, shows significantly different conductivity.

arrangements do not produce significantly different thermal conductivities. The reason for the deviation for case (d) is the relatively wide “heat channel” in the direction of the heat flow, which is absent in the other arrangements. The highest thermal conductivity difference between Figure 3.8d and the other arrangements is approximately $0.93 \text{ W/m}\cdot\text{K}$, which is also a function of the open channel’s area.

In the second case, different bubble sizes were used with constant total area. As the first case shows, bubble arrangement has minimal impact on the overall heat transfer unless it produces a significant heat transfer channel in direction of the heat flow. In this step, we kept the total area covered by the bubbles the same, but with different sizes of bubbles. To keep the area same while decreasing the bubble diameter, the number of bubbles increases. Figure 3.10 shows the four different arrangements with different bubble sizes. None of

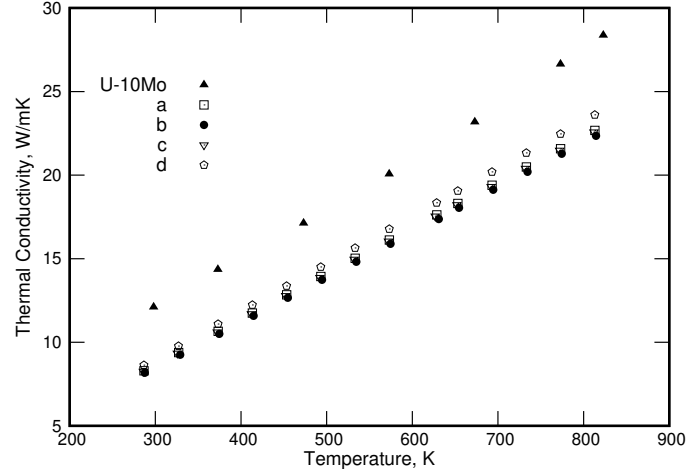


Figure 3.9. Comparison of the calculated thermal conductivity of different bubble arrangements (constant bubble area and diameter). Only arrangement (d), with its properly-oriented “heat channel,” shows significant differences from the others, and such differences are relatively insignificant compared to the bubble-free conductivity.

the arrangements creates a heat transfer channel in the direction of heat flow. The results are shown in Figure 3.11. The results show no significant change in the overall thermal conductivity. We conclude that the bubble arrangement has little impact unless it produces a significant bubble-free heat transfer channel.

In our calculation, grain boundary xenon gas bubbles had very minimal impact on the overall heat transfer. That is because our sample has very low grain boundary fission gas areal density, less than 2% of the total area. Grain boundary fission gas bubble size increases with an increase in burnup [5]. With an increase in fission density, more fission gas usually diffuses to the grain boundary area and recrystallization [46] subdivides the grains to accommodate the fission gas near the grain boundaries. This also increases the grain boundary fission gas density. Our results were also compared with porosity correction models, specifically those of Bauer [47] and Peddicord [48]. Bauer’s model ($\lambda = \lambda_0 e^{(-2.14\nu)}$, where λ_0 is the thermal conductivity of the 100% dense material and ν is the porosity) over-predicts the porosity correction factor for thermal conductivity. Peddicord’s model ($\lambda = \lambda_0 (1 - \nu)^{2.58}$) agrees better with the effective thermal conductivity from

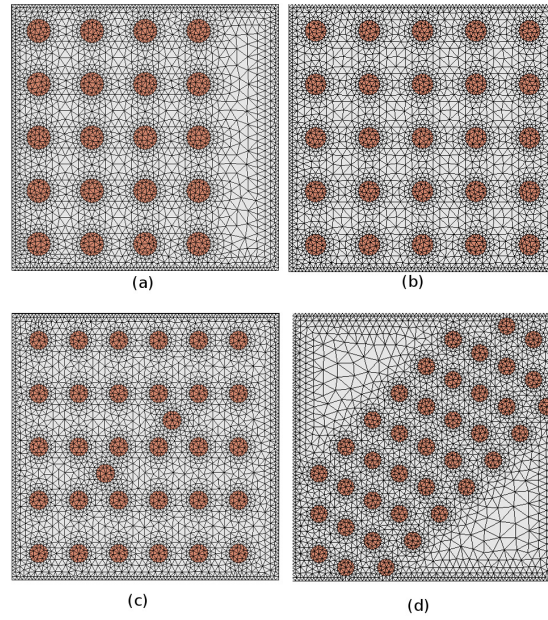


Figure 3.10. Different bubble arrangements where the area is the same but the bubbles have different diameters. (a) 20 bubbles, (b) 25 bubbles, (c) 32 bubbles, (d) 38 bubbles.

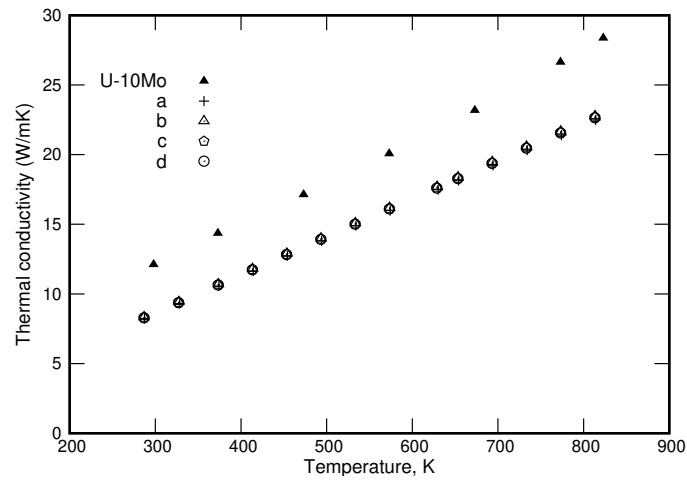


Figure 3.11. Comparison of thermal conductivity between different bubble diameters at constant total bubble area with bubble-free U-10Mo. Bubble arrangements are shown in Figure 3.10. Bubble diameters are (a) 0.894 nm (b) 0.8 nm (c) 0.707 nm and (d) 0.6488 nm; the bubble area fraction is 12.6% percent.

our simulations. All these empirical models are applicable to intragranular gas bubbles with uniform distribution and negligible fission gas thermal conductivity. In our calculation, all the thermal conductivities are measured from two-dimensional finite element models, but two-dimensional thermal conductivity usually represents the lower limit of the three-dimensional thermal conductivity [49]. Accurate estimation of this limit is very important.

3.4 Conclusions

Estimating the thermal conductivity of nuclear fuel is an important part of understanding fuel behavior in nuclear reactors. In our work, xenon gas was used to represent fission gas bubbles in U-10Mo monolithic fuels. The impact of distributed xenon bubbles on the overall thermal conductivity of U-10Mo is significant, resulting in a 25–35 percent drop in conductivity for the bubble volume fractions studied, largely independent of bubble arrangement. Both intra- and inter-granular gas bubble structures were used. For intra-granular bubbles, a gas bubble superlattice structure was used. The results indicate that the Maxwell–Eucken and Hashin–Shtrikman models overestimate thermal conductivities by at least 5% for the bubble volume fraction studied.

The pressure dependence of xenon’s thermal conductivity was also studied to estimate the impact of bubble pressure on the overall thermal conductivity of U-10Mo. Our results indicate that bubble pressure is not a significant factor for the bubble densities studied—the overall thermal conductivity remains largely unchanged between 1 bar and 1000 bar.

We find that both intra- and inter-granular xenon bubbles reduce the overall thermal conductivity by more than 25 percent. Different bubble arrangements have very little impact on the overall heat flow, unless the arrangement leads to a significant bubble-free channel through which heat can be conducted without interference from nearby bubbles. Bubble size is also not a significant factor, as different bubble sizes at the same bubble areal density produce a U-10Mo slab with identical overall conductivity.

References

1. D. E. Burkes, A. M. Casella, A. J. Casella, E. C. Buck, K. N. Pool, P. J. MacFarlan, M. K. Edwards, and F. N. Smith, *J. Nucl. Mater.* **464**, 331 (2015).
2. V. V. Rondinella and T. Wiss, *Mater. Today* **13**, 24 (2010).
3. A. T. Blades, W. H. Fleming, and H. G. Thode, *Can. J. Chem.* **34**, 233 (1956).
4. J. A. Petruska, H. G. Thode, and R. H. Tomlinson, *Can. J. Phys.* **33**, 693 (1955).
5. Y. S. Kim and G. L. Hofman, *J. Nucl. Mater.* **419**, 291 (2011).
6. B. D. Miller, J. Gan, D. D. Keiser, Jr, A. B. Robinson, J. F. Jue, J. W. Madden, and P. G. Medvedev, *J. Nucl. Mater.* **458**, 115 (2015).
7. B. D. Miller, J. Gan, J. Madden, J.-F. Jue, A. Robinson, and D. D. Keiser, *J. Nucl. Mater.* **424**, 38 (2012).
8. J. Gan, D. D. Keiser, D. M. Wachs, A. B. Robinson, B. D. Miller, and T. R. Allen, *J. Nucl. Mater.* **396**, 234 (2010).
9. J. Gan, D. D. Keiser, B. D. Miller, A. B. Robinson, J.-F. Jue, P. Medvedev, and D. M. Wachs, *J. Nucl. Mater.* **424**, 43 (2012).
10. P. B. Johnson and D. J. Mazey, *J. Nucl. Mater.* **93–94**, 721 (1980).
11. P. B. Johnson and D. J. Mazey, *J. Nucl. Mater.* **91**, 41 (1980).
12. J. H. Evans, *J. Nucl. Mater.* **119**, 180 (1983).
13. D. J. Mazey and J. H. Evans, *J. Nucl. Mater.* **138**, 16 (1986).
14. J. H. Evans and D. J. Mazey, *J. Nucl. Mater.* **138**, 176 (1986).
15. P. B. Johnson, K. J. Stevens, and R. W. Thomson, *Nucl. Instrum. Meth. Phys. Res. B* **62**, 218 (1991).
16. P. B. Johnson and D. J. Mazey, *J. Nucl. Mater.* **218**, 273 (1995).
17. F. E. Lawson and P. B. Johnson, *J. Nucl. Mater.* **252**, 34 (1998).
18. N. M. Ghoniem, D. Walgraef, and S. J. Zinkle, **8**, 1 (2001).
19. P. B. Johnson and F. Lawson, *Nucl. Instrum. Meth. Phys. Res. B* **243**, 325 (2006).
20. J. Gan, D. D. Keiser, Jr., B. D. Miller, A. B. Robinson, D. M. Wachs, and M. K. Meyer, *J. Nucl. Mater.* **464**, 1 (2015).
21. K. Bakker, *Int. J. Heat Mass Tran.* **40**, 3503 (1997).

22. J. C. Maxwell, *A Treatise on Electricity and Magnetism*, Vol. 1 (Clarendon Press, Oxford, 1881).
23. J. B. MacEwan, R. L. Stoute, and M. J. F. Notley, *J. Nucl. Mater.* **24**, 109 (1967).
24. L. A. Goldsmith and J. A. M. Douglas, *J. Nucl. Mater.* **47**, 31 (1973).
25. M. F. DeVries, *J. Heat Tran.* **111**, 281 (1989).
26. A. L. Loeb, *J. Am. Ceram. Soc.* **37**, 96 (1954).
27. M. E. Cunningham and K. L. Peddicord, *Int. J. Heat Mass Tran.* **24**, 1081 (1981).
28. D. Y. Tzou, *Int. J. Heat Mass Tran.* **34**, 1839 (1991).
29. T. H. Bauer, *Int. J. Heat Mass Tran.* **36**, 4181 (1993).
30. S. Hu, A. M. Casella, C. A. Lavender, D. J. Senior, and D. E. Burkes, *J. Nucl. Mater.* **462**, 64 (2015).
31. Trellis Pro (csimsoft, LLC., American Fork, Utah, 2012–2017).
32. V. A. Rabinovich, A. A. Vasserman, V. I. Nedostup, and L. S. Veksler, *Thermophysical Properties of Neon, Argon, Krypton, and Xenon* (Hemisphere Publishing Corporation, New York, NY, 1987).
33. A. R. Kaufmann, *Nuclear Reactor Fuel Elements: Metallurgy and Fabrication* (Interscience Publishers, New York, 1962).
34. D. E. Burkes, C. A. Papesch, A. P. Maddison, T. Hartmann, and F. J. Rice, *J. Nucl. Mater.* **403**, 160 (2010).
35. G. W. Greenwood, A. J. E. Foreman, and D. E. Rimmer, *J. Nucl. Mater.* **1**, 305 (1959).
36. H. Trinkaus, *Radiat. Eff.* **78**, 189 (1983).
37. H. Xiao, C. Long, X. Tian, and S. Li, *Mater. Des.* **74**, 55 (2015).
38. L. E. Thomas, in *Fundamental Aspects of Inert Gases in Solids* (Springer, New York, 1991) pp. 431–441.
39. M. Ross and A. K. McMahan, *Phys. Rev. B* **21**, 1658 (1980).
40. J. Zheng, Q. F. Chen, Y. J. Gu, Z. Y. Chen, and C. J. Li, *J. Chem. Phys.* **141**, 124 (2014).
41. D. Gaston, C. Newman, G. Hansen, and D. Lebrun-Grandie, *Nucl. Eng. Des.* **239**, 1768 (2009).
42. C. R. Clark, G. C. Knighton, M. K. Meyer, and G. L. Hofman, in *2003 International Meeting on Reduced Enrichment for Research and Test Reactors*, Vol. 1 (Chicago, Illinois, 2003).

- 43. D. S. Smith, A. Alzina, J. Bourret, B. Nait-Ali, F. Pennec, N. Tessier-Doyen, K. Otsu, H. Matsubara, P. Elser, and U. T. Gonzenbach, *J. Mater. Res.* **28**, 2260 (2013).
- 44. Z. Hashin and S. Shtrikman, *J. Appl. Phys.* **33**, 3125 (1962).
- 45. B. Schulz, *High Temp. High Press.* **13**, 649 (1981).
- 46. Y. S. Kim, G. Hofman, and J. S. Cheon, *J. Nucl. Mater.* **436**, 14 (2013).
- 47. T. H. Bauer and J. W. Holland, *Nucl. Technol.* **110**, 407 (1995).
- 48. K. L. Peddicord, M. E. Cunningham, and A. Tripathi, *Trans. Am. Nucl. Soc.* **28**, 548 (1978).
- 49. K. Bakker, H. Kwast, and E. H. P. Cordfunke, *J. Nucl. Mater.* **226**, 128 (1995).

CHAPTER 4

FIRST-PRINCIPLES STUDY OF METALLIC URANIUM

A portion of this chapter was published as an article in Computational Material Science. The authors are A. Rafi M. Iasir and Karl D. Hammond of the University of Missouri.

4.1 Introduction

Uranium is the heaviest naturally-occurring element on Earth. The discovery of fission in uranium (specifically, in ^{235}U) impacted not only scientists and engineers all over the world, it also changed global politics forever. In nuclear research, the nucleus of the uranium atom is of much more importance than the electrons surrounding it, but the electronic structure is important to the thermodynamic properties, including crystal structure. The structural features are particularly important to the study of next-generation nuclear fuels, such as U-10Mo, that are based on metallic uranium. The electronic behavior of uranium, along with other light actinides (Pa–Pu), results in a low-symmetry crystal structure at ambient temperature and pressure—most metallic elements take on relatively high-symmetry structures (bcc, fcc, and hcp), but the light actinides are either orthorhombic or monoclinic at standard temperature and pressure. Pure uranium exists in three different solid phases at atmospheric pressure, depending on the temperature: α (base-centered orthorhombic), β (tetragonal) and γ (body-centered cubic). At atmospheric pressure, α -U transforms to β -U at approximately 935 K, and β -U transforms to γ -U at approximately 1045 K [1, 2]. The influence of $5f$ electron–electron correlation plays a pivotal role in the crystallographic be-

havior of uranium and other light actinides [3, 4]; with this in mind, proper representation of uranium's $5f$ electrons is very important.

The stability of the crystal structures of the inner transition metals has been the target of several electronic structure studies. Eriksson and coworkers [5, 6] performed comparative studies of thorium, protactinium, and uranium's crystal structures, calculating the equilibrium volume and bulk modulus using the full-potential linear-muffin-tin-orbital (FP-LMTO) technique and the local density approximation (LDA). The calculated lattice parameters and equilibrium unit cell volumes showed good agreement with experiments; the bulk modulus of protactinium was significantly underestimated, but the values for uranium and thorium were within the range of experimental values. Crocombette *et al.* [7] used norm-conserving pseudopotentials to study three metallic phases of uranium (α , γ , and a hypothetical fcc structure). The calculated equilibrium volume for α uranium was underestimated by more than 6 percent. Söderlind [8] calculated the equilibrium lattice parameters and also estimated the elastic moduli of α uranium using the FP-LMTO method. The calculated equilibrium lattice parameters were in good agreement with experimental values, but the elastic moduli did not agree particularly well with experimental values. The calculated elastic moduli were likely higher than experimental values because uranium undergoes strong phonon softening with increases in temperature, and the experimental values (taken at room temperature) would likely be lower than they would be at low temperatures [9].

Söderlind's [8] was the first attempt to calculate α -uranium's elastic moduli. Other theoretical studies of light actinides prior to 2000 using full-core (*i.e.*, non-pseudopotential-based) techniques are summarized by Jones *et al.* [10]. Taylor [11] studied uranium phases using the projector augmented-wave (PAW) method [12] with Perdew and Wang's 1991 (PW91) exchange–correlation functional [13, 14]. Taylor investigated α , bcc, and fcc uranium. The equilibrium lattice parameters of α -uranium were within 1% of experimental values at 50 K [15]. The lattice parameter of γ -uranium was also in good agreement with experimental values, though the lattice parameter of fcc uranium was overestimated com-

pared to the value calculated by Crocombette *et al.* [7]. Xiang *et al.* [16] used the Perdew–Burke–Ernzerhof (PBE) exchange–correlation functional [17, 18] to study the equilibrium volume of the α and γ uranium. He also studied the bct structure, an approximation of the β phase. Their results were also in good agreement with previous full potential studies and experimental results. Li *et al.* [19] also studied the structure, formation energies, and elastic moduli of α , β , γ , fcc, and hcp uranium using the PW91 exchange–correlation functional. Their pseudopotential produced reasonably accurate lattice parameters and cell volumes for γ -uranium and α -uranium accompanied by reasonable elastic moduli. Beeler *et al.* [20] utilized the PBE exchange–correlation functional to study uranium, and found similar values to Li *et al.*, with the exception of the body-centered tetragonal case (approximating β -uranium).

In the present work, we investigate the crystal structure and elastic properties of metallic uranium with density functional theory (DFT) with a projector augmented wave (PAW) pseudopotential [12]. We investigate four structures of uranium: α , γ , bct, and fcc. Our results are compared with previously published electronic structure calculations and experiments. The electronic densities of states for all four crystal structures are also calculated. Our results for α -uranium are comparable to previous models, but predicted properties for γ -uranium are, in general, improvements on previously-published models.

4.2 Computational Details

We perform all calculations using density functional theory (DFT) with plane-wave basis sets as implemented in the software QUANTUMESPRESSO [32]. We generated a uranium pseudopotential for use with the Perdew–Burke–Ernzerhof (PBE) exchange–correlation functional [17, 18]. The projector augmented wave (PAW) pseudopotential-generating software `atompaw` [33, 34] was used to generate the PAW pseudopotential for uranium. The same pseudopotential was used for all subsequent calculations.

One of the major challenges in studying actinides using DFT is how to treat the large number of electrons. The pseudopotential approach effectively reduces the number of electrons by modeling the “core” as a potential energy surface, so generating a pseudopotential requires one to choose the number of electrons that will be treated explicitly. There are two approaches common for uranium: “small-core” pseudopotentials and “large-core” pseudopotentials. In a large-core pseudopotential, the valence electrons are the $5f$, $6s$, $6p$, $6d$ and $7s$ shells (14 electrons). In small-core pseudopotentials, the $5s$, $5p$, and $5d$ shells are also included, which treats 32 electrons as valence electrons. Iche-Tarrat and Marsden [35] have discussed this topic and shown that the explicit treatment of 32 electrons only marginally improves the performance of DFT at significantly higher computational cost. The valence electron configuration of uranium used when generating our pseudopotential was $6s^2 6p^6 7s^2 6d^1 5f^3$ (*i.e.*, it is a large-core pseudopotential). The radius of the augmentation region was chosen to be 2.5 bohr, which we determined by starting from half the experimental nearest-neighbor interatomic distance in α -uranium and adjusting based on energy–volume minimization. The pseudo-partial waves were generated using the RKKJ scheme [36], which uses a sum of Bessel functions to represent the pseudo-partial waves. A plane-wave cutoff energy analysis was performed and a 50 Ry energy cutoff was found to be sufficient based on a plot of total energy against cutoff energy. All calculations were performed on primitive cells using the cell geometries and coordinates given by Crocombette *et al.* [7] for α -uranium, Beeler *et al.* [20] for bct uranium, and values from the Structure of Crystals database [37] for all other structures. Periodic boundaries were applied in all directions. The Monkhorst–Pack scheme [38] was used for Brillouin zone sampling; the k -point meshes were $20 \times 20 \times 26$, $20 \times 20 \times 20$, $18 \times 18 \times 18$, and $20 \times 20 \times 20$ for the α , bct, γ , and fcc lattices, respectively. A Methfessel–Paxton [39] smearing method (width 0.02 Ry) was used to integrate the bands at the Fermi level. To calculate the nine unique elastic moduli of orthorhombic α -U, the energy–strain relationship (see appendix .1) was used as described by Ravindran *et al.* [40]. For cubic structures, the elastic moduli were

Table 4.1. Parameters used to generate the pseudopotential in atompaw [33, 34].

Cutoff	Value (bohr)
r_{PAW}	2.50
r_{shape}	2.02
r_{vloc}	1.50
r_{core}	1.80
$r_{c,i}$	r_{PAW}
EXCEPT	
$r_{c,6s}$	1.50
$r_{c,7s}$	1.50

evaluated using volume-conserving orthorhombic and monoclinic distortions as described by Beckstein *et al.* [41].

4.3 Results

The pseudopotential itself is generated by atompaw [33, 34], which takes as input the augmentation radius (r_{PAW}), core radius (r_{core}), shape function cutoff (r_{shape}), matching radius (r_{vloc}), valence and core electron configurations, density functional, and the cutoff radii for each of the partial waves ($r_{c,i}$). We assumed $r_c = r_{\text{PAW}}$ for all valence electrons except the 6s and 7s electrons, for which r_c was adjusted. The cutoff radii are given in Table 4.1. These cutoffs, combined with the choice of density functional and valence electrons, are sufficient to reproduce the pseudopotential in atompaw.

Properties of several uranium phases as calculated with the pseudopotential presented above are detailed in the rest of this section.

4.3.1 α -Uranium

Uranium's α phase has a base-centered orthorhombic structure with space group *Cmcm* (no. 63). The asymmetric unit has uranium atoms at Wyckoff position $4c \left(0, \pm y, \pm \frac{1}{4}\right)$, where the position parameter y has been found to be a function of temperature [15]. At room temperature, the value of y has been measured to be 0.1024 [15, 42]. There are four atoms

in the standard unit cell (two in the primitive cell). The α phase is thermodynamically favorable at temperatures below 935 K and pressures up to 100 GPa [2, 43]. This makes the α phase important to the nuclear energy community because it is the naturally-occurring phase of uranium. The solid-state physics community also shows interest in α -uranium because of certain unusual characteristics, including charge density wave transitions and superconductivity.

The total energy as a function of unit cell volume for α uranium is shown in Figure 4.1; Table 4.2 summarizes the optimized lattice parameters, the distance parameter y , and the calculated elastic moduli, along with results from previously published calculations and experiments. We confirm that α -U is the lowest-energy crystal structure among those we tested. Our pseudopotential predicts an equilibrium volume of 20.49 \AA^3 , which is in close agreement with the experimental value of 20.530 \AA^3 (at 50 K). The position parameter y exhibits a minimum-energy value of 0.0986 at the equilibrium volume of 20.49 \AA^3 . This trend in y is similar to that observed in the calculations of Wills and Eriksson [5].

Our cell volume results differ from previous calculations using PAW [20], which obtained an equilibrium volume of 19.987 \AA^3 . A Murnaghan [44] fit to the total energy as a function of volume for α -uranium yielded a bulk modulus of 132.1 GPa, which is larger than the experimental value of $104 \pm 2 \text{ GPa}$ [43], but agrees closely with the quantum molecular dynamics (QMD) results of Hood *et al.* [45] (133.5 GPa) and the diamond anvil cell (DAC) experiments of Yoo *et al.* [46], which reported a bulk modulus of 135.5 GPa. Our pseudopotential-based results are in close agreement with the all-electron FP-LMTO calculations of Söderlind [8], which gave an equilibrium volume of 20.67 \AA^3 and a bulk modulus of 133.0 GPa. A published PAW-based pseudopotential from Beeler *et al.* [20] yields an equilibrium volume of 19.92 \AA^3 , which is lower than our result and farther from both the experimental value and the result from all-electron calculations.

The elastic moduli predicted by our pseudopotential are presented in Table 4.2. Like all materials with orthorhombic symmetry, α -U has nine unique elastic moduli. Our model

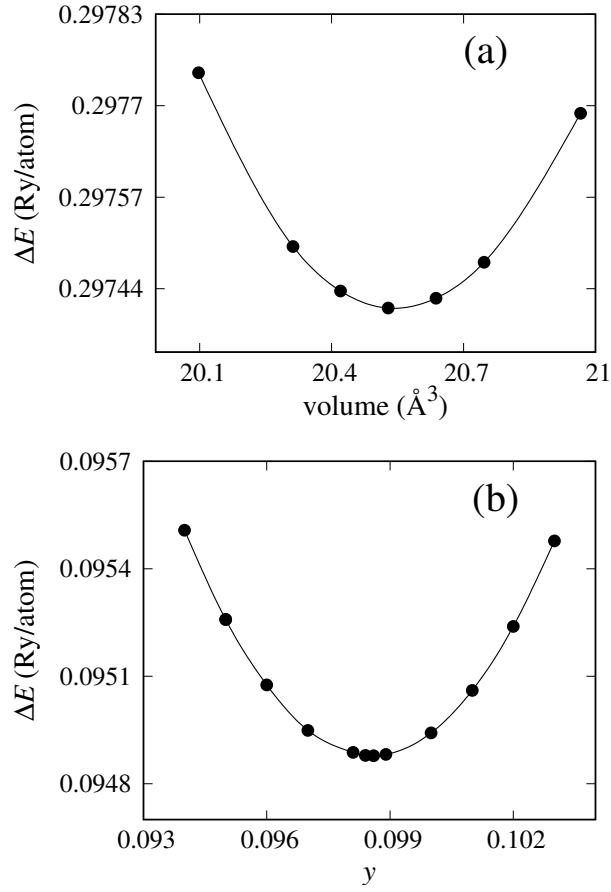


Figure 4.1. (a) Calculated total energy as a function of volume for α uranium. (b) Calculated total energy as a function of the positional parameter y for α uranium. The calculation of y is constrained to an equilibrium volume of 20.49 \AA^3 .

Table 4.2. Ground-state properties and elastic moduli of α -U from present work, compared with the PAW pseudopotential calculations of Beeler *et al.* [20], the full-core calculations of Söderlind [8], and experiments from Barrett [15], Le Bihan *et al.* [43], and Fisher and McSkimin [47] (295 K).

	Theory			Experiment		
	present work	Beeler [20]	Söderlind [8]	Barrett [15]	Le Bihan [43]	Fisher [47]
a (Å)	2.834	2.793	2.845	2.836	2.8553	-
b (Å)	5.862	5.849	5.818	5.867	5.8702	-
c (Å)	4.932	4.893	4.996	4.936	4.9568	-
γ	0.0986	0.097	0.103	0.102	0.102	-
volume/atom (Å ³)	20.48	19.987	20.674	20.535	20.770	-
B (GPa)	132.1	151	133	-	104(2)	-
B'	5.27	-	5.4	-	6.2	-
C_{11} (GPa)	315	299	300	-	-	215
C_{22} (GPa)	213	231	220	-	-	199
C_{33} (GPa)	387	364	320	-	-	267
C_{44} (GPa)	135	100	150	-	-	124
C_{55} (GPa)	87	150	93	-	-	73
C_{66} (GPa)	104	132	120	-	-	74
C_{12} (GPa)	58	59	50	-	-	46
C_{13} (GPa)	45	30	5	-	-	22
C_{23} (GPa)	146	144	110	-	-	108

overestimates most of the elastic moduli relative to experiments. The three primary-direction elastic moduli (C_{11} , C_{22} , and C_{33}) show good agreement with other theoretical results and with experiment, though all three principal elastic moduli are overestimated. The order ($C_{33} > C_{11} > C_{22}$) of these three elastic moduli is also consistent with experiments. For C_{55} and C_{13} , the present results also show good agreement with experiments. The value of C_{66} is overestimated relative to experiment, but closer than any existing prediction from a pseudopotential-based calculation. The other elastic moduli are generally similar to existing theoretical predictions.

4.3.2 γ -U: Crystal Structure and Elastic Moduli

The structure of γ -uranium at high temperature was first elucidated by Wilson and Rundle [48] at Iowa State University in 1949 using powdered uranium at 800 °C. The γ phase of uranium has a body-centered cubic (bcc; Strukturbericht designation A2) structure with

Table 4.3. The equilibrium lattice parameters and volume per atom of γ -uranium. Results are compared with the PAW pseudopotential calculations of Beeler *et al.* [20] and Taylor [11], as well as the norm-conserving pseudopotential calculations of Crocombette *et al.* [7] and the experiments of Wilson and Rundle [48] at room temperature. Elastic moduli are compared with previous PAW pseudopotential calculations from Beeler *et al.* [20] and Taylor [11].

	Theory				Experiment	
	present work	Beeler [20]	Taylor [11]	Crocombette [7]	Wilson [48]	Yoo [46]
a (Å)	3.45	3.427	3.43	3.37	3.47	-
volume/atom (Å ³)	20.56	20.124	20.18	19.14	20.89	-
C_{11} (GPa)	40	86	161	-	-	-
C_{12} (GPa)	145	155	184	-	-	-
C_{44} (GPa)	42	37	56	-	-	-
B (GPa)	110	132	176	170	-	113.3

two atoms in the standard unit cell [49, 50]. It is thermodynamically stable from 1050 K to the melting point of 1406 K [46].

In the nuclear fuels community, γ uranium is preferred to α -uranium because it undergoes isotropic thermal expansion and radiation-induced swelling [51]. As Wilson and Rundle observed [48], it is not possible to quench pure γ -uranium to room temperature, but a metastable bcc phase can be retained at room temperature in U–Mo alloys. Recently, it was found that the bcc structure can be retained by alloying uranium with other metals, such as platinum, palladium, niobium, and zirconium [52]. In particular, the eutectoid point of γ -uranium with molybdenum impurities is at approximately 89 weight-percent uranium; to take advantage of the depressed phase transition temperature (and the associated increase in stability of the bcc phase), uranium alloyed with 10 wt% molybdenum (≈ 21.6 at.%; U-10Mo) is currently being developed as a potential high-density low-enrichment uranium (LEU) fuel for high-performance research reactors. The lattice parameters, volume per atom, and elastic moduli as calculated with our pseudopotential-based model are presented in Table 4.3.

The lattice parameters for γ -uranium as calculated with the pseudopotential presented here are in good agreement with experiments. The elastic moduli are comparable with those of Beeler *et al.* [20] and Taylor [11]. The value of C_{12} is larger than that of C_{11} ,

Table 4.4. The optimized lattice parameters (\AA), volume per atom (\AA^3) and elastic moduli of bct uranium. Our calculated results are compared with those of Beeler *et al.* [20], Li *et al.* [19], Xiang *et al.* [16], and Söderlind [56].

	present work	Beeler [20]	Li [19]	Xiang [16]	Söderlind [56]
a (\AA)	3.44	3.695	3.72	-	-
c/a	0.8125	0.8	1.24	-	0.82
volume/atom (\AA^3)	20.44	20.268	31.896	20.5	-
C_{11} (GPa)	270	264	230	-	-
C_{33} (GPa)	257	254	204	-	-
C_{12} (GPa)	65	55	61	-	-
C_{13} (GPa)	32	68	61	-	-
C_{44} (GPa)	59	56	79	-	-
C_{55} (GPa)	71	56	39	-	-
B (GPa)	115.4	130	114	-	-

which is a violation of one of the stability criteria for cubic crystals ($C_{11} - C_{12} > 0$), often called the Born stability criteria [53–55]. This violation is expected, as the bcc phase of uranium is unstable at low temperatures. The experimental value of bulk modulus by Yoo *et al.* [46] is in good agreement with our result.

4.3.3 Body-centered Tetragonal Uranium

The β -phase of uranium is stable at atmospheric pressure between 935 and 1045 K [1]. Tucker [57] determined that it has a tetragonal structure with 30 atoms per unit cell, but his space group assignment was later disputed. The assignment of a space group remained a controversy until 1988, when Lawson and coworkers [1] published neutron powder diffraction results. The experimental difficulties lie in the preparation of a single crystal of β -uranium and the need to operate at high temperature. Single crystals of a β -uranium alloy containing 1.4 atom% chromium were created by Tucker [58] and quenched to room temperature, but he did not establish whether this alloy had the same crystal structure as pure β -uranium [1]. An overview of the development of the crystal structure of β -uranium is given by Donohue and Einspahr [59, 60]. The present consensus is that β -uranium has a

Table 4.5. The equilibrium lattice parameter, volume per atom, and elastic moduli of fcc uranium. Results are compared with PAW pseudopotential calculations of Beeler *et al.* [20], Taylor [11], and Crocombette *et al.* [7].

	present work	Beeler [20]	Taylor [11]	Crocombette [7]
a (Å)	4.300	4.433	4.48	4.30
volume/atom (Å ³)	21.765	21.774	22.48	19.88
C_{11} (GPa)	67	46	184	-
C_{12} (GPa)	130	144	267	-
C_{44} (GPa)	38	40	28	-
B (GPa)	108.7	111	239	148

tetragonal crystal structure with with space group $P4_2/mnm$ (no. 136) and 30 atoms in the unit cell.

We chose to simulate a body-centered tetragonal structure instead of β uranium because of the latter's complexity and computational expense. A similar simplification was used in studies similar to ours [19, 20]. The bct structure has only two atoms per unit cell, and is therefore less computationally expensive than β uranium. The equilibrium lattice parameters of bct uranium are presented in Table 4.4, alongside values from Beeler *et al.* [20] and Li *et al.* [19]. The volume per atom agrees well with Beeler *et al.* but is significantly different from that of Li *et al.* Xiang *et al.* [16] also studied the bct structure of uranium, though they did not provide the equilibrium lattice parameter or c/a ratio; their value of the equilibrium volume per atom was 20.5 Å³, similar but larger than our value. Our c/a ratio is in good agreement with both Beeler *et al.* [20] (0.8) and Söderlind [56] (0.82).

4.3.4 Face-centered Cubic Uranium

Face-centered cubic uranium does not exist in nature, but it is a reasonable way to check the pseudopotential. Beeler *et al.* [20] and Taylor [11] studied this structure as well, so we compare our results with theirs. Table 4.5 shows the equilibrium parameters and elastic moduli as calculated with our model and with several other published pseudopotentials.

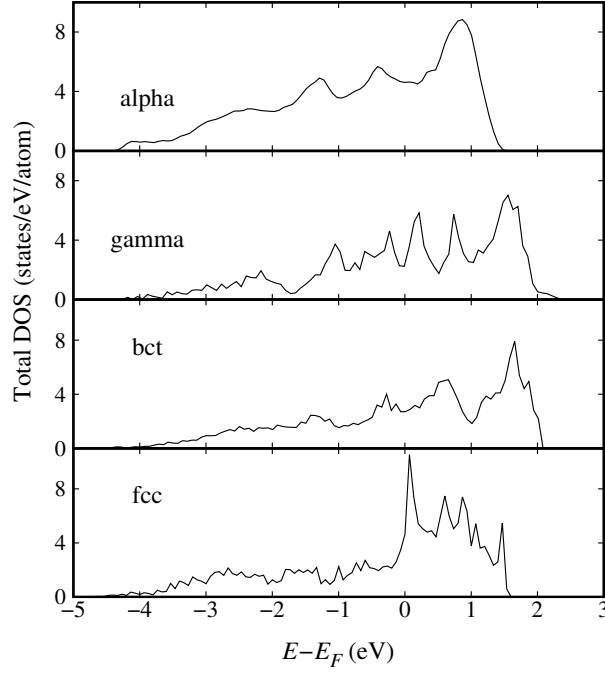


Figure 4.2. Total electronic densities of states of α , γ , bct, and fcc uranium near the Fermi level.

Our results are in good agreement with other pseudopotential calculations, particularly those of Beeler *et al.* [20]; the bulk modulus shows good agreement with their value as well. It should be noted that C_{12} is still higher than C_{11} , confirming that this model predicts the fcc phase to be unstable.

4.3.5 Electronic Density of States

The electronic densities of states (DOS) of α , bct, γ , and fcc uranium are shown in Figure 4.2. The partial densities of states for the $5f$ and $6d$ orbitals are shown in Figure 4.3. We have only shown the partial densities of states for the $5f$ and $6d$ orbitals because these are the dominant orbitals near the Fermi level of uranium. There are also contributions from $6s$, $6p$, and $7s$ orbitals near the Fermi level, but these contributions are not as significant as the dominant $5f$ and $6d$ orbitals. Electrons near the Fermi level are important because

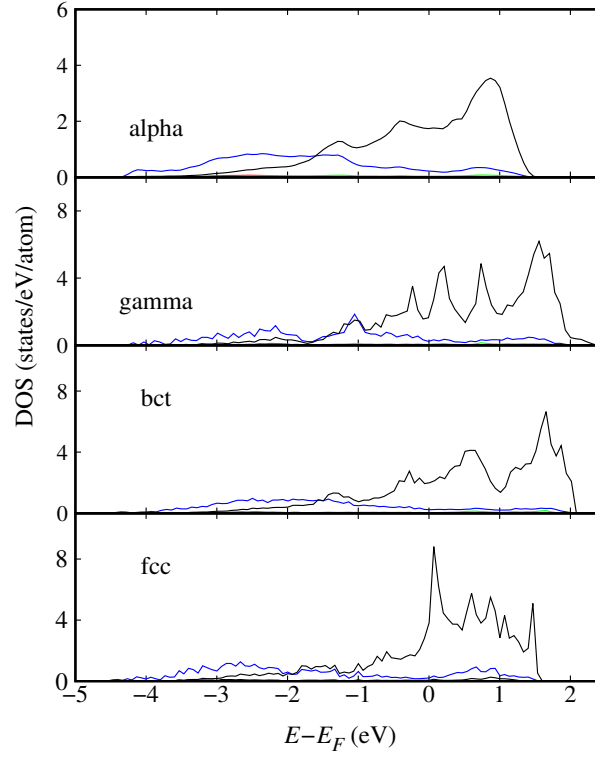


Figure 4.3. The partial electronic densities of states of α , γ , bct, and fcc uranium near the Fermi level. The $6d$ (blue line) and $5f$ (black line) electronic orbitals are shown. The s (red) and p (green) electronic orbitals are also included, but due to their very low contributions near the Fermi level, they are barely visible.

they are responsible for most of the metallic behavior. From Figure 4.2, it can be seen that the DOS spreads over energies between -4 eV and 2 eV relative to the Fermi level. The density of states with our model is comparable to those calculated by Beeler *et al.* [20] and Xiang *et al.* [16]. For bcc and bct uranium, the f orbitals spread over a broader range of energies near the Fermi level and show multiple peaks above the Fermi level. The high density of states at energies above the Fermi level in the bct and γ phases suggest that these phases would be favored over α -uranium at high temperature.

4.4 Conclusion

The equilibrium structures, cell volumes, and elastic moduli have been calculated using DFT with a newly parameterized pseudopotential model for four different uranium phases (α , γ , body-centered tetragonal, and face-centered cubic). Our results are either in good agreement with previous work or show improvement in comparison with experiments. Studying pure uranium is the first step in exploring different alloys of uranium that are of interest to the nuclear fuels community. Due to the lower cutoff energies that can typically be used, PAW-based pseudopotentials allow one to study larger supercells, which in turn provide more accurate studies of vacancy formation, grain boundaries, and fission gas transport.

According to our pseudopotential, α -uranium is the lowest-energy crystal structure of the ones tested. The calculated elastic moduli show good agreement with previous DFT studies and experiments. Our model shows good agreement with previous pseudopotentials, but generally provides results that are either comparable to previously published pseudopotentials or closer to experimental values than previously published pseudopotentials. The three elastic moduli associated with shear (C_{44} , C_{55} , and C_{66}) show better agreement with experimental results than the tensile components. The lattice parameters of the bct structure are also very similar to those predicted by Beeler *et al.* [20], but they deviate significantly from those of Li *et al.* [19]. The elastic moduli show very similar trends to previously published models, apart from C_{23} , which is over-predicted by our model.

For γ uranium, which is of great interest for the development of low-enrichment uranium fuel, the lattice parameters are in close agreement with those of Taylor *et al.* [11] and with experiments. Apart from the elastic modulus C_{11} , the values of all computed parameters show very little discrepancy compared with those from the work of Taylor *et al.* [11] and Beeler *et al.* [20]. The bulk modulus shows very good agreement with experiment.

For fcc uranium, a hypothetical crystal structure, the computed lattice parameter is in close agreement with values reported by Beeler *et al.* [20] and by Crocombette *et al.* [7]. The equilibrium volume per atom does show a discrepancy from Crocombette but is in good agreement with Beeler *et al.* The elastic modulus C_{44} is also in good agreement with Beeler *et al.*, whereas C_{11} is intermediate between the value predicted by Beeler *et al.* and that predicted by Taylor *et al.* Lastly, the electronic density of states shows that the $5f$ orbital partial density of states is the largest contribution to the total density of states at the Fermi energy, and the $5f$ electrons therefore contribute the most to the bonding and conductivity of uranium. Most of the $5f$ orbital electron density is spread over energies between -4 and 2 eV relative to the Fermi level. We also find that γ -uranium has the highest density of states at values above the Fermi level, confirming that it should be favored at high temperature.

Appendices

.1 Calculation of Elastic Parameters of α -uranium

In this appendix, we will discuss the stress-strain relationships that was used to calculate the nine independent elastic constants of α -uranium. The base-centered orthorhombic phase of uranium has three lattice parameters a , b , and c , with the Bravais lattice matrix.

$$\mathbf{R} = \begin{pmatrix} \frac{a}{2} & -\frac{b}{2} & 0 \\ \frac{a}{2} & \frac{b}{2} & 0 \\ 0 & 0 & c \end{pmatrix} \quad (1)$$

Applying a small strain to the equilibrium lattice changes the total energy, and from this information, the elastic parameters are deduced. The elastic parameters are identified as proportional to the second order coefficient in a polynomial fit of the total energy as a function of the distortion parameter δ [61]. The distortion of lattice vector follows the rule $\mathbf{R}' = \mathbf{R}\mathbf{D}$. Here \mathbf{R}' is a matrix containing the components of the distorted lattice vectors and \mathbf{D} is the symmetric distortion matrix.

The internal energy of a crystal under strain, δ , can be Taylor expanded in powers of the strain tensor with respect to initial energy of the unstrained crystal in the following way:

$$E(V, \delta) = E(V_0, 0) + V_0 \left(\sum_i \tau_i \xi_i d_i + 1/2 \sum_{ij} c_{ij} \delta_i \xi_i \delta_j \xi_j \right) + O(\delta^3) \quad (2)$$

The unstrained volume is V_0 , and $E(V_0, 0)$ is the energy of the unstrained system. The Voigt notation has been used in the above equation, i.e. xx , yy , zz , yz , xz and xy are replaced with 1–6. Here yz , xz and xy are equal to zy , zx and yx and for this reason ξ_i is equal to 1 for $i = 1, 2$, and 3 and 2 for $i = 4, 5$ and 6. τ_i is a component of stress tensor. The first three elastic constants c_{11} , c_{22} and c_{33} are obtained from the following distortions:

$$D_1 = \begin{pmatrix} 1 + \delta & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (3)$$

$$D_2 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 + \delta & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (4)$$

$$D_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 + \delta \end{pmatrix} \quad (5)$$

The internal energies for these three distortions can be obtained from

$$E(V, \delta) = E(V_0, 0) + V_0 \tau_i \delta + \frac{V_0 C_{ii} \delta^2}{2} \quad (6)$$

The c_{44} , c_{55} and c_{66} are related to the distortion equations:

$$D_4 = \begin{pmatrix} \frac{1}{(1-\delta^2)^{1/3}} & 0 & 0 \\ 0 & \frac{1}{(1-\delta^2)^{1/3}} & \frac{\delta}{(1-\delta^2)^{1/3}} \\ 0 & \frac{\delta}{(1-\delta^2)^{1/3}} & \frac{1}{(1-\delta^2)^{1/3}} \end{pmatrix} \quad (7)$$

$$D_5 = \begin{pmatrix} \frac{1}{(1-\delta^2)^{1/3}} & 0 & \frac{\delta}{(1-\delta^2)^{1/3}} \\ 0 & \frac{1}{(1-\delta^2)^{1/3}} & 0 \\ \frac{\delta}{(1-\delta^2)^{1/3}} & 0 & \frac{1}{(1-\delta^2)^{1/3}} \end{pmatrix} \quad (8)$$

$$D_6 = \begin{pmatrix} \frac{1}{(1-\delta^2)^{1/3}} & \frac{\delta}{(1-\delta^2)^{1/3}} & 0 \\ \frac{\delta}{(1-\delta^2)^{1/3}} & \frac{1}{(1-\delta^2)^{1/3}} & 0 \\ 0 & 0 & \frac{1}{(1-\delta^2)^{1/3}} \end{pmatrix} \quad (9)$$

These three elastic constants can be calculated from the corresponding internal energy:

$$E(V, \delta) = E(V_0, 0) + V_0 \tau_i \delta + \frac{V_0 C_{ii} \delta^2}{2} \quad (10)$$

The last three distortions are:

$$D_7 = \begin{pmatrix} \frac{1+\delta}{(1-\delta^2)^{1/3}} & 0 & 0 \\ 0 & \frac{1-\delta}{(1-\delta^2)^{1/3}} & 0 \\ 0 & 0 & \frac{1}{(1-\delta^2)^{1/3}} \end{pmatrix} \quad (11)$$

$$D_8 = \begin{pmatrix} \frac{1+\delta}{(1-\delta^2)^{1/3}} & 0 & 0 \\ 0 & \frac{1}{(1-\delta^2)^{1/3}} & 0 \\ 0 & 0 & \frac{1-\delta}{(1-\delta^2)^{1/3}} \end{pmatrix} \quad (12)$$

$$D_9 = \begin{pmatrix} \frac{1}{(1-\delta^2)^{1/3}} & 0 & 0 \\ 0 & \frac{1+\delta}{(1-\delta^2)^{1/3}} & 0 \\ 0 & 0 & \frac{1-\delta}{(1-\delta^2)^{1/3}} \end{pmatrix} \quad (13)$$

The internal energies related with these three distortions are given by the following equations:

$$E(V, \delta) = E(V_0, 0) + V_0 [\tau_1 - \tau_2] \delta + \frac{1}{2} (c_{11} + c_{22} - 2c_{12}) \delta^2 \quad (14)$$

$$E(V, \delta) = E(V_0, 0) + V_0 [\tau_1 - \tau_3] \delta + \frac{1}{2} (c_{11} + c_{33} - 2c_{13}) \delta^2 \quad (15)$$

$$E(V, \delta) = E(V_0, 0) + V_0 [\tau_2 - \tau_3] \delta + \frac{1}{2} (c_{22} + c_{33} - 2c_{23}) \delta^2 \quad (16)$$

The above equations can be used to calculate the remaining elastic constants c_{12} , c_{13} , and c_{23} . The energy and strain relations are calculated and included in Figure 4, 5, and 6.

2 Elastic Parameter Calculation for γ -uranium

Applying a small strain (δ) to the equilibrium lattice changes the total energy, and from this information, the elastic parameters are deduced. The distortion of a lattice vector

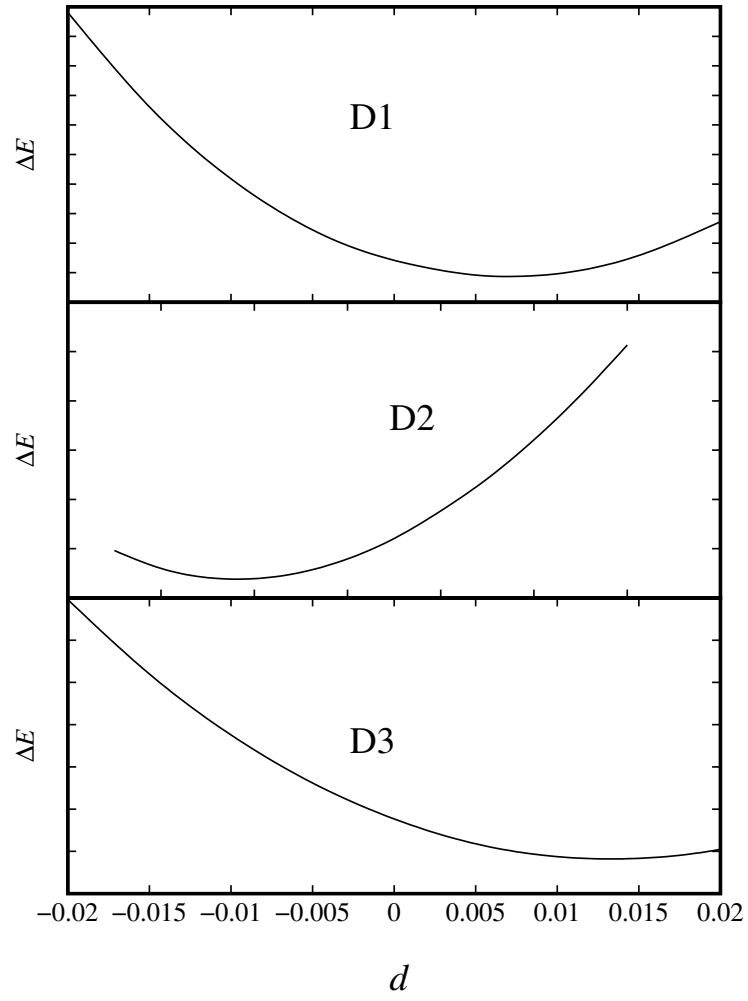


Figure 4. Changes in the strain energy as a function of strain using distortion matrix D_1 (3), D_2 (4) and D_3 (5).

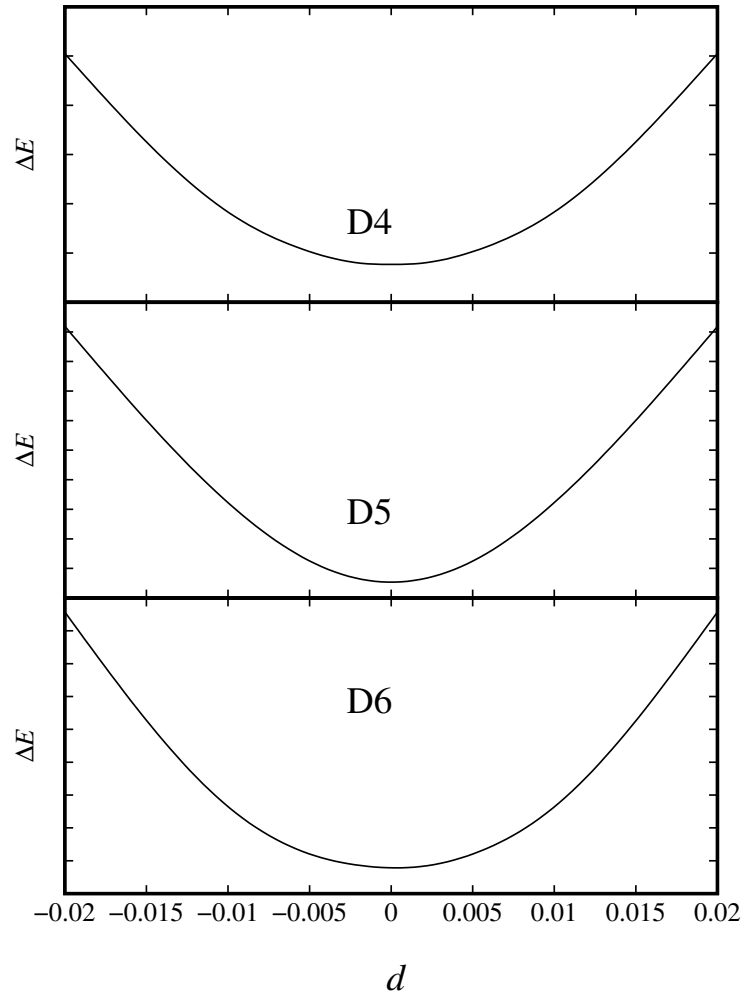


Figure 5. Changes in the strain energy as a function of strain using distortion matrix D_4 (7), D_5 (8) and D_6 (9).

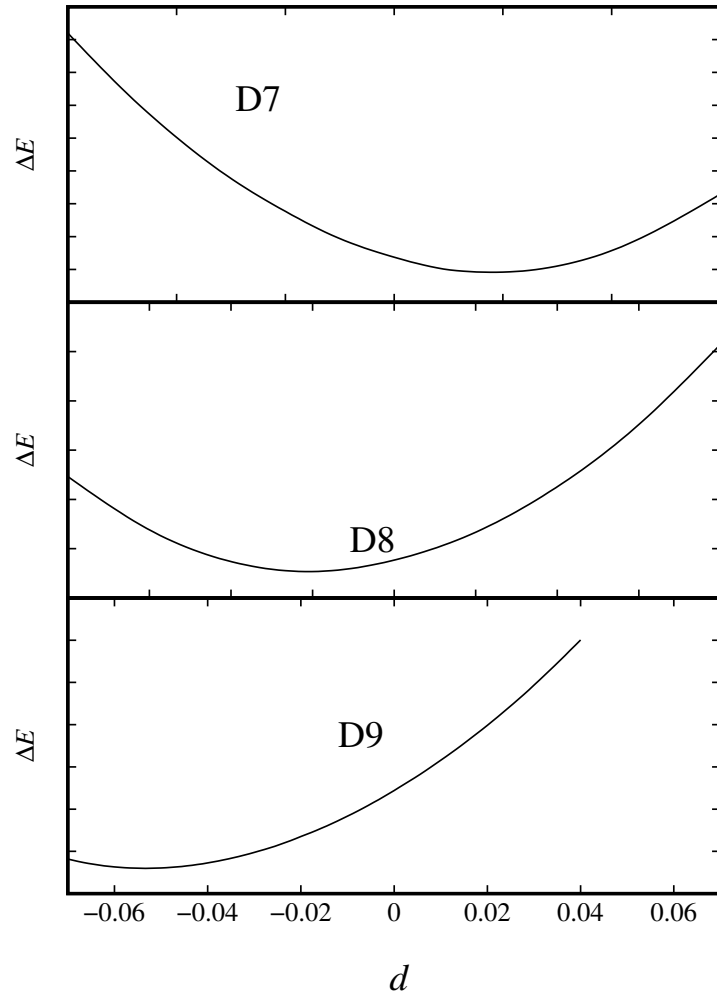


Figure 6. Changes in the strain energy as a function of strain using distortion matrix D_7 (11), D_8 (12) and D_9 (13).

follows the rule $\mathbf{R}' = \mathbf{R}\mathbf{D}$. Here, \mathbf{R} is the Bravais lattice vector, \mathbf{R}' is a matrix containing the components of the distorted lattice vectors, and \mathbf{D} is the symmetric distortion matrix.

By symmetry, there are only three independent elastic parameters for a cubic system (*i.e.*, C_{11} , C_{12} , and C_{44}). Elastic parameters are evaluated from the total energy of the crystal, to which volume-conserving orthorhombic [$C' = (C_{11} - C_{12})/2$] and monoclinic (C_{44}) distortions are applied. The relevant distortion matrices are

$$\mathbf{D}_{\text{ortho}} = \begin{bmatrix} 1 + \delta_o & 0 & 0 \\ 0 & 1 - \delta_o & 0 \\ 0 & 0 & \frac{1}{1 - \delta_o^2} \end{bmatrix} \quad (17)$$

and

$$\mathbf{D}_{\text{mono}} = \begin{bmatrix} 1 & \delta_m & 0 \\ \delta_m & 1 & 0 \\ 0 & 0 & \frac{1}{1 - \delta_m^2} \end{bmatrix}. \quad (18)$$

The associated total energy change for an orthorhombic distortion is

$$\Delta E = V(C_{11} - C_{12})\delta_o^2 + O(\delta_o^4). \quad (19)$$

For a monoclinic distortion, the energy change is

$$\Delta E = 2VC_{44}\delta_m^2 + O(\delta_m^4). \quad (20)$$

References

1. A. C. Lawson, C. E. Olsen, J. W. Richardson, M. H. Mueller, and G. H. Lander, *Acta Crystallogr. B* **44**, 89 (1988).
2. J. Akella, S. Weir, J. M. Wills, and P. Söderlind, *J. Phys. Condens. Matter* **9**, L549 (1997).

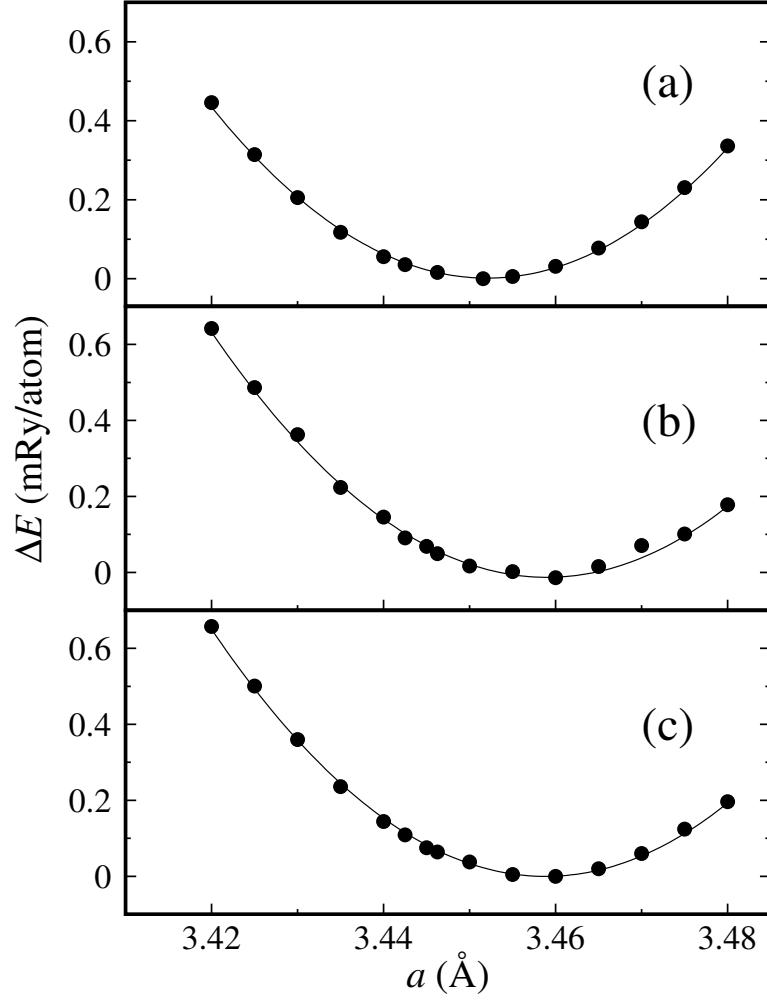


Figure 7. Energy as a function of lattice parameters for γ -uranium. (a) Our work [62] with a k -point mesh of $30 \times 30 \times 30$; (b) Pseudopotential from PS library [63, 64] with a k -point mesh of $30 \times 30 \times 30$; (c) Pseudopotential from PS library [63, 64] with $42 \times 42 \times 42$ k -point mesh.

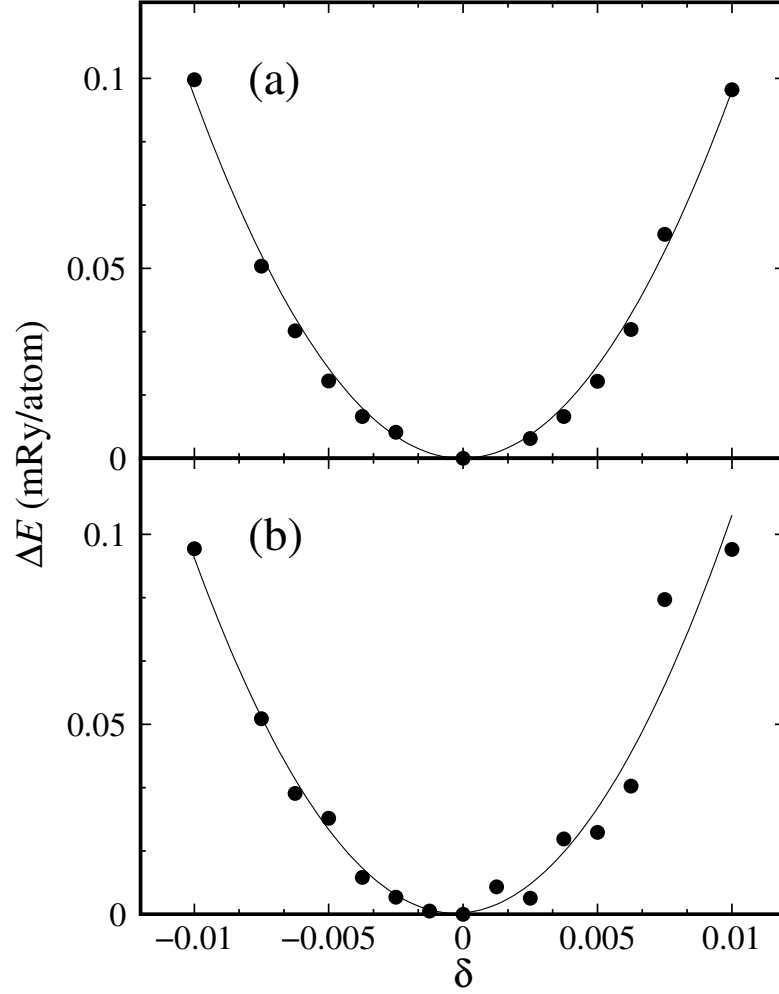


Figure 8. Changes in the strain energy as a function of strain (δ) for monoclinic distortions of γ -uranium (Eq. (18) and Eq. (20)). (a) Our work [62]; (b) Pseudopotential from the PS library [63, 64]. Increasing the k -points does not improve the smoothness of plot (b).

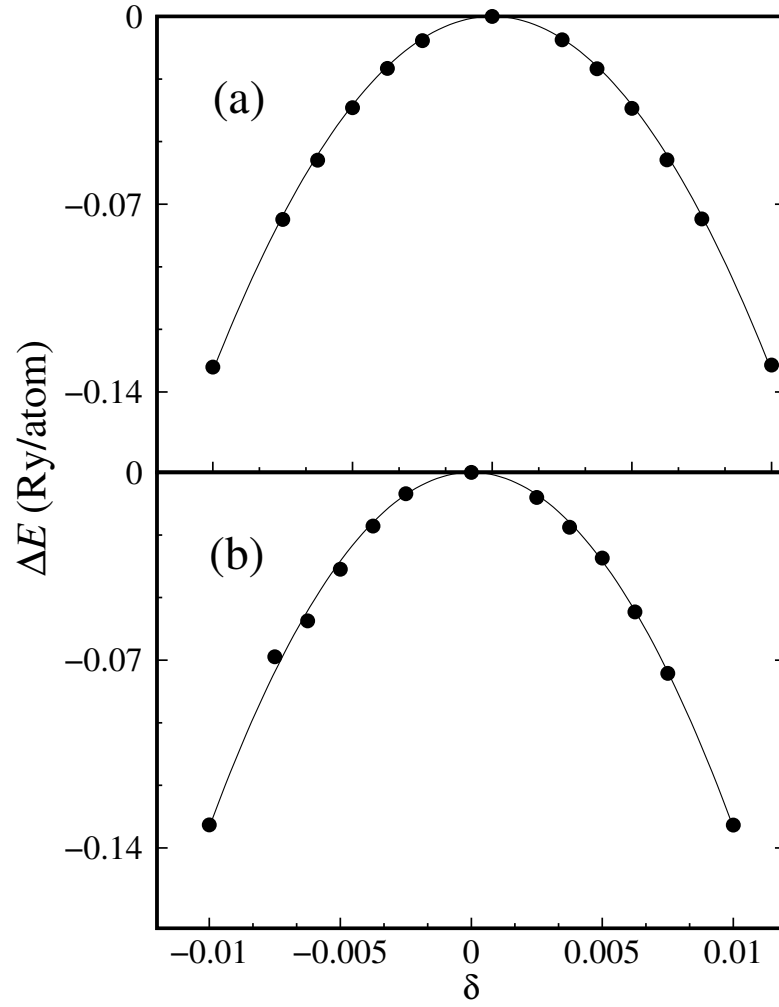


Figure 9. Changes in the strain energy as a function of strain (δ) for orthorhombic distortions of γ -uranium (Eq. (17) and Eq. (19)). (a) Our work [62]; (b) Pseudopotential from the PS library [63, 64].

3. G. H. Lander, *Science* **301**, 1057 (2003).
4. A. J. Freeman and G. H. Lander, *Handbook on the Physics and Chemistry of the Actinides*, Vol. 1,2 (North-Holland, Amsterdam, 1984).
5. J. M. Wills and O. Eriksson, *Phys. Rev. B* **45**, 13879 (1992).
6. O. Eriksson, P. Söderlind, J. M. Wills, and A. M. Boring, *Phys. C Supercond.* **190**, 5 (1993).
7. J. P. Crocombette, F. Jollet, L. Thien Nga, and T. Petit, *Phys. Rev. B* **64**, 104107 (2001).
8. P. Söderlind, *Phys. Rev. B* **66**, 085113 (2002).
9. A. C. Lawson, B. M. Artinez, J. A. Roberts, B. I. Bennett, and J. W. Richardson, Jr., *Philos. Mag. B* **80**, 53 (2000).
10. M. D. Jones, J. C. Boettger, R. C. Albers, and D. J. Singh, *Phys. Rev. B* **61**, 4644 (2000).
11. C. D. Taylor, *Phys. Rev. B* **77**, 094119 (2008).
12. P. E. Blöchl, *Phys. Rev. B* **50**, 17953 (1994).
13. J. P. Perdew, J. A. Chevary, S. H. Vosko, K. A. Jackson, M. R. Pederson, D. J. Singh, and C. Fiolhais, *Phys. Rev. B* **46**, 6671 (1992).
14. J. P. Perdew, J. A. Chevary, S. H. Vosko, K. A. Jackson, M. R. Pederson, D. J. Singh, and C. Fiolhais, *Phys. Rev. B* **48**, 4978 (1993).
15. C. S. Barrett, M. H. Mueller, and R. L. Hitterman, *Phys. Rev.* **129**, 625 (1963).
16. S. Xiang, H. Huang, and L. M. Hsiung, *J. Nucl. Mater.* **375**, 113 (2008).
17. J. P. Perdew, K. Burke, and M. Ernzerhof, *Phys. Rev. Lett.* **77**, 3865 (1996).
18. J. P. Perdew, K. Burke, and M. Ernzerhof, *Phys. Rev. Lett.* **78**, 1396 (1997).
19. J. H. Li, Q. B. Ren, C. H. Lu, L. Lu, Y. Dai, and B. X. Liu, *J. Alloy Compd.* **516**, 139 (2012).
20. B. Beeler, C. Deo, M. Baskes, and M. Okuniewski, *J. Nucl. Mater.* **433**, 143 (2013).
21. D. R. Hartree, *Mat. Proc. Cambridge Philos. Soc.* **24**, 89 (1928).
22. V. Fock, *Zeitschrift für Physik* **61**, 126 (1930).
23. L. H. Thomas, in *Mathematical Proceedings of the Cambridge Philosophical Society*, Vol. 23 (Cambridge University Press, 1927) pp. 542–548.
24. E. Fermi, *Rend. Accad. Naz. Lincei* **6**, 32 (1927).

25. P. Hohenberg and W. Kohn, Phys. Rev. **136**, B864 (1964).
26. C. Herring, Phys. Rev. **57**, 1169 (1940).
27. J. C. Phillips and L. Kleinman, Phys. Rev. **116**, 287 (1959).
28. D. R. Hamann, M. Schlüter, and C. Chiang, Phys. Rev. Lett. **43**, 1494 (1979).
29. N. Troullier and J. L. Martins, Phys. Rev. B **43**, 1993 (1991).
30. D. Vanderbilt, Phys. Rev. B **41**, 7892 (1990).
31. G. Kresse and D. Joubert, Phys. Rev. B **59**, 1758 (1999).
32. P. Giannozzi, S. Baroni, N. Bonini, M. Calandra, R. Car, C. Cavazzoni, D. Ceresoli, G. L. Chiarotti, M. Cococcioni, I. Dabo, A. Dal Corso, S. de Gironcoli, S. Fabris, G. Fratesi, R. Gebauer, U. Gerstmann, C. Gougoussis, A. Kokalj, M. Lazzeri, L. Martin-Samos, N. Marzari, F. Mauri, R. Mazzarello, S. Paolini, A. Pasquarello, L. Paulatto, C. Sbraccia, S. Scandolo, G. Sclauzero, A. P. Seitsonen, A. Smogunov, P. Umari, and R. M. Wentzcovitch, J. Phys. Condens. Matter **21**, 395502 (2009).
33. N. A. W. Holzwarth, A. R. Tackett, and G. E. Matthews, Comput. Phys. Commun. **135**, 329 (2001).
34. A. R. Tackett, N. A. W. Holzwarth, and G. E. Matthews, Comput. Phys. Commun. **135**, 348 (2001).
35. N. Iché-Tarrat and C. J. Marsden, The Journal of Physical Chemistry A **112**, 7632 (2008).
36. A. M. Rappe, K. M. Rabe, E. Kaxiras, and J. D. Joannopoulos, Phys. Rev. B **41**, 1227 (1990).
37. Naval Research Laboratories, “Structure of Crystals,” <http://aflowlib.duke.edu/users/egossett/lattice/> (2015).
38. J. D. Pack and H. J. Monkhorst, Phys. Rev. B **16**, 1748 (1977).
39. M. Methfessel and A. T. Paxton, Phys. Rev. B **40**, 3616 (1989).
40. P. Ravindran, L. Fast, P. A. Korzhavyi, B. Johansson, J. Wills, and O. Eriksson, J. Appl. Phys. **84**, 4891 (1998).
41. O. Beckstein, J. E. Klepeis, G. L. W. Hart, and O. Pankratov, Phys. Rev. B **63**, 134112 (2001).
42. G. H. Lander, E. S. Fisher, and S. D. Bader, Adv. Phys. **43**, 1 (1994).
43. T. Le Bihan, S. Heathman, M. Idiri, G. H. Lander, J. M. Wills, A. C. Lawson, and A. Lindbaum, Phys. Rev. B **67**, 134102 (2003).

44. F. D. Murnaghan, Proc. Natl. Acad. Sci. U. S. A. **30**, 244 (1944).
45. R. Q. Hood, L. H. Yang, and J. A. Moriarty, Phys. Rev. B **78**, 024116 (2008).
46. C.-S. Yoo, H. Cynn, and P. Söderlind, Phys. Rev. B **57**, 10359 (1998).
47. E. S. Fisher and H. J. McSkimin, J. Appl. Phys. **29**, 1473 (1958).
48. A. S. Wilson and R. E. Rundle, Acta Crystallogr. **2**, 126 (1949).
49. H. L. Yakel, *Review of X-ray Diffraction Studies in Uranium Alloys*, Tech. Rep. (Oak Ridge National Laboratory, Tennessee (USA), 1973).
50. I. Grenthe, J. Drozdowski, T. Fujino, E. C. Buck, T. E. Albrecht-Schmitt, and S. F. Wolf, *The Chemistry of the Actinide and Transactinide Elements*, Vol. 1 (Springer, Dordrecht, 2006) pp. 253–698.
51. J. H. Kittel, B. R. T. Frost, J. P. Mustelier, K. Q. Bagley, G. C. Crittenden, and J. Van Dievoet, J. Nucl. Mater. **204**, 1 (1993).
52. N.-T. H. Kim-Ngan and L. Havela, J. Sci. Adv. Mater. Dev. **1**, 121 (2016).
53. M. Born, Proc. Camb. Phil. Soc. **36**, 160 (1940).
54. M. Born and K. Huang, *Dynamical Theory of Crystal Lattices* (Clarendon Press, 1954).
55. F. Mouhat and F.-X. Coudert, Phys. Rev. B **90**, 224104 (2014).
56. P. Söderlind, Adv. Phys. **47**, 959 (1998).
57. C. W. Tucker, Jr., *An Approximate Crystal Structure for the Beta Phase of Uranium*, Tech. Rep. KAPL-388 (Knolls Atomic Power Laboratory, 1950).
58. C. W. Tucker, Acta Crystallogr. **4**, 425 (1951).
59. J. Donohue and H. Einspahr, Acta Crystallogr. B **27**, 1740 (1971).
60. J. Donohue, *Structures of the Elements* (John Wiley and Sons, 1974) pp. 134–148.
61. D. C. Wallace, *Thermodynamics of Crystals* (Courier Corporation, 1998).
62. A. R. M. Iasir and K. D. Hammond, Comput. Mater. Sci. **171**, 109221 (2020).
63. A. Dal Corso, Computational Materials Science **95**, 337 (2014).
64. Quantum Espresso, “PS library,” <http://www.quantum-espresso.org/pseudopotentials> (2019).

CHAPTER 5

XENON MOBILITY IN BCC-URANIUM AND URANIUM–MOLYBDENEUM ALLOYS

This chapter is based on work that will be submitted for publication to the Journal of Physics: Condensed Matter. The authors are A. Rafi M. Iasir and Karl D. Hammond of the University of Missouri.

5.1 Introduction

High performance research reactors require high-enrichment uranium (HEU) fuels to attain the desired neutron flux. The replacement of HEU fuels with low-enrichment uranium (LEU) is an important antiproliferation initiative. The United States High-Performance Research Reactor (USHPRR) program is currently aiming to replace the HEU fuels currently used in high performance reactors with LEU fuels [1]. LEU fuels require a higher uranium density than that of uranium oxides to compensate the decrease in ^{235}U enrichment. Metallic uranium shows a great promise in this regard.

Metallic fuels are usually chosen because of their high thermal conductivity and high density. Isotropic swelling behaviour is desirable, but uranium, like other light actinides (Pa–Pu), has a low-symmetry crystal structure (the orthorhombic α phase) at ambient temperature and pressure, which results in anisotropic thermal and radiation-induced expansion. Pure uranium has three allotropes at atmospheric pressure: α (base-centred orthorhombic), β (tetragonal), and γ (body-centred cubic). At atmospheric pressure, α -U

transforms to β -U at approximately 935 K, and β -U transforms to γ -U at approximately 1045 K [2, 3].

The γ -uranium allotrope (which is body-centred cubic) is preferred to α -uranium by nuclear engineers because it undergoes both isotropic thermal expansion and isotropic radiation-induced swelling [4]. It is not possible to quench pure γ -uranium to room temperature; however, a metastable bcc phase can be obtained at room temperature by alloying with molybdenum [5–8]. A study by Kim-Ngan and Havela [9] showed that the bcc structure can also be retained at temperatures below the ordinary phase transition temperature by alloying uranium with metals such as platinum, palladium, niobium, and zirconium. Molybdenum stabilises uranium's γ phase at concentrations near the eutectoid point (11.1 wt% Mo) and lowers the phase transition temperature from 1045 K for pure γ -uranium to 828 K for a U–Mo alloy at the eutectoid point [10, 11]. Uranium alloyed with 10 wt% molybdenum (U-10Mo, which is approximately 21.6 at.% molybdenum) is currently being developed as a potential high-density, low-enrichment uranium fuel for high-performance research reactors [12–14].

Uranium–molybdenum alloys have been studied extensively both experimentally [6, 15, 16] and theoretically [17–21]. Castellano *et al.* [22] showed that the addition of molybdenum to uranium leads to the stabilisation of the γ phase using *ab initio* molecular dynamics. This thermodynamic stabilisation is important because un-alloyed γ -uranium would quickly revert back to α -uranium, causing high stresses and cracking of the fuel and cladding.

Fission creates a variety of products, resulting in gas bubbles, metallic precipitates, and solutes in the fuel matrix. Among the many fission products, fission gas (*i.e.*, xenon and krypton) produces some of the most significant challenges associated with nuclear fuel development. Fission gas influences the thermal conductivity, causes swelling, and impacts the neutron economy of the reactor [23, 24]. The ratio of xenon and krypton in fission gases is nine to one [25]. The important fission gas isotopes with short half lives are ^{133}Xe (5.25 d) and ^{135}Xe (9.1 h). Among them, ^{135}Xe has a very high neutron absorption cross-section

($\sigma_a = 2.7 \times 10^6 \pm 0.1$ barns) that can lower the fuel reactivity. Hence, the evolution of fission gases are directly related to the fuel performance.

Large fission gas atoms (*i.e.*, xenon) are mostly insoluble in the fuel matrix [26, 27]. There is a significant driving force for segregation of fission gas atoms to defects such as grain boundaries or dislocations and consequently form gas bubbles at these sinks. Post irradiation analysis of U–Mo showed that, the fission gases distribute themselves inside the grain and grain boundaries [28–31]. Fission gas in U–Mo alloys also forms superlattices, where they distribute themselves in an organised array [31, 32]. To understand the mechanism, the rate-limiting steps of fission gas diffusion need to be studied. One of them is the individual gas atom movements through the fuel matrix using vacancies.

The behaviour of fission gas has been extensively researched for common fuels such as UO_2 [33–37]. A number of theoretical approaches have also been used to understand the behaviour of fission products in UO_2 , including electronic structure theory [26, 27, 38–44]. In particular, vacancies play an important role in the diffusion of xenon because of its size relative to the metal atoms.

Solute diffusion in light actinides is a very interesting phenomenon because such solutes typically have very high diffusivities. Diffusion of solutes in metallic uranium has not been studied extensively. However, there are some early works that provide some information about defect and impurity diffusion in uranium [45–52]. Recently, Smirnova *et al.* [53] studied self-diffusion in γ -uranium and U–Mo alloys using molecular dynamics. They showed that diffusion in γ -uranium is anomalously fast compared to other bcc metals.

In recent years, there have been many attempts to calculate diffusion coefficients using electronic structure and atomistic methods [54–61]. Electronic structure calculations based on DFT and multi-frequency models have shown their usefulness in various works. Five-frequency models of face-centred cubic crystals [62–64] and nine-frequency (or sometimes four-frequency) models of bcc crystals [65, 66] have been widely used. Methods based on electronic structure theory involve calculating the activation energies of an atom jumping

to a vacancy in one of the atom's nearest-neighbour positions. This is often referred to as vacancy-mediated diffusion. The calculations employed here are based on DFT coupled with classical transition state theory (TST), which treats vibration using the harmonic oscillator approximation [67, 68].

In this study, we use DFT and TST to study the diffusion of xenon and molybdenum in γ -uranium alloys such as U-7Mo and U-10Mo by varying the local molybdenum concentration around the diffusing solute atom. We find that molybdenum's migration energy is much higher than xenon's in γ -U alloys and that the presence of molybdenum in the local environment of a xenon atom tends to decrease the mobility of xenon in γ -uranium alloys. We also calculate the vacancy-solute binding energies of several solutes in γ -uranium and find that such binding energies are generally higher in γ -uranium than in iron or aluminium.

5.2 Theory

Diffusion coefficients in crystalline solids are often described by an Arrhenius equation over a wide range of temperatures. This model consists of two parameters, the migration energy, E_m , and the pre-exponential factor, D_0 , with the diffusion coefficient given by

$$D = D_0 e^{-E_m/k_B T}, \quad (5.1)$$

where k_B is the Boltzmann constant and T is the absolute temperature. If D_0 is independent of temperature, an Arrhenius plot (D against $1/T$) gives a straight line; if D_0 changes with T , it yields a curve that falls away from the constant- D_0 line at high temperature (the left of the plot).

The migration energy is the activation energy for an atom to jump onto a nearby vacancy. According to classical transition state theory (TST), the rate at which a vacancy exchanges its place with neighbouring atom can be expressed by the Eyring-Polanyi equa-

tion [68–70],

$$\nu = \nu^\ddagger \exp\left(\frac{-\Delta G_m}{k_B T}\right) \approx \frac{k_B T}{h} \frac{Q_{\text{TS}}}{Q_{\text{IS}}} \exp\left(\frac{-E_m}{k_B T}\right) \approx \frac{k_B T}{h} \exp\left(\frac{-E_m}{k_B T}\right), \quad (5.2)$$

where Q_{IS} is the vibrational partition function of the initial state and Q_{TS} is the vibrational partition function of the transition state with the vibrational mode along the minimum-energy pathway removed. In the current work, we did not calculate the jump frequencies, which are part of the Q_i terms; we instead make the approximation that the vibrational partition functions not associated with the minimum energy pathway are unity (*i.e.*, $Q_{\text{TS}}/Q_{\text{IS}} \approx 1$). The diffusion coefficient is proportional to the rate of a jump: $D = \nu \lambda^2/6$, where $\lambda = a/\sqrt{8}$ for bcc lattices [71] and a is the lattice parameter.

Metals that undergo irradiation produce point defects such as self-vacancies and self-interstitials in the lattice. The diffusion of these defects results in microstructural changes that impact the mechanical properties. The diffusion of vacancies is of significant interest because they form voids, dislocation loops, and clusters, and they facilitate the diffusion of substitutional solute atoms. This method of solute diffusion is controlled by the interaction between a vacancy and a solute atom. The diffusion of vacancies is particularly influenced by the presence of nearby substitutional solute atoms. Sometimes the vacancy and the solute can coexist as an atom–vacancy complex. Hence, understanding solute–vacancy interactions is an important step in developing models of diffusion in irradiated materials. The binding energy between vacancies and solute atoms is a key factor in understanding solute diffusion [72, 73]. Nearby solute atoms can influence the energy of solute binding with vacancies. The authors are not aware of any previous results regarding solute–vacancy binding in γ -uranium for any solutes, so we calculated them as part of this work.

We used defects in supercells to calculate the binding energies of solute–vacancy ($X-\square$) pairs. The binding energy is the difference between the energy at infinite separation and

the energy at nearest-neighbour separation. We used the following expression to calculate the binding energy of a solute to a vacancy:

$$E_{\text{bind}}^{X-\square} = E_{\text{U}_{N-1}}^{X_1} + E_{\text{U}_{N-1}}^{\square_1} - E_{\text{U}_{N-2}}^{X_1\square_1} - E_{\text{U}_N} \quad (5.3)$$

For a bcc supercell with N sites, the cell may contain no defects (energy E_{U_N}), may contain a vacancy (energy $E_{\text{U}_{N-1}}^{\square_1}$), a solute impurity ($E_{\text{U}_{N-1}}^{X_1}$) or a solute–vacancy pair ($E_{\text{U}_{N-2}}^{X_1\square_1}$). A positive binding energy means the complex is bound. Equation (5.3) can also be conveniently written as the energy required to form a vacancy next to a solute (X) atom. The vacancy formation energy is

$$E_f^{\square} = E_{\text{U}_{N-1}}^{\square_1} - \frac{N-1}{N} E_{\text{U}_N}, \quad (5.4)$$

where E_{U_N} is the energy of a supercell with N uranium atoms.

The disordered nature of U–Mo alloys creates some challenges for electronic structure studies. The manner in which molybdenum is distributed among the uranium atoms produces different diffusion pathways for xenon, and there are several ways to arrange molybdenum atoms on the lattice sites around a xenon atom. We use a combinatorial approach to assess the probabilities (Table 5.1) of having various numbers of molybdenum atoms in the first-nearest-neighbour shell of the bcc structure around a xenon atom. Assuming the molybdenum atoms are arranged randomly, the probability of a particular U/Mo combination on the sites near a xenon atom can be calculated using the following equation:

$$\mathcal{P} = \binom{n}{k} x_{\text{Mo}}^k (1 - x_{\text{Mo}})^{n-k}, \quad (5.5)$$

where n is the number of available nearest-neighbour positions not occupied by the vacancy (for bcc, $n = 7$), k is the number of molybdenum atoms in the nearest-neighbour shell, and x_{Mo} is the (overall) mole fraction of molybdenum. According to Table 5.1, the

Table 5.1. Probability of having different numbers of molybdenum atoms in the nearest-neighbour (NN) location for a bcc uranium–molybdenum alloy. We have used Eq. (5.5) to calculate the probabilities.

# of Mo	U–10Mo	U–7Mo
	($x_{\text{Mo}} = 0.216$)	($x_{\text{Mo}} = 0.157$)
0	0.182	0.302
1	0.351	0.394
2	0.290	0.221
3	0.133	0.069
4	0.037	0.013
5	0.006	0.001
6	0.0006	8.95×10^{-5}
7	2.19×10^{-5}	2.39×10^{-6}

probability (\mathcal{P}) of having more than three molybdenum atoms in the first nearest-neighbour shell is low ($< 5\%$). We assume, for simplicity, that $x_{\text{Xe}} \approx 0$.

5.3 Methodology

All calculations used the QUANTUM ESPRESSO [74] simulation package with the projector-augmented wave (PAW) method [75]. A full description of the uranium pseudopotential can be found in our earlier work [76]. For the elements Mo, Xe, Fe, Co, Au, Nb, and Zr, we used PAW-based pseudopotentials from the QUANTUM ESPRESSO PS Library [77, 78]. We used the exchange–correlation functional of Perdew, Burke, and Ernzerhof (PBE) [79, 80] for all calculations.

DFT calculates the ground state properties of a system; however, γ -uranium is mechanically unstable at 0 K, which results in negative shear moduli [81]. Other elements (*e.g.*, Ti, Zr, Pr, and Hf) also have high-temperature bcc structures that are unstable at low temperature [82, 83]. It is consequently challenging to study γ -uranium with DFT, particularly using a supercell that includes vacancies or defects. To perform our calculations, we used the so-called shell method [84], in which the outer layer of atoms is fixed at crystallographic

coordinates and the rest of the atoms are allowed to move freely. We used a $3 \times 3 \times 3$ supercell of bcc uranium, which consists of 54 atoms in the absence of heteroatoms or vacancies. A convergence test showed that a Monkhorst–Pack k -point mesh of $5 \times 5 \times 5$ is suitable to yield formation and migration energies that are converged to within $0.01 \text{ eV}\text{\AA}^{-1}$.

To calculate the migration energy, each initial state was relaxed with respect to internal coordinates and volume. We determined the transition state by way of a nudged elastic band (NEB) [85, 86] calculation with a climbing image as implemented in QUANTUM ESPRESSO. We used five images in the NEB calculations.

5.4 Results and Discussion

5.4.1 Vacancy Formation and Impurity–Vacancy Binding Energies

The formation energy of a single vacancy is calculated using Eq. (5.4). Our results are compared with previously-published DFT calculations and experimental results in Table 5.2. Our results are in good agreement with both previous DFT studies. Xian *et al.* [87] also used 54 atoms in their supercell, but our vacancy formation energy is higher by 0.2 eV. Discrepancies could arise from their use of a $6 \times 6 \times 6$ k -point mesh, whereas we used $5 \times 5 \times 5$. Beeler *et al.* [84] used a supercell of 128 atoms to calculate the vacancy formation energy. The experimental values bracket our results and those of Beeler *et al.* [84]: The earlier work of Matter *et al.* [88] found a formation energy of $1.2 \pm 0.3 \text{ eV}$, whereas Lund *et al.* [89] found $1.6 \pm 0.2 \text{ eV}$.

We are not aware of any previous reports of calculations of solute–vacancy ($X-\square$) binding energies in γ -uranium, so we calculated these ourselves. We chose solutes so as to compare to diffusion measurements by Rothman and coworkers [46–48]. The results are shown in Table 5.3. All of the solute–vacancy binding energies in γ -uranium are substantially higher than in other bcc metals. For example, in aluminium and magnesium, the $X-\square$ binding energy varies from -0.4 to 0.5 eV for a variety of solutes [73, 90, 91]. In γ -uranium, however, the binding energy varies from 5.715 eV ($\text{Fe}-\square$) to 6.619 eV ($\text{Cr}-\square$),

Table 5.2. Vacancy formation energy (eV) of γ -U compared with previously-published results.

Source	Energy (eV)
Present work	1.28
Beeler <i>et al.</i> [84]	1.384
Xian <i>et al.</i> [87]	1.08
Matter <i>et al.</i> (expt.) [88]	1.2 ± 0.3
Lund <i>et al.</i> (expt.) [89]	1.6 ± 0.2

which indicates that the solute–vacancy binding energy is much higher in bcc uranium than it is in other bcc metals.

The solute–vacancy binding energy characterizes the interaction between a solute and a vacancy, which modifies the local concentration of vacancies near a solute. In the case of γ -uranium, the interaction between solute and vacancy is strongly attractive. The total solute–vacancy binding energy can be decomposed into two factors: elastic effects and electrostatic effects [92]. The elastic energy (or elastic binding energy) is the energy that is released if the strain fields of a solute and a vacancy interact [93, 94]. Due to the unstable nature of γ -U at low temperatures, the elastic binding energy contributes the most to the total solute–vacancy binding energy and is the primary reason for the high value of the solute–vacancy binding energy in bcc uranium.

5.4.2 Xenon and Molybdenum Diffusion

Migration energies are calculated using the climbing-image nudged elastic band method. We calculated the migration energies of xenon and molybdenum moving from the centre of the supercell to one of the nearest-neighbour lattice sites. Such solute–vacancy exchange is the primary mechanism of diffusion of xenon and molybdenum because of their size relative to uranium. Table 5.4 presents our findings. Note that in bcc lattices, all eight nearest-neighbour sites are symmetrically equivalent, so there is only one unique migration energy for xenon near seven uranium atoms and one vacancy. As the amount of molybde-

Table 5.3. Solute–vacancy binding energies in γ -uranium for various solutes near a vacancy. Positive energies indicate energetically-favourable binding.

Solute	Binding energy (eV)
Xe	6.034
Mo	6.249
Fe	5.715
Co	5.876
Au	6.450
Cr	6.619
Zr	6.318
Nb	6.113

num in the nearest-neighbor shell increases, there are more and more symmetrically distinct migration pathways. Xenon’s migration energy in the absence of any molybdenum in the nearest-neighbour positions is significantly lower than molybdenum’s migration energy. The Xe– \square binding energy is also lower than the Mo– \square binding energy, which may occur in part because xenon tends to find its energetic minimum location in between the empty lattice site and the site closest to the xenon atom, resulting in shorter jump distances and lower barriers.

We studied the xenon migration energy in the presence of molybdenum in a systematic way by including various numbers of molybdenum atoms in the nearest-neighbour (NN) shell around a xenon atom and calculating all symmetrically distinct xenon migration energies associated with each distinct arrangement of molybdenum atoms around a central xenon atom. One molybdenum in the NN shell creates three symmetrically equivalent xenon jumps (see Fig. 5.1b). These three migration pathways (labeled 1, 2, and 3) show higher activation energies than the case with no molybdenum in the NN shell.

In the presence of a vacancy, xenon tends to move towards the vacancy and takes position in between the vacancy and lattice site. This results a very low migration path and lower barrier for xenon to move to the nearest vacancy. This behaviour is very similar to

how xenon moves in UO_2 fuel. In UO_2 , the xenon atoms prefer to find their lowest energy location in between the original trap site and the second uranium vacancy (V_U) [27]. Adding one molybdenum in the nearest neighbour increases the migration barriers for all three migration paths. The nearest location of a molybdenum and a vacancy changes the lowest energy location of xenon atom. Xenon tends to move towards the vacancy and the extra space created by molybdenum atom. It finds a place in between its original site, the vacancy and molybdenum atom, and increases the migration barrier.

There is more than one way to put two molybdenum atoms in the NN shell around a solute atom in a bcc crystal, and each of these arrangements creates a distinct xenon migration pathway. Figure 5.2 shows all symmetrically-distinct locations for two molybdenum atoms around a xenon atom and the resulting symmetrically-distinct jumps that could result if a vacancy were in another position nearby. Migration energies with two molybdenum atoms present range from 0.110 eV to 0.532 eV. Both the positions of the two molybdenum atoms and direction of the migration influence the migration energy. Directions 1 and 2 (Fig. 5.2a) have migration energies of 0.110 and 0.212 eV, respectively; direction 2 has almost double the migration energy of direction 1. Directions 1, 4 and 6, which all have a molybdenum atom on the corner of the cube adjacent to the vacancy, have the lowest migration energies. The lowest energy location for xenon in the case of direction 1, 4 and 6 are near to each other. Which produces very low migration barrier.

Figure 5.3 shows the symmetrically-distinct arrangements of three molybdenum atoms in the nearest neighbour shell. This local concentration creates ten distinct jumps of a xenon atom to the nearest neighbour vacancy (Fig. 5.3). The migration energies for three-molybdenum configurations vary from 0.201 eV for direction 4 to 1.213 eV for direction 7. The highest migration energy is for a xenon atom that jumps to a site between two molybdenum atoms (site 7 in Fig. 5.3c). Figure 5.3a shows the arrangements of three molybdenum on the same (100) plane, which produces three distinct jumps with migration energies ranging from 0.515 eV to 0.917 eV, the highest one being for direction 3, where xenon

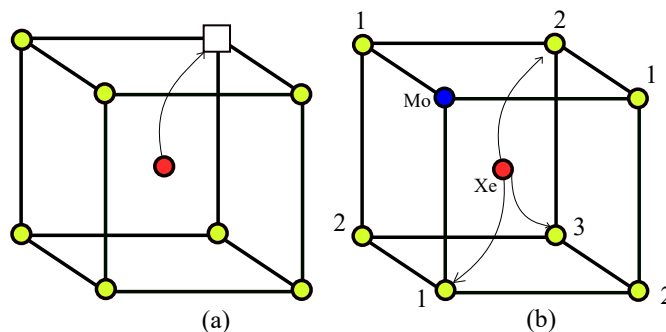


Figure 5.1. (a) Diagram of a xenon jump from the centre site to a nearest-neighbour vacancy in γ -uranium. (a) All eight jumps are symmetrically equivalent with no molybdenum present; (b) with one molybdenum atom in the nearest neighbour shell, there are three unique solute jumps (1, 2, and 3).

moves to the opposite corner from the three molybdenum atoms. Figure 5.3b has a combination of two molybdenum atoms on one face of the cell and one molybdenum in the lower corner on the opposite site. This configuration reduces the migration energy compared to the configuration in which all three molybdenum atoms are coplanar. Direction 7 (Figure 5.3c) produces the highest migration barrier for xenon. In this configuration, initial minimum energy position for xenon is equidistant from all three molybdenum atoms. The final position is not equidistant but creates a larger energy barrier. In the case of direction 8 and 9 the location of the vacancy changes the lowest energy location (for final position) for xenon and reduces the barrier.

We did not calculate the migration energy of xenon with more than three molybdenum atoms in the nearest-neighbour shell. The assumption of a random (binomial) distribution (Table 5.1) implies that the probability of having 0–3 molybdenum is much higher (> 96%) than having more than three molybdenum in U-10Mo or U-7Mo.

5.5 Conclusions

We calculated solute–vacancy binding energies for different solutes in bcc uranium. Uranium shows relatively high vacancy–solute binding energies compared to iron and alu-

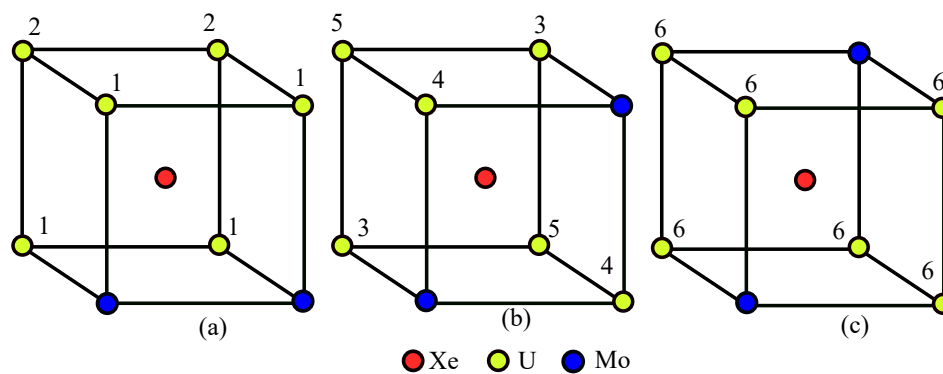


Figure 5.2. The three sets of symmetrically-inequivalent hops of xenon from the centre with two molybdenum atoms in the nearest-neighbour shell. The numbers denote symmetrically distinct pathways.

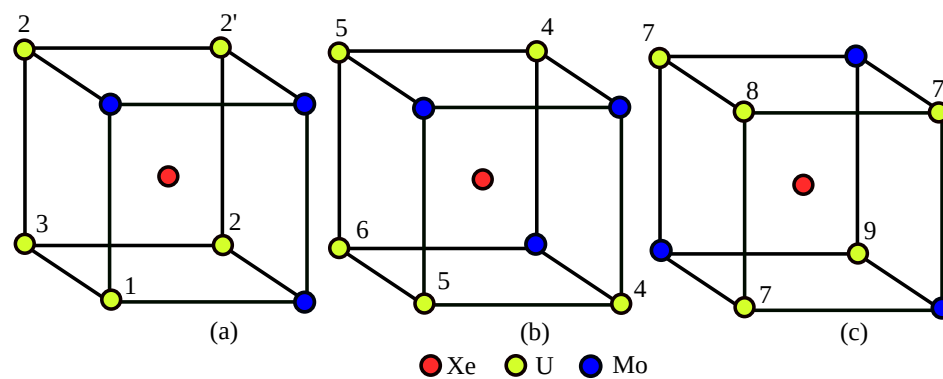


Figure 5.3. The three sets of symmetrically-distinct hops from the centre site with three molybdenum atoms in the nearest-neighbour shell. The numbers denote symmetrically distinct pathways.

Table 5.4. Xenon migration energy (E_m) for different configurations.

Composition ^a	Xe Jump	E_m (eV)
7 U	$\langle 1\ 1\ 1 \rangle$ (Fig. 5.1a)	0.161
1 Mo	1 (Fig. 5.1b)	0.313
	2 (Fig. 5.1b)	0.172
	3 (Fig. 5.1b)	0.261
2 Mo	1 (Fig. 5.2a)	0.110
	2 (Fig. 5.2a)	0.212
	3 (Fig. 5.2b)	0.532
	4 (Fig. 5.2b)	0.108
	5 (Fig. 5.2b)	0.224
	6 (Fig. 5.2c)	0.110
3 Mo	1 (Fig. 5.3a)	0.515
	2' (Fig. 5.3a)	0.917
	3 (Fig. 5.3a)	0.579
	4 (Fig. 5.3b)	0.201
	5 (Fig. 5.3b)	0.384
	6 (Fig. 5.3b)	0.386
	7 (Fig. 5.3c)	1.213
	8 (Fig. 5.3c)	0.461
	9 (Fig. 5.3c)	0.435
	Mo Jump	E_m (eV)
7 U	$\langle 1\ 1\ 1 \rangle$ (Fig. 5.1a)	2.067

^aThe eight nearest-neighbour sites consist of one vacancy plus the atoms listed, with the remaining sites occupied by uranium atoms.

minium. The unstable nature of γ -U at low temperature contributes to a significant increase in solute–vacancy binding energy relative to other bcc metals. The higher elastic binding energy in bcc uranium produces a high solute–vacancy binding energy.

We also calculated migration energies of xenon and molybdenum in pure bcc uranium. Molybdenum’s migration energy is very high compared to that of xenon, indicating that in pure bcc uranium, xenon moves much faster than molybdenum. The relatively low diffusivity of molybdenum also supports our assumptions that molybdenum is randomly distributed in uranium–molybdenum alloys. We also studied migration energies of xenon in the presence of molybdenum in U–Mo alloys. Different combinations of molybdenum in the nearest neighbour and xenon’s distinct jump paths are identified and studied. A combinatorial analysis suggests that having up to three molybdenum atoms in the nearest-neighbour shell is highly probable in U-10Mo and U-7Mo alloys. The presence of molybdenum in the nearest neighbour shell of a xenon atom has an impact on the migration energy, but it does not generally increase or decrease the migration energy; both the location of the molybdenum atoms and direction of the jump influence the migration energy. Having one molybdenum atom in the nearest-neighbour shell increases the activation energy between 0.01 eV and 0.15 eV, depending on the location of the molybdenum atom relative to the xenon atom and the vacancy. If xenon has two molybdenum atoms nearby, we found a similar increase, though there are combinations for which the migration energy is lower than it is in the single-molybdenum cases. For xenon with three nearby molybdenum atoms, the migration energy increases for all molybdenum/vacancy arrangements. While there are several molybdenum arrangements that result in decreased migration energies relative to some of the two-molybdenum configurations, the general trend with the addition of molybdenum in the nearest neighbour shell near xenon is to increase the migration energy, hence reducing xenon mobility in U–Mo alloys.

We did not consider the influence of molybdenum in the second-nearest neighbour shell in bcc uranium. Future work should include a determination of diffusion coefficient of xenon using the kinetic Monte Carlo method.

References

1. J. L. Snelgrove, G. L. Hofman, M. K. Meyer, C. L. Trybus, and T. C. Wiencek, Nucl. Eng. Des. **178**, 119 (1997).
2. A. C. Lawson, C. E. Olsen, J. W. Richardson, M. H. Mueller, and G. H. Lander, Acta Crystallogr. B **44**, 89 (1988).
3. J. Akella, S. Weir, J. M. Wills, and P. Söderlind, J. Phys. Condens. Matter **9**, L549 (1997).
4. J. H. Kittel, B. R. T. Frost, J. P. Mustelier, K. Q. Bagley, G. C. Crittenden, and J. Van Dievoet, J. Nucl. Mater. **204**, 1 (1993).
5. A. S. Wilson and R. E. Rundle, Acta Crystallogr. **2**, 126 (1949).
6. V. P. Sinha, P. V. Hegde, G. J. Prasad, G. K. Dey, and H. S. Kamath, J. Alloy Compd. **506**, 253 (2010).
7. H. L. Yakel, J. Nucl. Mater. **33**, 286 (1969).
8. V. P. Sinha, P. V. Hegde, G. J. Prasad, G. K. Dey, and H. S. Kamath, J. Alloy Compd. **491**, 753 (2010).
9. N.-T. H. Kim-Ngan and L. Havela, J. Sci. Adv. Mater. Dev. **1**, 121 (2016).
10. H. Okamoto, M. E. Schlesinger, and E. M. Mueller, eds., “Mo (molybdenum) binary alloy phase diagrams,” in *Alloy Phase Diagrams*, ASM Handbook, Vol. 3 (ASM International, 2016) pp. 489–498.
11. A. Berche, N. Dupin, C. Guénau, C. Rado, B. Sundman, and J. C. Dumas, J. Nucl. Mater. **411**, 131 (2011).
12. R. Prabhakaran, JOM **69**, 2529 (2017).
13. M. K. Meyer, J. Gan, J. F. Jue, D. D. Keiser, E. Perez, A. Robinson, D. M. Wachs, N. Woolstenhulme, G. L. Hofman, and Y. S. Kim, Nucl. Eng. Technol. **46**, 169 (2014).
14. W. Williams, A. Robinson, and B. Rabin, JOM **69**, 2546 (2017).
15. A. E. Dwight, J. Nucl. Mater. **2**, 81 (1960).
16. K. Tangri and G. Williams, J. Nucl. Mater. **4**, 226 (1961).

17. A. Berche, N. Dupin, C. Guéneau, C. Rado, B. Sundman, and J. C. Dumas, *J. Nucl. Mater.* **411**, 131 (2011).
18. X. Zhang, Y. F. Cui, G. L. Xu, W. J. Zhu, H. S. Liu, B. Y. Yin, and Z. P. Jin, *J. Nucl. Mater.* **402**, 15 (2010).
19. E. L. Losada and J. E. Garcés, *J. Nucl. Mater.* **518**, 380 (2019).
20. A. Landa, P. Söderlind, and P. E. A. Turchi, *J. Nucl. Mater.* **414**, 132 (2011).
21. P. R. Alonso and G. H. Rubiolo, *Model. Simulat. Mater. Sci. Eng.* **15**, 263 (2007).
22. A. Castellano, F. Bottin, B. Dorado, and J. Bouchet, *Phys. Rev. B* **101**, 184111 (2020).
23. V. V. Rondinella and T. Wiss, *Mater. Today* **13**, 24 (2010).
24. A. R. M. Iasir, N. J. Peters, and K. D. Hammond, *J. Nucl. Mater.* **508**, 159 (2018).
25. J. Rest, Y. S. Kim, G. L. Hofman, M. K. Meyer, and S. L. Hayes, *U-Mo fuels handbook. Version 1.0*, Tech. Rep. (Argonne National Lab.(ANL), Argonne, IL (United States), 2006).
26. R. W. Grimes and C. R. A. Catlow, *Phil. Trans. A Math. Phys. Eng. Sci.* **335**, 609 (1991).
27. D. A. Andersson, B. P. Uberuaga, P. V. Nerikar, C. Unal, and C. R. Stanek, *Phys. Rev. B* **84**, 054105 (2011).
28. B. D. Miller, J. Gan, J. Madden, J.-F. Jue, A. Robinson, and D. D. Keiser, *J. Nucl. Mater.* **424**, 38 (2012).
29. B. D. Miller, J. Gan, D. D. Keiser, Jr, A. B. Robinson, J. F. Jue, J. W. Madden, and P. G. Medvedev, *J. Nucl. Mater.* **458**, 115 (2015).
30. J. Gan, D. D. Keiser, D. M. Wachs, A. B. Robinson, B. D. Miller, and T. R. Allen, *J. Nucl. Mater.* **396**, 234 (2010).
31. J. Gan, D. D. Keiser, B. D. Miller, A. B. Robinson, J.-F. Jue, P. Medvedev, and D. M. Wachs, *J. Nucl. Mater.* **424**, 43 (2012).
32. S. Van den Berghe, W. Van Renterghem, and A. Leenaers, *J. Nucl. Mater.* **375**, 340 (2008).
33. Y. Yun, H. Kim, H. Kim, and K. Park, *J. Nucl. Mater.* **378**, 40 (2008).
34. J. C. Carter, E. J. Driscoll, and T. S. Elleman, *Phys. Status Solidi A* **14**, 673 (1972).
35. H. Matzke, *Nucl. Appl.* **2**, 131 (1966).
36. J. R. MacEwan and W. H. Stevens, *J. Nucl. Mater.* **11**, 77 (1964).

37. K. Une, I. Tanabe, and M. Oguma, J. Nucl. Mater. **150**, 93 (1987).
38. C. R. A. Catlow, Proc. Roy. Soc. Lond. Math. Phys. Sci. **364**, 473 (1978).
39. R. A. Jackson, A. D. Murray, J. H. Harding, and C. R. A. Catlow, Philos. Mag. A **53**, 27 (1986).
40. R. W. Grimes, C. R. A. Catlow, and A. M. Stoneham, J. Am. Ceram. Soc. **72**, 1856 (1989).
41. R. G. J. Ball and R. W. Grimes, J. Chem. Soc. Faraday Trans. **86**, 1257 (1990).
42. T. Petit, G. Jomard, C. Lemaignan, B. Bigot, and A. Pasturel, J. Nucl. Mater. **275**, 119 (1999).
43. J.-P. Crocombette, J. Nucl. Mater. **305**, 29 (2002).
44. M. Freyss, N. Vergnet, and T. Petit, J. Nucl. Mater. **352**, 144 (2006).
45. Y. Adda and A. Kirianenko, J. Nucl. Mater. **1**, 120 (1959).
46. N. L. Peterson and S. J. Rothman, Phys. Rev. **136**, A842 (1964).
47. S. J. Rothman, L. T. Lloyd, R. Weil, and A. L. Harkness, *Self-Diffusion in gamma Uranium*, Tech. Rep. (Argonne National Lab., Lemont, Ill., 1959).
48. S. J. Rothman, J. Nucl. Mater. **3**, 77 (1961).
49. Y. Adda and A. Kirianenko, J. Nucl. Mater. **6**, 130 (1962).
50. R. Resnick and L. L. Seigle, J. Nucl. Mater. **5**, 5 (1962).
51. S. J. Rothman, J. Gray, Jr, J. P. Hughes, and A. L. Harkness, J. Nucl. Mater. **3**, 72 (1961).
52. Y. Liu, D. Yu, Y. Du, G. Sheng, Z. Long, J. Wang, and L. Zhang, Calphad **37**, 49 (2012).
53. D. E. Smirnova, A. Y. Kuksin, S. V. Starikov, and V. V. Stegailov, Phys. Met. Metallogr. **116**, 445 (2015).
54. J. B. Adams, S. M. Foiles, and W. G. Wolfer, J. Mater. Res. **4**, 102 (1989).
55. P. E. Blöchl, E. Smargiassi, R. Car, D. B. Laks, W. Andreoni, and S. T. Pantelides, Phys. Rev. Lett. **70**, 2435 (1993).
56. P. E. Blöchl, C. G. Van de Walle, and S. T. Pantelides, Phys. Rev. Lett. **64**, 1401 (1990).
57. W. Frank, U. Breier, C. Elsässer, and M. Fähnle, Phys. Rev. Lett. **77**, 518 (1996).
58. A. Janotti, M. Krčmar, C. L. Fu, and R. C. Reed, Phys. Rev. Lett. **92**, 085901 (2004).

59. M. Krčmar, C. L. Fu, A. Janotti, and R. C. Reed, *Acta Mater.* **53**, 2369 (2005).
60. V. Milman, M. C. Payne, V. Heine, R. J. Needs, J. S. Lin, and M. H. Lee, *Phys. Rev. Lett.* **70**, 2928 (1993).
61. N. Sandberg, B. Magyari-Köpe, and T. R. Mattsson, *Phys. Rev. Lett.* **89**, 065901 (2002).
62. A. B. Lidiard, *Philos. Mag. Series 7* **46**, 1218 (1955).
63. A. B. Lidiard, *Philos. Mag. A* **5**, 1171 (1960).
64. A. D. Leclaire and A. B. Lidiard, *Philos. Mag. A* **1**, 518 (1956).
65. A. D. Le Claire, *Philos. Mag. A* **21**, 819 (1970).
66. H. Mehrer, *Diffusion in Solids: Fundamentals, Methods, Materials, Diffusion-Controlled Processes*, Vol. 155 (Springer Science & Business Media, 2007) pp. 116–122.
67. G. H. Vineyard and G. J. Dienes, *Phys. Rev.* **93**, 265 (1954).
68. G. H. Vineyard, *J. Phys. Chem. Solid* **3**, 121 (1957).
69. H. Eyring, *J. Chem. Phys.* **3**, 107 (1935).
70. M. G. Evans and M. Polanyi, *Trans. Faraday Soc.* **31**, 875 (1935).
71. K. Heinola and T. Ahlgren, *J. Appl. Phys.* **107**, 113531 (2010).
72. R. W. Balluffi and P. S. Ho, “Diffusion,” (American Society for Metals, Metals Park, Ohio, 1973) p. 83.
73. C. Wolverton, *Acta Mater.* **55**, 5867 (2007).
74. P. Giannozzi, S. Baroni, N. Bonini, M. Calandra, R. Car, C. Cavazzoni, D. Ceresoli, G. L. Chiarotti, M. Cococcioni, I. Dabo, A. Dal Corso, S. de Gironcoli, S. Fabris, G. Fratesi, R. Gebauer, U. Gerstmann, C. Gougoussis, A. Kokalj, M. Lazzeri, L. Martin-Samos, N. Marzari, F. Mauri, R. Mazzarello, S. Paolini, A. Pasquarello, L. Paulatto, C. Sbraccia, S. Scandolo, G. Sclauzero, A. P. Seitsonen, A. Smogunov, P. Umari, and R. M. Wentzcovitch, *J. Phys. Condens. Matter* **21**, 395502 (2009), <http://www.quantum-espresso.org/>.
75. P. E. Blöchl, *Phys. Rev. B* **50**, 17953 (1994).
76. A. R. M. Iasir and K. D. Hammond, *Comput. Mater. Sci.* **171**, 109221 (2020).
77. QUANTUM ESPRESSO, “PS library,” <http://www.quantum-espresso.org/pseudopotentials> (2019).
78. A. Dal Corso, *Comput. Mater. Sci.* **95**, 337 (2014).

79. J. P. Perdew, K. Burke, and M. Ernzerhof, Phys. Rev. Lett. **77**, 3865 (1996).
80. J. P. Perdew, K. Burke, and M. Ernzerhof, Phys. Rev. Lett. **78**, 1396 (1997).
81. P. Soderlind, Adv. Phys. **47**, 959 (1998).
82. Y.-Y. Ye, Y. Chen, K.-M. Ho, B. N. Harmon, and P.-A. Lindgrd, Phys. Rev. Lett. **58**, 1769 (1987).
83. J. M. Sanchez and D. De Fontaine, Phys. Rev. Lett. **35**, 227 (1975).
84. B. Beeler, B. Good, S. Rashkeev, C. Deo, M. Baskes, and M. Okuniewski, J. Phys. Condens. Matter **22**, 505703 (2010).
85. G. Henkelman, B. P. Uberuaga, and H. Jónsson, J. Chem. Phys. **113**, 9901 (2000).
86. G. Henkelman and H. Jónsson, J. Chem. Phys. **113**, 9978 (2000).
87. S. Xiang, H. Huang, and L. Hsiung, J. Nucl. Mater. **375**, 113 (2008).
88. H. Matter, J. Winter, and W. Triftshäuser, J. Nucl. Mater. **88**, 273 (1980).
89. K. R. Lund, K. G. Lynn, M. H. Weber, and M. A. Okuniewski, J. Phys. Conf. Ser. **443**, 012021 (2013).
90. D. Shin and C. Wolverton, Acta Mater. **58**, 531 (2010).
91. J. E. Saal and C. Wolverton, Acta Mater. **60**, 5151 (2012).
92. J. Burke, Journal of the Less-Common Metals **28**, 441 (1972).
93. X.-S. Kong, X. Wu, Y.-W. You, C. Liu, Q. Fang, J.-L. Chen, G.-N. Luo, and Z. Wang, Acta Mater. **66**, 172 (2014).
94. T. Ohnuma, N. Soneda, and M. Iwasawa, Acta Mater. **57**, 5947 (2009).

CHAPTER 6

CONCLUSIONS AND FUTURE WORK

We have studied the impact of fission gas in U–Mo alloy. The distributed xenon and krypton gas inside the fuel has significant impact on the thermal properties on the fuel. Krypton is also a fission products which constitutes almost 10% of the fission gas. In comparison to pure xenon bubbles in U–10Mo, their mixture has very little differences. This reaffirms that, xenon contributes the most in the reduction of thermal conductivity. Both intra- and inter-granular xenon bubbles impacts on the heat transfer. The arrangements of the bubbles inside the fuel has significant impact the direction of the heat transfer.

APPENDIX A

ATOMIC UNITS

There are special units of measurement which is convenient for atomic physics and DFT calculations. They are named after the Physicist Douglas Hatree [1]. In this system the numerical values of the four fundamental physical constants are assumed to be unity. They are as follows:

- Reduced planck constant: $\hbar = 1$, atomic unit of action.
- Elementary Charge: $e = 1$, atomic unit of charge.
- Bohr radius: $a_0 = 1$, atomic unit of length.
- Electronic mass: $m_e = 1$, atomic unit of mass.

Now we will explore how it simplifies quantum mechanical calculation of hydrogen atom. The hydrogen atom consists of a heavy proton (charge e) with a much lighter electron (charge $-e$) that orbits around it. The potential energy (in SI units) is

$$V(\mathbf{r}) = -\frac{Ze^2}{4\pi\epsilon_0|r|} \quad (\text{A.1})$$

where Z is the atomic number and \mathbf{r} is the position relative to the nuclear site. The radial Schrödinger equation including the centrifugal term is:

$$\left[-\frac{\hbar^2}{2m_e} \nabla_r^2 + \frac{\hbar^2 \ell(\ell+1)}{2m_e r^2} - \frac{Ze^2}{4\pi\epsilon_0|r|} - E \right] rR(r) = 0 \quad (\text{A.2})$$

The above equation can be simplified by introducing dimensionless quantities. Multiplying Eq. (A.2) with m_e/\hbar^2 the equation becomes:

$$\begin{aligned} \left[-\nabla_r^2 + \frac{\ell(\ell+1)}{r^2} + \frac{2m_eZe^2}{4\pi\epsilon_0\hbar^2} \frac{1}{r} - \frac{2m_eE}{\hbar^2} \right] rR(r) &= 0 \\ \left[-\frac{1}{2}\nabla_r^2 + \frac{\ell(\ell+1)}{2r^2} + \frac{Z}{a_0r} - \frac{E}{E_0a_0^2} \right] rR(r) &= 0 \\ \left[-\frac{1}{2}\nabla_\zeta^2 + \frac{\ell(\ell+1)}{2\zeta^2} + \frac{Z}{\zeta} - \frac{E}{E_0} \right] \zeta R(\zeta a_0) &= 0 \end{aligned} \quad (\text{A.3})$$

The above equation has two units, one is for length scale, the Bohr radius a_0 and the other one is an energy scale, the Hartree E_0 .

A.0.1 Bohr Radius

$$a_0 = \frac{4\pi\epsilon_0\hbar^2}{m_e e^2} \quad (\text{A.4})$$

The Bohr radius is the length unit of the Hatree atomic unit system. It corresponds to the radius of a classical electron circling a proton at the ground energy of the hydrogen atom. Using all the fundamental constants in Eq. (A.4) the standard atomic unit of Bohr becomes

$$1 \text{ bohr} = \frac{4\pi\epsilon_0\hbar^2}{m_e e^2} = 0.529 \, 177 \, 25 \times 10^{-10} \text{ m} = 0.52917725 \, \text{\AA} \quad (\text{A.5})$$

A.0.2 Hatree

$$E_0 = \frac{\hbar^2}{m_e a_0^2} = \frac{m_e e^4}{(4\pi\epsilon_0\hbar)^2} \quad (\text{A.6})$$

The Hartree is the energy unit in the Hatree atomic unit system. One Hartree is twice the binding energy of an electron in the hydrogen atom. To satisfy $a_0 = 1$, all the fundamental units becomes unity ($\hbar = m_e = e = 4\pi\epsilon_0 = 1$), according to Eq. (A.4). The unit of Hatree

can also be calculated from the fundamental units.

$$1 \text{ hartree} = \frac{\hbar^2}{m_e a_0^2} = \frac{m_e e^4}{(4\pi\epsilon_0 \hbar)^2} = 4.359\,748\,2 \times 10^{-10} \text{ J} = 27.211396 \text{ eV} \quad (\text{A.7})$$

In Hatree units, the Schrödinger equation of an electron in the Coulomb potential of the nucleus has the following form:

$$\left(-\frac{1}{2} \nabla^2 - \frac{Z}{r} - E \right) |\psi\rangle = 0 \quad (\text{A.8})$$

A.0.3 Rydberg Atomic Units

The Rydberg atomic unit is another useful atomic unit which is widely used in DFT and atomic physics. In Hatree atomic units, the assumption is $\hbar^2/2m_e = \frac{1}{2}$. In Rydberg atomic units the assumption is:

$$\hbar = 2m_e = e^2/2 = 1$$

Using the above relations, the length unit does not change in Rydberg units.

$$a_0 = \frac{4\pi\epsilon_0 \hbar^2}{2m_e e^2/2} = \frac{4\pi\epsilon_0 \hbar^2}{m_e e^2} = 0.52917725 \text{ Å} \quad (\text{A.9})$$

The energy unit does change as follows:

$$1 \text{ Ry} = \frac{\hbar^2}{2m_e a_0^2} = \frac{1}{2} \frac{\hbar^2}{m_e a_0^2} = 13.605693 \text{ eV} \quad (\text{A.10})$$

References

1. Hartree D R 1928 *Mat. Proc. Cambridge Philos. Soc.* **24** 89

APPENDIX B

HELIUM INTERACTION WITH BCC LITHIUM

Lithium is becoming one of the important materials in the context of plasma-facing in thermonuclear magnetic fusion devices. Lithium-coated surfaces are being used in several fusion devices in the world [1–6]. There are earlier example of using lithium in the fusion reactor. Erents *et al.* [7] used lithium to trap deuterons in solid and liquid lithium. Liquid lithium proven to be efficient trapper. Lithium reacts with deuterium and forms lithium hydride (LiH) which is ionic in nature. Lithium was also proposed as a breeding material in fusion reactors [8]. For this, lithium needs to be enriched to ^6Li . The recent interest of using solid lithium (applied to graphite surface) in fusion reactor is for density and impurity control in the temperature range of 30–50 °C [9]. In the near surface of plasma facing materials high density of interstitials and vacancies are being produced in addition to higher concentration of hydrogen and helium. This defects and gases will change the microstructure of the material. It is therefore important to determine the property of point defects in Lithium and its interaction with helium atom. The goal of this study is to calculate some important data regarding point defects in lithium and helium in lithium using first principle methods.

We perform all our calculations using density functional theory (DFT) with plane-wave basis sets as implemented in the software QUANTUMESPRESSO[10]. The PAW [11] based pseudopotential were used from PS library [12, 13]. The generalized gradient approximation of Perdew–Burke–Ernzerhof (PBE) was used as exchange-correlation functional [14, 15]. We used a $4 \times 4 \times 4$ of bcc lithium, which consists of 128 atoms to sim-

ulate point defects. Brillouin zone sampling was performed using Monkhorst and Pack scheme [16]. The plane wave cutoff energy was 50 Ry. The equilibrium lattice parameter obtained was 3.436 Å for bcc lithium. All the calculations were performed at constant volume fully relaxing the atomic positions in the supercells. The migration energies were calculated using the nudged elastic band [17, 18] method with five images along the migration path.

The formation energies are calculated as follows:

$$\begin{aligned}
E_f^{\text{oct}} &= E_{\text{Li+He}_{\text{oct}}} - E_{\text{Li}_N} - E_{\text{He}_{\text{isolated}}} \\
E_f^{\text{tet}} &= E_{\text{Li+He}_{\text{tet}}} - E_{\text{Li}_N} - E_{\text{He}_{\text{isolated}}} \\
E_f^{\square} &= E_{\text{Li}_{N-1}^{\square_1}} - \frac{N-1}{N} E_{\text{Li}_N} \\
E_f^{\text{subs}} &= E_{\text{Li+He}_{\square}} - \frac{N-1}{N} E_{\text{Li}_N} - E_{\text{He}_{\text{isolated}}}
\end{aligned} \tag{B.1}$$

Here $E_{\text{Li+He}_{\text{tetra/octa}}}$ is the energy of the system where He is in either octahedral and tetrahedral location of bcc lithium. $E_{\text{Li+He}_{\square}}$ is the energy of the system where He is in substitutional position of the lattice. E_{Li_N} is the reference energy of the bulk bcc lithium, and $E_{\text{He}_{\text{isolated}}}$ is the energy of an isolated He atom. $E_{\text{Li}_{N-1}^{\square_1}}$ is the energy of a lithium bcc supercell with a vacancy.

The formation energy of an SIA is calculated using

$$E_f^{\text{SIA}} = E_{\text{Li}_{N+1}^{\text{SIA}}} - \frac{N+1}{N} E_{\text{Li}_N} \tag{B.2}$$

where, $E_{\text{Li}_{N+1}^{\text{SIA}}}$ is the energy of a system with a self interstitial (Li) atom in either octahedral and tetrahedral position.

The binding energies of two helium atoms is determined as obtained as:

$$E_b^{A_1-A_2} = E_{\text{Li}}^{A_1} + E_{\text{Li}}^{A_2} - E_{\text{Li}_N}^{A_1+A_2} - E_{\text{Li}_N} \tag{B.3}$$

Table B.1. Calculated vacancy formation energy E_f^\square , vacancy migration energy, and self-interstitial formation energy in lithium. Calculated results are compared with some of the previous work and experimental results (in italics).

Defect	Formation Energy (eV)	Previous Work
vacancy (E_f^\square)	0.496	0.52 [19]
		0.506 [20]
		<i>0.508</i> [21]
$\langle 111 \rangle$	0.589	0.573 [22]
$\langle 110 \rangle^a$	0.646	0.637 [22]
$\langle 010 \rangle^b$	0.791	0.782 [22]
tetrahedral (E_f^{tetr})	0.646	0.696 [22]
octahedral (E_f^{oct})	0.793	0.785 [22]
Vacancy migration energy	0.102	0.053 [20]
		<i>0.038</i> [21]

^aequivalent to tetrahedral SIA formation

^bequivalent to octahedral SIA formation

Here, E_{Li_N} is the energy of the supercell without any A_1 and A_2 , $E_{\text{Li}}^{A_1/A_2}$ is the energy of the supercell with A_1 or A_2 . $E_{\text{Li}}^{A_1+A_2}$ is the energy of the supercell containing both A_1 and A_2 interacting. For more than two entities, the following equation is used to calculate the binding energies between them.

$$E_b^{(A_1, A_2, \dots, A_n)} = \sum_{i=1, \dots, n} E_{\text{Li}}^{A_i} - \left[E_{\text{Li}}^{(A_1+A_2+\dots+A_n)} + (n-1)E_{\text{Li}_N} \right] \quad (\text{B.4})$$

The He–He dumbbell formation energy (around a vacancy) can be calculated using the following equation:

$$E_f^{\text{He}-\square-\text{He}} = E_{\text{Li}}^{\text{He}-\square-\text{He}} - E_{\text{Li}_N} + \frac{E_{\text{Li}_N}}{N} - E_{\text{He}_{\text{isolated}}} \quad (\text{B.5})$$

Here, $E_{\text{Li}}^{\text{He}-\square-\text{He}}$ is the energy of the system containing helium dumbbell.

We have calculated the formation energies for different configurations of the self-interstitial atom and the vacancy formation energy for lithium. The results are presented in Table B.1.

Table B.2. Formation energies (in eV) for a single He atom positioned in the octahedral or tetrahedral interstitial sites as well as in substitution. He migration energy (eV). The Calculations are done using 128 atom supercells.

Configuration	Li-He	W-He [26]	Fe-He [27]
E_{oct}^f	1.142	6.38	4.60
E_{tetr}^f	1.132	6.16	4.37
E_{subs}^f	1.213	4.70	4.08
E_{mig}^{t-t}	0.003	0.06	0.06
E_{mig}^{t-o-t}	0.013		
E_{mig}^{o-o}	0.004		
$E_b^{\text{He-He}}$		1.03	

Table B.3. Formation of He-He dumbbells around a vacancy

Dumbbell Configuration	Formation Energy (eV)
$\langle 111 \rangle$	1.844
$\langle 110 \rangle$	1.863
$\langle 010 \rangle$	1.879

Our results are compatible with previous DFT works and experiments. The earlier DFT works produced formation energies range from 0.52–0.57 eV [19, 23–25]. The discrepancy could come from the size of the supercell (54), elastic interaction and the quality of the pseudopotential. We have also calculated the self-interstitial formation energy in lithium. The octahedral self-interstitial forms a dumbbell in $\langle 010 \rangle$ direction, and the tetrahedral interstitial forms a $\langle 110 \rangle$ dumbbell. The most stable dumbbell being in the direction of $\langle 111 \rangle$, which is very similar to other nonmagnetic bcc materials. The vacancy formation energy is slightly underestimated while the migration energy of the vacancy in $\langle 111 \rangle$ direction is over estimated. The self-interstitial dumbbell formation shows similar comparable values as reported by Ma and Dudarev [22].

During the operation of the fusion reactor, the lithium coated surface will be interacting with high flux of different hydrogen isotopes and helium plasmas. This could initiate neu-

tron activated reaction and transmute hydrogen and helium. All these processes will build a substantial amount of hydrogen and helium inside the material. Numerous research has been and still being performed to understand the behaviour of helium in metals. One of the major challenges is the low solubility of helium in metal. Helium atoms in a metal may find its low energy position either in substitutional or interstitial lattice sites. We have calculated the formation energies of different configuration of helium in substitutional as well as interstitial positions using Eq. (B.1). The results are presented in Table B.2. We have compared our results with tungsten and iron's interaction with helium. Our calculation predicts that, tetrahedral interstitial position is the most stable configuration for helium, which is also common for tungsten and iron [26, 28]. The difference between the octahedral and tetrahedral interstitial formation energy is 0.01 eV. This is low compared to tungsten–helium (0.22 eV) and iron–helium (0.23 eV). The formation energy of helium in a substitutional location is about 1.213 eV. This value is higher than both tetrahedral and octahedral interstitial formation energy. This is an atypical result compared to tungsten–helium and iron–helium system. We have reproduced our results of having higher substitutional energy using different DFT package (*i.e.* Abinit) and ultrasoft pseudopotential.

We have also calculated the binding energy of helium with monovacancy. Even though, the substitutional energy is higher, a single helium still finds its place in lattice side. The binding energy of a helium in lattice site with a nearby vacancy is 0.21 eV. The binding energy of a helium in tetrahedral interstitial location and nearest vacancy is 0.42 eV. This indicates that a interstitial helium favors the vacancy. Two helium atoms around a vacancy forms dumbbell. The formation energies are based on the orientation of the dumbbell. The helium dumbbell formation energies are presented in Table B.3. The lowest energy configuration is $\langle 111 \rangle$ dumbbell. The migration energies of helium from one tetrahedral site to nearest tetrahedral site (Fig. B.2) is calculated using nudged elastic band method. The calculated energy is 0.003 eV. Tungsten–helium and iron–helium have a little higher

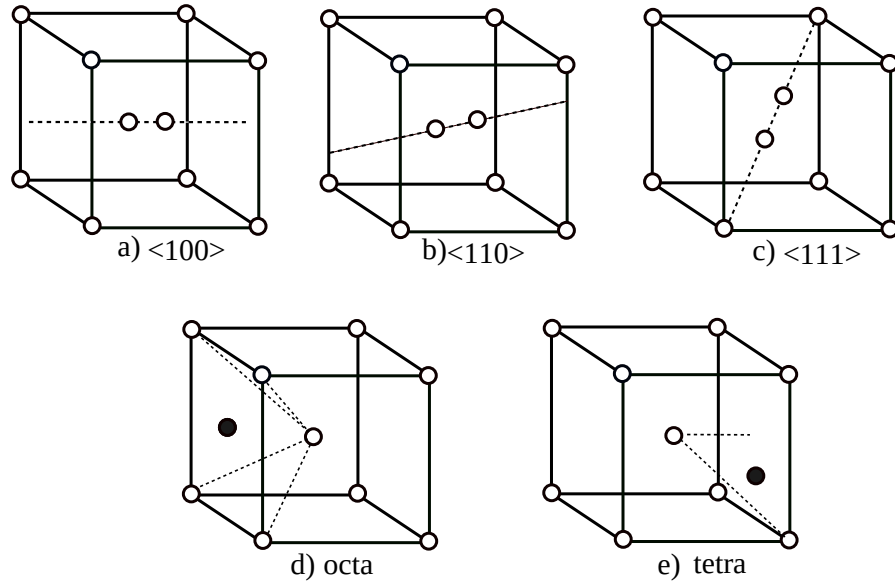


Figure B.1. Different dumbbell configuration in bcc crystal. a) $\langle 100 \rangle$ dumbbell. b) $\langle 110 \rangle$ dumbbell. c) $\langle 111 \rangle$ dumbbell. d) octahedral interstitial. e) tetrahedral interstitial.

migration (E_{mig}^{t-t}) energy of 0.006 eV. The migration energy from one octahedral site to the next octahedral site is 0.004, which is also very low.

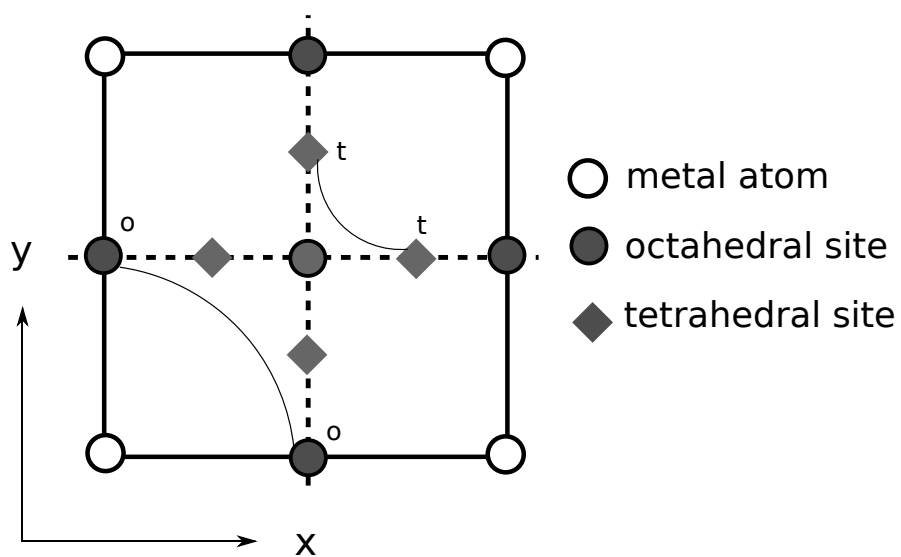


Figure B.2. Tetrahedral (t) and octahedral (o) site on the (001) plane of the bcc lattice.

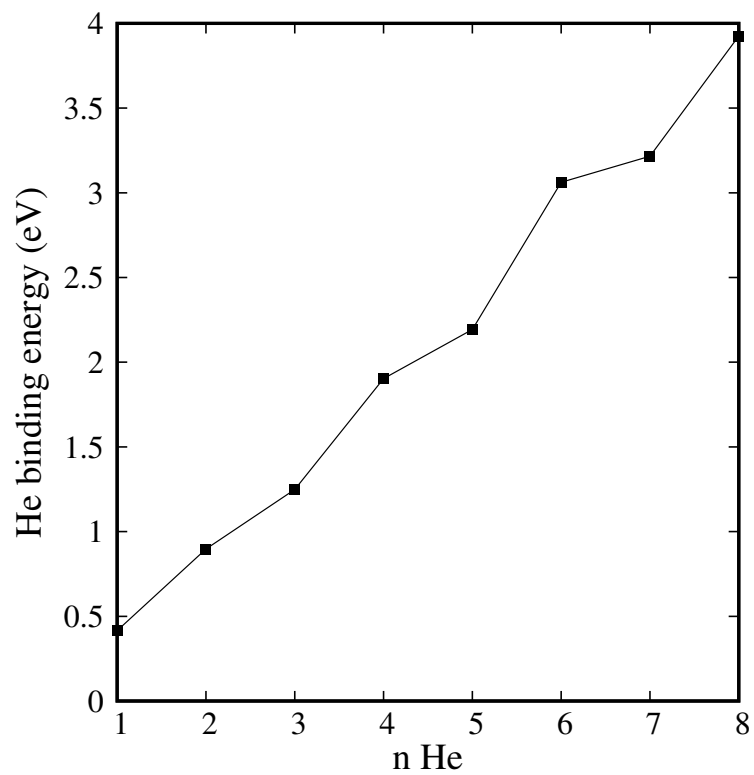


Figure B.3. Helium binding energy around a vacancy

References

1. M. Bell, H. Kugel, R. Kaita, L. Zakharov, H. Schneider, B. LeBlanc, D. Mansfield, R. Bell, R. Maingi, S. Ding, *et al.*, Plasma Physics and Controlled Fusion **51**, 124054 (2009).
2. S. Mirnov, V. Lazarev, S. Sotnikov, V. Evtikhin, I. Lyublinski, A. Vertkov, *et al.*, Fusion Engineering and Design **65**, 455 (2003).
3. J. Sánchez, F. Tabarés, D. Tafalla, J. Ferreira, I. García-Cortés, C. Hidalgo, F. Medina, M. Ochando, M. Pedrosa, and T.-I. The, Journal of nuclear materials **390**, 852 (2009).
4. A. Tuccillo, A. Alekseyev, B. Angelini, S. V. Annibaldi, M. Apicella, G. Apruzzese, J. Berrino, E. Barbato, A. Bertocchi, A. Biancalani, *et al.*, Nuclear Fusion **49**, 104013 (2009).
5. G. Xu, B. Wan, J. Li, X. Gong, J. Hu, J. Shan, H. Li, D. Mansfield, D. Humphreys, V. Naulin, *et al.*, Nuclear Fusion **51**, 072001 (2011).
6. S. Munaretto, S. Dal Bello, P. Innocente, M. Agostini, F. Auriemma, S. Barison, A. Canton, L. Carraro, G. De Masi, S. Fiameni, *et al.*, Nuclear Fusion **52**, 023012 (2012).
7. S. Erents, G. McCracken, and P. Goldsmith, Journal of Physics D: Applied Physics **4**, 672 (1971).
8. J. Hartley, B. Gore, and J. Young, Lithium Needs and Resources , 337 (1978).
9. J. P. Allain and C. N. Taylor, Physics of Plasmas **19**, 056126 (2012).
10. P. Giannozzi, S. Baroni, N. Bonini, M. Calandra, R. Car, C. Cavazzoni, D. Ceresoli, G. L. Chiarotti, M. Cococcioni, I. Dabo, A. Dal Corso, S. de Gironcoli, S. Fabris, G. Fratesi, R. Gebauer, U. Gerstmann, C. Gougoussis, A. Kokalj, M. Lazzeri, L. Martin-Samos, N. Marzari, F. Mauri, R. Mazzarello, S. Paolini, A. Pasquarello, L. Paulatto, C. Sbraccia, S. Scandolo, G. Sclauzero, A. P. Seitsonen, A. Smogunov, P. Umari, and R. M. Wentzcovitch, J. Phys. Condens. Matter **21**, 395502 (2009), <http://www.quantum-espresso.org/>.
11. P. E. Blöchl, Phys. Rev. B **50**, 17953 (1994).
12. A. Dal Corso, Computational Materials Science **95**, 337 (2014).
13. Quantum Espresso, “PS library,” <http://www.quantum-espresso.org/pseudopotentials> (2019).
14. J. P. Perdew, K. Burke, and M. Ernzerhof, Phys. Rev. Lett. **77**, 3865 (1996).
15. J. P. Perdew, K. Burke, and M. Ernzerhof, Phys. Rev. Lett. **78**, 1396 (1997).
16. J. D. Pack and H. J. Monkhorst, Phys. Rev. B **16**, 1748 (1977).

17. G. Henkelman, B. P. Uberuaga, and H. Jónsson, *J. Chem. Phys.* **113**, 9901 (2000).
18. G. Henkelman and H. Jónsson, *J. Chem. Phys.* **113**, 9978 (2000).
19. W. Frank, U. Breier, C. Elsässer, and M. Fähnle, *Phys. Rev. Lett.* **77**, 518 (1996).
20. P.-W. Ma and S. Dudarev, *Phys. Rev. Mater.* **3**, 063601 (2019).
21. P. Ehrnhar, P. Jung, H. Schultz, and H. Ullmaier, in *Atomic Defects in Metals*, Vol. 25, edited by H. Ullmaier (Springer-Verlag Berlin Heidelberg, 1991).
22. P.-W. Ma and S. L. Dudarev, *Phys. Rev. Mater.* **3**, 013605 (2019).
23. R. Benedek, L. Yang, C. Woodward, and B. Min, *Phys. Rev. B* **45**, 2607 (1992).
24. R. Pawellek, M. Fahnle, C. Elsasser, K. M. Ho, and C. T. Chan, *J. Phys. Condens. Matter* **3**, 2451 (1991).
25. W. Frank, U. Breier, C. Elsässer, and M. Fähnle, *Phys. Rev. B* **48**, 7676 (1993).
26. C. Becquart and C. Domain, *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* **255**, 23 (2007).
27. T. Seletskiaia, Y. Osetsky, R. E. Stoller, and G. M. Stocks, *Phys. Rev. Lett.* **94**, 046403 (2005).
28. C.-C. Fu and F. Willaime, *Phys. Rev. B* **72**, 064117 (2005).

APPENDIX C

ORTHOGONAL PLANE WAVE

For now we will try to approximate time-independent Schrödinger equation so that we can achieve self-consistency. We let $V(r)$ the potential seen by each electron. Then each energy eigenfunction will satisfy the following equation:

$$H\psi_i = (T + V(r))\psi_i = E_i\psi_i \quad (\text{C.1})$$

Here T is the kinetic energy $(-\hbar^2\nabla^2/2m)$, and E_i is the energy of the i th state. The next step is to distinguish between the core and the valance state. The index α will be used for core and v will be used for conduction band. According to our second assumption, the core states are the same as in the isolated ion, but their energies are different, i.e. E_α , are different:

$$(T + V(r))\psi_\alpha = E_\alpha\psi_\alpha \quad (\text{C.2})$$

Here, the subscript α not only denotes the position of the ion as well as the energy and angular-momentum quantum numbers of the state in the equation. We have an well defined eigen value problem, apart from not knowing $V(r)$. We can approach the problem in several ways. The choice of basis function is often used physics. The plane wave basis sets is often used in band structure calculations. If we expand the Schrödinger equation C.2 with complete set of states, then we may obtain a linear simultaneous equations in the expansion coefficients. The problem of solving differential equations become a matrix diagonalizing problem. The choice of plane waves has its pros and cons. One of the difficulties of

using plane waves, is that, it requires a large number of plane waves to give a reasonable description of the wave function. Thus the solution becomes very difficult. Core electron has higher kinetic energy (s orbital) near the nucleus (see Fig. 2.2), which makes it really hard for plane wave to approximate those oscillation. Herring [1] suggested that, rather than expanding the conduction electron wave function in plane waves, a more rapidly convergent procedure is to expand in *orthogonalized* plane waves (OPWs). Hopefully, the expansions in terms of OPWs, would require fewer terms and therefore yield a easier calculation. The OPWs with wave number \mathbf{k} can be defined as follows:

$$OPW_{\mathbf{k}} = e^{i\mathbf{k}\cdot\mathbf{r}} - \sum_{\alpha} \psi_{\alpha}(\mathbf{r})\psi_{\alpha}^{*}e^{i\mathbf{k}\cdot\mathbf{r}}d\tau' \quad (C.3)$$

An example would be sodium, where it has a ground state configuration of $1s^22s^22p^63s^1$, the core level would represent $1s^22s^22p^6$. For so-called simple metal (i.e. Na, Mg and Al), the convergent electron wave function is rapidly convergent in the OPW basis. Before going any further, lets check whether this OPW (C.3) is orthogonal to the core states. Lets assume an arbitrary core wave function ψ_{β} and check the orthogonality with C.3.

$$\int \psi_{\beta}^{*}(\mathbf{r})OPW_{\mathbf{k}}d\tau' = \int \psi^{*}(\mathbf{r})e^{i\mathbf{k}\cdot\mathbf{r}}d\tau - \sum_{\alpha} \delta_{\alpha\beta} \int \psi^{*}(\mathbf{r}')e^{i\mathbf{k}\cdot\mathbf{r}'}d\tau' = 0 \quad (C.4)$$

It is convenient to normalize the plane waves in the unit cell volume of the metal Ω , and we will bra and ket notation for the wave functions from now on. The plane wave becomes

$$|\mathbf{k}\rangle \equiv \Omega^{-1/2}e^{i\mathbf{k}\cdot\mathbf{r}} \quad (C.5)$$

For core electron wave functions

$$|\alpha\rangle \equiv \psi_{\alpha}(\mathbf{r}) \quad (C.6)$$

where a bra operators is defined as $\langle\alpha| = |\alpha\rangle^*$, the other representation an integral:

$$\langle\alpha|\mathbf{k}\rangle = \Omega^{-1/2} \int \psi_{\alpha}^*(\mathbf{r}) e^{i\mathbf{k}\cdot\mathbf{r}} \quad (\text{C.7})$$

Thus the OPW equations becomes

$$OPW_{\mathbf{k}} = |\mathbf{k}\rangle - \sum_{\alpha} |\alpha\rangle \langle\alpha|\mathbf{k}\rangle \quad (\text{C.8})$$

The projection operator P can be defined as follows:

$$P = \sum_{\alpha} |\alpha\rangle\langle\alpha| \quad (\text{C.9})$$

The P operator projects any function onto core states. In terms of P operator the OPW can take following form

$$OPW_{\mathbf{k}} = (1 - P) |\mathbf{k}\rangle \quad (\text{C.10})$$

Now, we can expand the conduction-band (valence electron) state in terms of the general linear combination of OPW's:

$$\psi_k = \sum_q a_q(\mathbf{k})(1 - P) |\mathbf{k} + \mathbf{q}\rangle \quad (\text{C.11})$$

Before going a bit further, lets see how kinetic energy is represented by planewaves.

$$\langle q' | -\frac{\hbar^2}{2m} \nabla^2 | q \rangle = \frac{1}{2} \frac{\hbar^2}{2m} |\vec{q}|^2 \delta_{\vec{q}\vec{q}'} \quad (\text{C.12})$$

In the above approximation of kinetic energy we assumed the normalizing factor is one.

Now we are going to expand C.2 with OPWs, and the Schrödinger equation becomes

$$H\psi_k = \sum_q a_q(\mathbf{k}) H(1 - P) |\mathbf{k} + \mathbf{q}\rangle = E_k \sum_q a_q(\mathbf{k})(1 - P) |\mathbf{k} + \mathbf{q}\rangle \quad (\text{C.13})$$

Where , H consists both the kinetic energy and the potential. Multiplying on the left by $\langle \mathbf{k} + \mathbf{q}' |$, and using Equation (C.12) we obtain

$$a_{q'}(\mathbf{k}) \frac{\hbar^2}{2m} |\mathbf{k} + \mathbf{q}'|^2 + \sum_q a_q(\mathbf{k}) \times [\langle \mathbf{k} + \mathbf{q}' | V | \mathbf{k} + \mathbf{q} \rangle - \sum_\alpha E_\alpha \langle \mathbf{k} + \mathbf{q}' | \alpha \rangle \langle \alpha | \mathbf{k} + \mathbf{q} \rangle] = [a_{q'}(\mathbf{k}) - \sum_q a_q(\mathbf{k}) \langle \mathbf{k} + \mathbf{q}' | P | \mathbf{k} + \mathbf{q} \rangle] E_{\mathbf{k}} \quad (\text{C.14})$$

The above equation can be solve by diagonalizing some of matrix element. If we can evaluate some of the various matrix elements (integrals), we obtain a set of linear algebraic equation.

References

1. Conyers Herring. A new method for calculating wave functions in crystals. *Phys. Rev.*, 57(12):1169, 1940.

APPENDIX D

PROJECTOR AUGMENTED WAVE

Pseudopotential technique has been proven to be accurate for a large variety of systems, but there is no strict guarantee that it will produce the same results as an all-electron calculation. The challenge with norm-conserving pseudopotentials is that it limits the *softness*. Another way to say it, it needs higher cut-off energy. In the plane-wave basis set for the pseudo wavefunctions is defined by the shortest wave length $\lambda = 2\pi/|\vec{G}|$, where \vec{G} is the wave vector. Projector augmented waves (PAW) introduces projectors and auxiliary localized functions to increase the softness of the pseudopotential, at the same time keeping full wave function. In this section I will try to introduce PAW with some basic formalism. The origin of the PAW method lies a transformation that maps the true wavefunctions with their complete nodal structure into auxiliary wavefunctions. The purpose of this transformation is to have a smooth auxiliary wavefunctions, which have a rapidly convergent plane-wave expansion. The PAW method was first proposed by Blöchl in 1994 [1]. The linear transformation is as follows.

$$|\Psi_n\rangle = \hat{\mathcal{T}} |\tilde{\Psi}_n\rangle \quad (\text{D.1})$$

Where, $|\Psi_n\rangle$ is the true all-electron KS single particle wave function, $|\tilde{\Psi}_n\rangle$ is auxiliary smooth wave function, and $\hat{\mathcal{T}}$ is a linear transformation operator. Since the true wave functions are already smooth at a certain minimum distance from the core, $\tilde{\mathcal{T}}$ should only modify the wave function close to the nuclei. Thus the transformation operator becomes

$$\tilde{\mathcal{T}} = 1 + \sum_a \tilde{\mathcal{T}}^a \quad (\text{D.2})$$

Where a is an atom index, $\tilde{\mathcal{T}}^a$, has no effect outside a certain atom-specific augmentation region, r_c^a . Inside the augmentation spheres, the true wave function can be expanded in the partial waves ϕ_i^a , for a corresponding auxiliary smooth partial wave can be defined as $\tilde{\phi}_i^a$, and they connected by the following relation.

$$|\phi_i^a\rangle = (1 + \hat{\mathcal{T}}^a) |\tilde{\phi}_i^a\rangle \Rightarrow \hat{\mathcal{T}}^a |\phi_i^a\rangle = |\phi_i^a\rangle - |\tilde{\phi}_i^a\rangle \quad (\text{D.3})$$

Here a is an atom index, i comes from partial waves. Outside the augmentation sphere, the partial wave and its smooth counterpart should be identical.

$$\phi_i^a(\mathbf{r}) = \tilde{\phi}_i^a(\mathbf{r}), \text{ for } r > r_c^a \quad (\text{D.4})$$

Where $\phi_i^a(\mathbf{r}) = \langle \mathbf{r} | \phi_i^a \rangle$, and similar for $\tilde{\phi}_i^a$. If the smooth partial waves form a complete set inside the augmentation sphere, we can expand the smooth all electron wave functions as

$$|\tilde{\Psi}_i^a\rangle = \sum_i P_{ni}^a |\tilde{\phi}_i^a\rangle, \quad |\mathbf{r} - \mathbf{R}| < r_c^a \quad (\text{D.5})$$

Where, P_{na}^a are expansion coefficients, and need to be determined. And also, the index a stands for atomic sites, i to distinguish different partials waves and n connected to quantum numbers (l, m) . Since the transformation operator connects the smooth pseudo wave function to true wave function.

$$|\Psi_n\rangle = \hat{\mathcal{T}} |\tilde{\Psi}_n\rangle = \sum_i P_{ni}^a |\psi_i^a\rangle, \quad |\mathbf{r} - \mathbf{R}| < r_c^a \quad (\text{D.6})$$

Something really interesting about the above equation, the true wave function has the same expansion coefficient (P_{ni}^a) as the pseudo wavefunction. The transformation operator $\hat{\mathcal{T}}$ is required to be linear, the coefficient must be linear functionals of $|\tilde{\Psi}_n\rangle$, i.e.

$$P_{ni}^a = \langle \tilde{\phi}_i^a | \tilde{\Psi}_n \rangle \quad (\text{D.7})$$

Where $|\tilde{p}_i^a\rangle$ are some fixed functions termed smooth projector functions. As there is no overlap between the augmentation spheres, we expect the smooth all electron wave function, $|\tilde{\Psi}_n^a\rangle = \sum_i |\tilde{\phi}_i^a\rangle \langle \tilde{p}_i^a | \tilde{\Psi}_n \rangle$. The projectors have to be localized within an augmentation region

$$\sum_i |\tilde{\phi}_i^a\rangle \langle \tilde{p}_i^a| = 1 \quad (\text{D.8})$$

This also implied that

$$\langle \tilde{p}_{i_1}^a | \tilde{\phi}_{i_2}^a \rangle = \delta_{i_1, i_2}, \quad \text{for } < r_c^a \quad (\text{D.9})$$

the projector functions should be orthonormal to the smooth partial waves inside the augmentation sphere. The choice of projectors and partial waves can be found more detailed form original work of Blöchl [1]. Using the completeness relation from Eqn D.8

$$\hat{\mathcal{T}}^a = \sum_i \hat{\mathcal{T}}^a |\tilde{\phi}_i^a\rangle \langle \tilde{p}_i^a| = \sum_i (|\phi_i^a\rangle - |\tilde{\phi}_i^a\rangle) \langle \tilde{p}_i^a| \quad (\text{D.10})$$

Remember, the operator $\hat{\mathcal{T}}^a$ operates only inside the sphere, outside sphere it behave like this $|\phi_i^a\rangle - |\tilde{\phi}_i^a\rangle$. Thus the total transformation operator becomes

$$\hat{\mathcal{T}} = 1 + \sum_a \sum_i (|\phi_i^a\rangle - |\tilde{\phi}_i^a\rangle) \langle \tilde{p}_i^a| \quad (\text{D.11})$$

To summarize, we obtain the all electron KS wave function $|\Psi_n(\mathbf{r})\rangle = \langle \mathbf{r} | \Psi_n \rangle$ from the transformation

$$\Psi_n(\mathbf{r}) = \tilde{\Psi}_n(\mathbf{r}) + \sum_a \sum_i (\phi_i^a(\mathbf{r}) - \tilde{\phi}_i^a(\mathbf{r})) \langle \tilde{p}_i^a | \tilde{\Psi}_n \rangle \quad (\text{D.12})$$

The equation above has three different components in the right. The first is the auxiliary wave function. The second term is the sum of partial waves, the last term is the sum of pseudo partial waves that must be subtracted inside the augmentation region. To make it a

simple KS wave function representation

$$\psi_n(\mathbf{r}) = \tilde{\psi}_n(\mathbf{r}) + \sum_a \left(\psi_n^a(\mathbf{r} - \mathbf{R}^a) - \tilde{\psi}_n^a(\mathbf{r} - \mathbf{R}^a) \right) \quad (\text{D.13})$$

The trouble of the original KS wave functions, was that they display rapid oscillations in some of the space and smooth behavior in other parts of space. By decomposing the wave function, the achievement is that the original wave function is separated into auxiliary wave functions which are smooth everywhere.

D.1 PAW Pseudopotential Generation

PAW calculation method requires a set of basis (partial-waves) and projectors functions and some additional atomic data in the so called *PAW dataset*. The PAW dataset generation is done using the following procedure.

- Solve the all-electron atomic problem in the DFT formalism using an exchange-correlation functional (with scalar-relativistic approximation). It is a spherical problem and usually solved in logarithmic grid.
- Separation of core and valence electron. The core density is then deduced from the core electron wave functions. For a given radius (r_{core}), the outer density is calculated so that the core density is identical to the outer.
- Choose the PAW basis (number of partial-waves and projectors).
- Generation of the pseudo partial-waves.
- Test the PAW dataset on electronic structure calculation. Repeat the procedure if necessary to satisfy the calculated property.

The atompaw input file used to generate the pseudopotential for uranium is below:

```

1 U 92
2 GGA-PBE scalarrelativistic loggridv4 700
3 7 6 6 5 0 !6s2 6p6 5f3 6d1 7s2 (from Beelar (2012), ns_max np_max
   nd_max nf_max ng_max
4 6 2 1 !6d1, only empty or partially occupied shells are entered
5 5 3 3 !5f3
6 0 0 0
7 c !1s2 1
8 c !2s2 2
9 c !3s2 3
10 c !4s2 4
11 c !5s2 5
12 v !6s2 6 1
13 v !7s2 7 2
14 c !2p6 8
15 c !3p6 9
16 c !4p6 10
17 c !5p6 11
18 v !6p6 12 3
19 c !3d10 13
20 c !4d10 14
21 c !5d10 15
22 v !6d1 16 4
23 c !4f14 17
24 v !5f3 18 5
25 3
26 2.5 2.02 1.5 1.8 !rpaw, rshape, rvloc, rcore, in a.u , changesd the
   rshape for the first time below 2.0
27 n
28 y !one additional p partial wave
29 0.00
30 n !no additional p partial wave
31 y !one additional d partial wave
32 0.2 !
33 n !no additional d partial wave
34 y !one additional f partial wave
35 3.0
36 n !no additional f partial wave
37 custom rrkjesselshape !for PWscf, UPF format needs bessels
38 4 0.0 !bessel !l quantum number, reference energy (Ry),
   bessel for simplicity
39 1.5 !1 s ! r_c matching radius for second s partial wave
40 1.5 !2 s ! rc for s
41 2.5 !3 p ! rc for p
42 2.5 !4 p ! rc for p
43 2.5 !5 d ! rc for d, 1.3 gives very good result
44 2.5 !6 d ! rc for d, 1.3 gives very good result, 4.0 energy
45 2.5 !7 f ! rc for f
46 2.5 !8 f ! rc for f
47 PWSCFOUT
48 default
49 0

```

References

1. Blöchl P E 1994 *Phys. Rev. B* **50** 17953

APPENDIX E

FINITE ELEMENT METHOD IN MOOSE

Divergence theorem transforms and volume integral into a surface integral:

$$\int_{\Omega} \nabla \cdot \vec{g} \, dx = \int_{\partial\Omega} \vec{g} \cdot \hat{n} \, ds \quad (\text{E.1})$$

The strong form of the diffusion equation without a source term is as follows:

$$\nabla \cdot (K(T)\nabla T) = 0$$

Multiplying by a test function (\mathcal{T}_f), and integrating over the domain Ω :

$$\begin{aligned} \int_{\Omega} \mathcal{T}_f (\nabla \cdot \underbrace{K(T)\nabla T}_{\mathcal{G}}) &= 0 \\ \int_{\Omega} \mathcal{T}_f \nabla \cdot \mathcal{G} &= 0 \\ \int_{\Omega} \nabla \cdot (\mathcal{T}_f \mathcal{G}) - \int_{\Omega} \nabla \mathcal{T}_f \cdot \mathcal{G} &= 0 \end{aligned}$$

Using the divergence theorem (E.1) the above equation becomes:

$$\begin{aligned} \int_{\partial\Omega} \mathcal{T}_f \mathcal{G} \cdot \hat{n} \, ds - \int_{\Omega} \nabla \mathcal{T}_f \cdot \mathcal{G} \, dx &= 0 \\ \int_{\Omega} \nabla \mathcal{T}_f \cdot K(T)\nabla T \, dx - \int_{\partial\Omega} \mathcal{T}_f K(T)\nabla T \cdot \hat{n} \, ds &= 0 \end{aligned}$$

Using the inner product notation the above equation can be written as follows:

$$(\nabla \mathcal{T}_f, K \nabla T) - \langle \mathcal{T}_f, K \nabla T \cdot \hat{n} \rangle = 0 \quad (\text{E.2})$$

Each of these term inherits an existing MOOSE type to solve the problem.

$$\underbrace{(\nabla \mathcal{T}_f, K \nabla T)}_{\text{Kernel}} - \underbrace{\langle \mathcal{T}_f, K \nabla T \cdot \hat{n} \rangle}_{\text{BoundaryCondition}} = 0 \quad (\text{E.3})$$

APPENDIX F

INPUT FILES

Input files for different software are included in this chapter. Because of the complexity and number, I have included samples of them.

F.1 MOOSE Framework

This is the main.C file for moose simulation. Depends on the problem, moose requires a number of header files and source file.

```
1  /* this is a main app file created for the purpose of simulating
   heat conduction
2  *      This is file is created by Rafi, Sepetember 27, 2016
3  *      **** */
4
5  #include "HeatCondRafiApp.h"
6  #include "MooseInit.h"
7  #include "Moose.h"
8  #include "MooseApp.h"
9  #include "AppFactory.h"
10
11 // Creat a performance log
12 PerfLog Moose::perf_log("HeatCondRafi");
13
14 //Begin the main problem.
15 int main(int argc, char *argv[])
16 {
17     // Initialize MPI, solvers and MOOSE
18     MooseInit init(argc, argv);
19
20     // Register this application's MooseApp and any it depends on
21     HeatCondRafiApp::registerApps();
22
23     // This creates dynamic memory that we're responsible for
    deleting
24     //MooseApp * app = AppFactory::createAppShared("HeatCondRafiApp
    ", argc, argv);
25     std::shared_ptr<MooseApp> app = AppFactory::createAppShared("
    HeatCondRafiApp", argc, argv);
26
27     //Execute the application
```

```
28     app->run();
29
30     // Free up the memory we created earlier
31     //delete app;
32
33     return 0;
34 }
```

This is a sample of source file (kernel in MOOSE) of heat transfer in U-10Mo

```

1 // this file is edited by rafi fro temperature dependent thermal
  conductivity
2 #include "Tempdepk.h"
3
4 template<>
5 InputParameters validParams<Tempdepk>()
6 {
7   InputParameters params = validParams<Diffusion>();
8   params.addClassDescription("This will solve heat diffusion with
  temperature dependent thermal conductivity");
9   return params;
10 }
11
12 Tempdepk::Tempdepk(const InputParameters & parameters) :
13   Diffusion(parameters),
14   _thermal_conductivity(getMaterialProperty<Real>("
  thermal_conductivity")) /*be sure u use the "thermal_conductivity,
  otherwise it will
15 not read the thermal_conductivity from the input*/
16 {
17 }
18
19 Real
20 Tempdepk::computeQpResidual()
21 {
22   //return _grad_u[_qp] * _grad_test[_i][_qp];
23   //Real _k=0.606+0.0351*_u[_qp]; // from D.E. Burkes et al./ Journal
  of Nuc Material 2010
24
25   return _thermal_conductivity[_qp]*Diffusion::computeQpResidual();
26 }
27
28 Real
29 Tempdepk::computeQpJacobian()
30 {
31   //Real _k=0.606+0.0351*_u[_qp];
32   //return _grad_phi[_j][_qp] * _grad_test[_i][_qp];
33
34   return _thermal_conductivity[_qp]*Diffusion::computeQpJacobian();
35 }

```

```

1 // this file is edited by rafi fro temperature dependent thermal
  conductivity
2 #include "TXenon.h"
3
4
5 template<>
6 InputParameters validParams<TXenon>()
7 {
8   InputParameters params = validParams<Diffusion>();
9   params.addClassDescription("This will solve heat diffusion with
    temperature dependent thermal conductivity");
10  return params;
11 }
12
13 TXenon::TXenon(const InputParameters & parameters) :
14   Diffusion(parameters),
15   _thermal_conductivity(getMaterialProperty<Real>("
    thermal_conductivity")) /*be sure u use the "thermal_conductivity,
    otherwise it will
16 not read the thermal_conductivity from the input*/
17 {
18 }
19
20 Real
21 TXenon::computeQpResidual()
22 {
23   //return _grad_u[_qp] * _grad_test[_i][_qp];
24   //Real _k=0.606+0.0351*_u[_qp]; // from D.E. Burkes et al./ Journal
    of Nuc Material 2010
25
26   /* return _thermal_conductivity[_qp]*Diffusion::computeQpResidual() +
    380E3*_test[_i][_qp]; */
27
28   // the above one for a constant forcing function
29
30   return _thermal_conductivity[_qp]*Diffusion::computeQpResidual();
31 }
32
33 Real
34 TXenon::computeQpJacobian()
35 {
36   //Real _k=0.606+0.0351*_u[_qp];
37   //return _grad_phi[_j][_qp] * _grad_test[_i][_qp];
38
39   return _thermal_conductivity[_qp]*Diffusion::computeQpJacobian() +
40   (-2*4.72984E-09*_u[_qp]^2.+2.0891E-5)*_grad_u[_qp]*_grad_test[_i][
    _qp];
41 }

```

Material source code for U-10Mo property.

```
1 // this file is edited by Rafi January 24, 2017
2 //
3 #include "Tconductivity.h"
4
5 template<>
6 InputParameters validParams<Tconductivity>()
7 {
8     InputParameters params = validParams<Material>();
9     // we do not need to add any data from the input file
10    params.addClassDescription("This is to calculate the temperature
        dependent thermal conductivity of U-10Mo");
11    // the "temperature" variable has to be defined in the input files
12    params.addCoupledVar("dep_variable", "The thermal conductivity is
        calculated from temperature");
13    return params;
14 }
15
16 Tconductivity::Tconductivity(const InputParameters & parameters) :
17     Material(parameters),
18
19     // Declare material properties. This returns references that we
20     // hold onto as member variables
21     _permeability(declareProperty<Real>("permeability")),
22     _thermal_conductivity(declareProperty<Real>("thermal_conductivity"))
23     ,
24     _dep_variable(isCoupled("dep_variable"))
25     _dep_variable(coupledValue("dep_variable"))
26 {
27 }
28
29 void
30 Tconductivity::computeQpProperties()
31 {
32     // Sample the LinearInterpolation object to get the permeability for
33     // the ball size
34     _permeability[_qp] = _permeability_interpolation.sample(
35         _ball_radius);
36     _thermal_conductivity[_qp]=0.606+0.0351*_dep_variable[_qp];
37 }
```

Source file for xenon material property.

```
1 // this file is edited by Rafi February 13, 2017
2 //
3 #include "XenonT.h"
4
5 template<>
6 InputParameters validParams<XenonT>()
7 {
8     InputParameters params = validParams<Material>();
9     // we do not need to add any data from the input file
10    params.addClassDescription("This is to calculate the temperature
        dependent thermal conductivity of Xenon");
11    // the "temperature" variable has to be defined in the input files
12    params.addCoupledVar("dep_variable", "The thermal conductivity is
        calculated from temperature");
13    return params;
14 }
15
16
17 XenonT::XenonT(const InputParameters & parameters) :
18     Material(parameters),
19
20     // Declare material properties. This returns references that we
21     // hold onto as member variables
22     //_permeability(declareProperty<Real>("permeability")),
23     _thermal_conductivity(declareProperty<Real>("thermal_conductivity"))
24     ,
25     //_dep_variable(isCoupled("dep_variable"))
26     _dep_variable(coupledValue("dep_variable"))
27 {
28 }
29
30 void
31 XenonT::computeQpProperties()
32 {
33     // Sample the LinearInterpolation object to get the permeability for
34     // the ball size
35     //_permeability[_qp] = _permeability_interpolation.sample(
36         _ball_radius);
37     //_thermal_conductivity[_qp]=0.0000000001+0.000000000001*_dep_variable
38         [_qp];
39     /*abobe correlation is wrong, is calculated wrong, the next equation
40     is calcuated from Robinovich et al. Thermophy
41     sical property of Neon, Argon, Krypton, and Xenon */
42     _thermal_conductivity[_qp]=-4.72984E-09*_dep_variable[_qp]*
43         _dep_variable[_qp] + 2.0891E-5*_dep_variable[_qp]+ 2.83137E-05 ;
44 }
```


Source file for heat flux calculation.

```
1
2 #include "HeatFlux.h"
3
4 template<>
5 InputParameters validParams<HeatFlux>()
6 {
7     InputParameters params = validParams<AuxKernel>();
8
9     MooseEnum component("x y z");
10    // Declare the options for a MooseEnum.
11    // These options will be presented to the user in Peacock
12    // and if something other than these options is in the input file
13    // an error will be printed
14    params.addClassDescription("This is to calculate the heat flux for
        over all material");
15    // Add a "coupling paramater" to get a variable from the input file.
16    params.addRequiredCoupledVar("field_temperature", "The temperature
        field.");
17    params.addRequiredParam<MooseEnum>("component", component, "The
        desired component of temperature");
18
19    return params;
20 }
21
22 HeatFlux::HeatFlux(const InputParameters & parameters) :
23     AuxKernel(parameters),
24
25     // Get the gradient of the variable
26     _temperature_gradient(coupledGradient("field_temperature")),
27
28     // Snag thermal_coductivity from the Material system.
29     // Only AuxKernels operating on Elemental Auxiliary Variables can
    do this
30     _t_thermal_conductivity(getMaterialProperty<Real>("
        thermal_conductivity")),
31     _component(getParam<MooseEnum>("component"))
32
33 {
34 }
35
36 Real
37 HeatFlux::computeValue()
38 {
39     // Access the gradient of the pressure at this quadrature point
40     // Then pull out the "component" of it we are looking for (x, y or z
        )
41     // Note that getting a particular component of a gradient is done
        using the
42     // parenthesis operator
43     return _t_thermal_conductivity[_qp]*_temperature_gradient[_qp](
        _component);
44 }
```

This source file is to calculate the gradient of the temperature.

```
1
2 #include "TGradient.h"
3
```

```

4 template<>
5 InputParameters validParams<TGradient>()
6 {
7     InputParameters params = validParams<AuxKernel>();
8
9     // Declare the options for a MooseEnum.
10    // These options will be presented to the user in Peacock
11    // and if something other than these options is in the input file
12    // an error will be printed
13    params.addClassDescription("This is to calculate the temperature
        gradient for over all material");
14    // Add a "coupling paramater" to get a variable from the input file.
15    //params.addRequiredCoupledVar("field_temperature", "The temperature
        field.");
16    MooseEnum component("x y z");
17
18    // Use the MooseEnum to add a parameter called "component"
19    params.addRequiredCoupledVar("field_temperature", "The Temperature
        field");
20    params.addRequiredParam<MooseEnum>("component", component, "The
        desired component of velocity.");
21    return params;
22 }
23
24 TGradient::TGradient(const InputParameters & parameters) :
25     AuxKernel(parameters),
26
27     // Get the gradient of the variable
28     _temperature_gradient(coupledGradient("field_temperature")),
29
30     _component(getParam<MooseEnum>("component"))
31     // Snag thermal_coductivity from the Material system.
32     // Only AuxKernels operating on Elemental Auxiliary Variables can
    do this
33     //_t_thermal_conductivity(getMaterialProperty<Real>("
        thermal_conductivity"))
34
35 {
36 }
37
38 Real
39 TGradient::computeValue()
40 {
41     // Access the gradient of the pressure at this quadrature point
42     // Then pull out the "component" of it we are looking for (x, y or z
        )
43     // Note that getting a particular component of a gradient is done
        using the
44     // parenthesis operator
45     return _temperature_gradient[_qp](_component);
46 }

```

For every source file, we need header files. The required header files are below. Tempdepk.h

```
1 // this file created by Rafi, January 24, 2017
2 #ifndef TEMPDEPK_H
3 #define TEMPDEPK_H
4 #include "Diffusion.h"
5 class Tempdepk;
6 template<>
7 InputParameters validParams<Tempdepk>();
8
9 /**
10  * This kernel will solve a temperature dependent thermal conductivity
11  * with diffusion of temperature
12  */
13 class Tempdepk : public Diffusion
14 {
15 public:
16     Tempdepk(const InputParameters & parameters);
17 protected:
18     virtual Real computeQpResidual() override;
19     virtual Real computeQpJacobian() override;
20     // creating a moose array for material property
21     const MaterialProperty<Real> & _thermal_conductivity;
22 };
23 #endif
```

TXenon.h

```
1 / this file created by Rafi, January 24, 2017
2 #ifndef TXENON_H
3 #define TXENON_H
4
5 #include "Diffusion.h"
6
7 class TXenon;
8 template<>
9 InputParameters validParams<TXenon>();
10
11 /**
12  * This kernel will solve a temperature dependent thermal conductivity
13   with diffusion of temperature
14  */
15 class TXenon : public Diffusion
16 {
17 public:
18     TXenon(const InputParameters & parameters);
19
20 protected:
21     virtual Real computeQpResidual() override;
22     virtual Real computeQpJacobian() override;
23     // creating a moose array for material property
24
25     const MaterialProperty<Real> & _thermal_conductivity;
26 };
27 #endif
```

```

1 // this file is created by Rafi at February 13, 2017
2
3 #ifndef TCONDUCTIVITY_H
4 #define TCONDUCTIVITY_H
5
6 #include "Material.h"
7
8 class Tconductivity;
9
10 template<>
11 InputParameters validParams<Tconductivity>();
12
13 /**
14  * Material objects inherit from Material and override
15  * computeQpProperties.
16  * Their job is to declare properties for use by other objects in the
17  * calculation such as Kernels and BoundaryConditions.
18  */
19 class Tconductivity : public Material
20 {
21 public:
22   Tconductivity(const InputParameters & parameters);
23
24 protected:
25   /**
26    * Necessary override. This is where the values of the properties
27    * are computed.
28    */
29   virtual void computeQpProperties() override;
30
31 private:
32   // The thermal conductivity
33   MaterialProperty<Real> & _thermal_conductivity; // for u-10 Mo
34
35   // const VariableGradient & _dep_variable; // this will get the
36   // temperature
37   //std::vector<const VariableValue> & _dep_variable;
38   //VariableValue<Real> & _dep_variable;
39   const VariableValue & _dep_variable;
40 };
41 #endif //Tconductivity

```

XenonT.h

```
1 / this file is created by Rafi at February 13, 2017
2 // The reference is Rabinovich et al.
3 // Thermophysical Properties of Neon, Argon, Krypton and Xenon// for
   the purpose of temperature dependent thermal conductivity for U-10
   Mo
4 #ifndef XENONT_H
5 #define XENONT_H
6
7 #include "Material.h"
8 class XenonT;
9
10 template<>
11 InputParameters validParams<XenonT>();
12
13 /**
14  * Material objects inherit from Material and override
   computeQpProperties.
15  *
16  * Their job is to declare properties for use by other objects in the
17  * calculation such as Kernels and BoundaryConditions.
18  */
19 class XenonT : public Material
20 {
21 public:
22     XenonT(const InputParameters & parameters);
23
24 protected:
25     /**
26      * Necessary override. This is where the values of the properties
27      * are computed.
28      */
29     virtual void computeQpProperties() override;
30 private:
31
32     // The thermal conductivity
33     MaterialProperty<Real> & _thermal_conductivity; // for u-10 Mo
34
35     // const VariableGradient & _dep_variable; // this will get the
   temperature
36     //std::vector<const VariableValue> & _dep_variable;
37     //VariableValue<Real> & _dep_variable;
38     const VariableValue & _dep_variable;
39 };
40
41 #endif //XENONT_H
```

HeatFlux.h

```
1  #ifndef HEATFLUX_H
2  #define HEATFLUX_H
3
4  #include "AuxKernel.h"
5
6  //Forward Declarations
7  class HeatFlux;
8
9  template<>
10 InputParameters validParams<HeatFlux>();
11
12 /**
13  * Constant auxiliary value
14  */
15 class HeatFlux : public AuxKernel
16 {
17 public:
18     HeatFlux(const InputParameters & parameters);
19
20     virtual ~HeatFlux() {}
21
22 protected:
23     /**
24      * AuxKernels MUST override computeValue.  computeValue() is called
25      * on
26      * every quadrature point.  For Nodal Auxiliary variables those
27      * quadrature
28      * points coincide with the nodes.
29      */
30     virtual Real computeValue() override;
31
32     /// The gradient of a coupled variable
33     const VariableGradient & _temperature_gradient;
34
35     /// Holds the permeability and viscosity from the material system
36     const MaterialProperty<Real> & _t_thermal_conductivity;
37     // const MaterialProperty<Real> & _viscosity;
38
39     int _component;
40 };
41 #endif // end of HEATFLUX_H
```

TGradient.h

```
1  #ifndef TGRADIENT_H
2  #define TGRADIENT_H
3
4  #include "AuxKernel.h"
5
6  //Forward Declarations
7  class TGradient;
8
9  template<>
10 InputParameters validParams<TGradient>();
11
12 /**
13  * Constant auxiliary value
14  */
15 class TGradient : public AuxKernel
16 {
17 public:
18   TGradient(const InputParameters & parameters);
19
20   virtual ~TGradient() {}
21
22 protected:
23   /**
24    * AuxKernels MUST override computeValue.  computeValue() is called
25    * on
26    * every quadrature point.  For Nodal Auxiliary variables those
27    * quadrature
28    * points coincide with the nodes.
29    */
30   virtual Real computeValue() override;
31
32   /// The gradient of a coupled variable
33   const VariableGradient & _temperature_gradient;
34
35   /// Holds the permeability and viscosity from the material system
36   //const MaterialProperty<Real> & _t_thermal_conductivity;
37   int _component;
38   // const MaterialProperty<Real> & _viscosity;
39 };
40 #endif // end of TGRADIENT_H
```


F.2 ATOMPAW

This is an input file for Atompaw to generate the paw database for electronic structure calculation.

```

1 U 92
2 GGA-PBE scalarrelativistic loggridv4 700
3 7 6 6 5 0
4 6 2 1
5 5 3 3
6 0 0 0
7 c !1s2 1
8 c !2s2 2
9 c !3s2 3
10 c !4s2 4
11 c !5s2 5
12 v !6s2 6 1
13 v !7s2 7 2
14 c !2p6 8
15 c !3p6 9
16 c !4p6 10
17 c !5p6 11
18 v !6p6 12 3
19 c !3d10 13
20 c !4d10 14
21 c !5d10 15
22 v !6d1 16 4
23 c !4f14 17
24 v !5f3 18 5
25 3
26 2.5 2.02 1.5 1.8 !rpaw, rshape, rvloc, rcore, in a.u
27 n
28 y !one additional p partial wave
29 0.00
30 n !no additional p partial wave
31 y !one additional d partial wave
32 0.2 !
33 n !no additional d partial wave
34 y !one additional f partial wave
35 3.0
36 n !no additional f partial wave
37 custom rrkj besselshape !UPF format needs bessels
38 4 0.0 !bessel !l quantum number, reference energy (Ry),
    bessel for simplicity
39 1.3 !1 s ! rc s partial wave
40 1.3 !2 s ! rc for s
41 2.5 !3 p ! rc for p
42 2.5 !4 p ! rc for p
43 1.55 !5 d ! rc for d, 1.3 gives very good result
44 1.55 !6 d ! rc for d, 1.3 gives very good result, 4.0
    energy
45 2.5 !7 f ! rc for f
46 2.5 !8 f ! rc for f
47 PWSCFOUT
48 default
49 0

```

F.3 DFT Calculation

F.3.1 SCF of a primitive cell

This is sample input file to calculate the self consistent field study using Quantum Espresso. It contains the lattice parameter of α -uranium.

```
1 &CONTROL
2             title = 'alphaU'
3             calculation = 'scf'
4             restart_mode = 'from_scratch'
5             outdir = '/home/iasir/quantum_espresso/
Uranium_PAW/rvloc_96/y_value_plot/lat01'
6             pseudo_dir = '/home/iasir/quantum_espresso/
Uranium_PAW/rvloc_96/y_value_plot/lat01'
7             prefix = 'alphaU'
8             verbosity = 'default'
9             tstress = .true.
10            tprnfor = .true.
11 /
12 &SYSTEM
13             ibrav = 0
14             A = 2.8383
15             at = 2
16             ntyp = 1
17             ntyp = 1
18             ecutwfc = 50
19             ecutrho = 250
20             smearing = 'methfessel-paxton'
21 /
22 &ELECTRONS
23             diagonalization = 'david'
24 /
25 &IONS
26
27 /
28 CELL_PARAMETERS {alat}
29 0.5000000000000000 -1.031658697792153 0.0000000000000000
30 0.5000000000000000 1.031658697792153 0.0000000000000000
31 0.0000000000000000 0.0000000000000000 1.73379271551118
32 ATOMIC_SPECIES
33 U 238.0290000000 U.GGA-PBE-paw.UPF
34
35 ATOMIC_POSITIONS {crystal}
36 U 0.0986000000000000 -0.0986000000000000 -0.2500000000000000
37 U -0.0986000000000000 0.0986000000000000 0.2500000000000000
38
39 K_POINTS automatic
40 20 20 26 0 0 0
```

F.3.2 Supercell of uranium

The following input is for performing a relax calculation using supercell of γ -uranium with molybdenum and xenon.

```
1 &CONTROL
2                                     title = 'supercellgammaU'
3                                     calculation = 'relax'
4                                     restart_mode = 'from_scratch'
5                                     outdir = '/group/hammond/sysyphus/3x3/2prim-2
6                                     pseudo_dir = '/group/hammond/sysyphus/
7                                     prefix = 'supercell_gammaU'
8                                     etot_conv_thr = 1.0D-6
9                                     forc_conv_thr = 1.0D-6
10                                    verbosity = 'default'
11                                    tstress = .true.
12                                    tprnfor = .true.
13                                    nstep = 200
14 /
15 &SYSTEM
16                                     ibrav = 0
17                                     A = 10.35
18                                     nat = 53
19                                     ntyp = 3
20                                     ecutwfc = 50
21                                     ecutrho = 260
22                                     occupations = 'smearing'
23                                     degauss = 0.02
24                                     smearing = 'mp'
25 /
26 &ELECTRONS
27                                     diagonalization = 'david'
28                                     electron_maxstep = 900
29                                     mixing_beta = 0.1
30 /
31 &IONS
32
33 /
34 &CELL
35
36 /
37 CELL_PARAMETERS {alat}
38 1.00 0.00 0.00
39 0.00 1.00 0.00
40 0.00 0.00 1.00
41
42 ATOMIC_SPECIES
43 U 238.02800 U.GGA-PBE-paw.UPF
44 Xe 131.29 Xe.GGA-PBE-paw.UPF
45 Mo 95.94 Mo.GGA-PBE-paw.UPF
46
47 ATOMIC_POSITIONS (crystal)
48 U 0.0000000000 0.0000000000 0.0000000000 0 0 0
49 U 0.210984461 0.204688901 0.229195736
50 U 0.0000000000 0.0000000000 0.333333333 0 0 0
51 U 0.0000000000 0.0000000000 0.666666667 0 0 0
52 U 0.333333333 0.0000000000 0.0000000000 0 0 0
```

53	U	0.666666667	0.000000000	0.000000000	0	0	0
54	U	0.000000000	0.333333333	0.000000000	0	0	0
55	U	0.000000000	0.666666667	0.000000000	0	0	0
56	U	0.137231091	0.153757182	0.530873483			
57	U	0.174376372	0.129124170	0.859923969			
58	U	0.526508957	0.134953713	0.159596399			
59	U	0.862089662	0.133706169	0.175813941			
60	U	0.158683128	0.524614679	0.202129442			
61	U	0.148170903	0.848856345	0.127554382			
62	U	0.000000000	0.333333333	0.333333333	0	0	0
63	U	0.000000000	0.666666667	0.666666667	0	0	0
64	U	0.000000000	0.666666667	0.333333333	0	0	0
65	U	0.000000000	0.333333333	0.666666667	0	0	0
66	U	0.333333333	0.000000000	0.333333333	0	0	0
67	U	0.666666667	0.000000000	0.666666667	0	0	0
68	U	0.333333333	0.000000000	0.666666667	0	0	0
69	U	0.666666667	0.000000000	0.333333333	0	0	0
70	U	0.333333333	0.333333333	0.000000000	0	0	0
71	U	0.666666667	0.666666667	0.000000000	0	0	0
72	U	0.666666667	0.333333333	0.000000000	0	0	0
73	U	0.333333333	0.666666667	0.000000000	0	0	0
74	U	0.137231091	0.153757182	0.530873483			
75	U	0.174376372	0.129124170	0.859923969			
76	U	0.526508957	0.134953713	0.159596399			
77	U	0.862089662	0.133706169	0.175813941			
78	U	0.158683128	0.524614679	0.202129442			
79	U	0.148170903	0.848856345	0.127554382			
80	U	0.000000000	0.333333333	0.333333333	0	0	0
81	U	0.000000000	0.666666667	0.666666667	0	0	0
82	U	0.000000000	0.666666667	0.333333333	0	0	0
83	U	0.000000000	0.333333333	0.666666667	0	0	0
84	U	0.333333333	0.000000000	0.333333333	0	0	0
85	U	0.666666667	0.000000000	0.666666667	0	0	0
86	U	0.333333333	0.000000000	0.666666667	0	0	0
87	U	0.666666667	0.000000000	0.333333333	0	0	0
88	U	0.333333333	0.333333333	0.000000000	0	0	0
89	U	0.666666667	0.666666667	0.000000000	0	0	0
90	U	0.666666667	0.333333333	0.000000000	0	0	0
91	U	0.333333333	0.666666667	0.000000000	0	0	0
92	U	0.179014193	0.490220525	0.515819257			
93	U	0.211529991	0.769018260	0.787411348			
94	U	0.174791835	0.807115343	0.456517964			
95	U	0.138750516	0.465098823	0.842421942			
96	U	0.460277126	0.148072446	0.492479910			
97	U	0.853185555	0.205057669	0.814927365			
98	U	0.517574914	0.155283842	0.808674767			
99	U	0.797006954	0.141631469	0.505322942			
100	U	0.472193561	0.445111610	0.164972643			
101	U	0.797427656	0.818792499	0.205498630			
102	U	0.849105689	0.447077449	0.157067159			
103	U	0.477316581	0.824076376	0.198019584			
104	U	0.357811109	0.358247142	0.377740929			
105	Mo	0.317120589	0.314631326	0.680448732			
106	Mo	0.607263578	0.351682511	0.642824966			
107	U	0.340594168	0.659454747	0.325699754			
108	U	0.361075015	0.621507036	0.637398808			
109	Mo	0.660724290	0.302342735	0.343336983			
110	U	0.864625684	0.823864687	0.866239386			
111	U	0.857300550	0.828682348	0.537389462			
112	U	0.459239378	0.501675726	0.851462699			

```

113 U      0.787353995    0.504077862    0.849782744
114 U      0.483651729    0.821500104    0.546062842
115 U      0.525967152    0.834454416    0.872311707
116 U      0.803327765    0.439115905    0.558594712
117 U      0.678734725    0.684452016    0.648081893
118 Xe     0.649495337    0.596675850    0.354354426
119
120
121
122 !Xe     0.5000000000    0.5000000000    0.5000000000
123
124 K_POINTS automatic
125 4 4 4      0 0 0

```

F.3.3 Nudged Elastic Band Calculation

The following input file is to perform nudged elastic band calculation using Quantum

Espresso.

```
1 BEGIN
2 BEGIN_PATH_INPUT
3 &PATH
4   restart_mode      = 'from_scratch',
5   string_method     = 'neb',
6   nstep_path        = 100,
7   ds                = 1.00,
8   opt_scheme        = "broyden",
9   num_of_images      = 5,
10  k_max              = 0.6169D0,
11  k_min              = 0.6169D0,
12  CI_scheme          = "auto",
13  path_thr           = 0.1D0,
14 /
15 END_PATH_INPUT
16 BEGIN_ENGINE_INPUT
17 &CONTROL
18  outdir = '/group/hammond/sysyphus/3x3/2prim-2nd/neb',
19  pseudo_dir = '/group/hammond/sysyphus/pp_dir',
20  prefix = 'xe01neb' ,
21  verbosity = 'high' ,
22  etot_conv_thr = 1e-6 ,
23  forc_conv_thr = 1e-5 ,
24  nstep = 200 ,
25  tstress = .true.,
26  tprnfor = .true.,
27  max_seconds = 1.0D+18,
28 /
29 &SYSTEM
30                                     ibrav = 0,
31                                     A = 10.35,
32                                     nat = 53,
33                                     ntyp = 3,
34                                     ecutwfc = 50,
35                                     ecutrho = 260,
36                                     occupations = 'smearing',
37                                     degauss = 0.02,
38                                     smearing = 'mp',
39 /
40 &ELECTRONS
41                                     electron_maxstep = 900,
42                                     conv_thr = 1e-7 ,
43                                     mixing_beta = 0.1 ,
44                                     diagonalization = 'david' ,
45 /
46 &IONS
47 /
48 ATOMIC_SPECIES
49   U  238.02800  U.GGA-PBE-paw.UPF
50   Xe 131.29    Xe.GGA-PBE-paw.UPF
51   Mo 95.94     Mo.GGA-PBE-paw.UPF
52 BEGIN_POSITIONS
53 FIRST_IMAGE
54 ATOMIC_POSITIONS (crystal)
```

55	U	0.0000000000	0.0000000000	0.0000000000	0	0	0
56	U	0.175109924	0.144562064	0.206801126			
57	U	0.0000000000	0.0000000000	0.333333333	0	0	0
58	U	0.0000000000	0.0000000000	0.666666667	0	0	0
59	U	0.333333333	0.0000000000	0.0000000000	0	0	0
60	U	0.666666667	0.0000000000	0.0000000000	0	0	0
61	U	0.0000000000	0.333333333	0.0000000000	0	0	0
62	U	0.0000000000	0.666666667	0.0000000000	0	0	0
63	U	0.172966137	0.162988305	0.549703444			
64	U	0.170611892	0.151612185	0.878052143			
65	U	0.495257014	0.208922221	0.160293502			
66	U	0.831518767	0.131820848	0.145403232			
67	U	0.187663248	0.516383543	0.207043480			
68	U	0.141733995	0.833501726	0.124057856			
69	U	0.0000000000	0.333333333	0.333333333	0	0	0
70	U	0.0000000000	0.666666667	0.666666667	0	0	0
71	U	0.0000000000	0.666666667	0.333333333	0	0	0
72	U	0.0000000000	0.333333333	0.666666667	0	0	0
73	U	0.333333333	0.0000000000	0.333333333	0	0	0
74	U	0.666666667	0.0000000000	0.666666667	0	0	0
75	U	0.333333333	0.0000000000	0.666666667	0	0	0
76	U	0.666666667	0.0000000000	0.333333333	0	0	0
77	U	0.333333333	0.333333333	0.0000000000	0	0	0
78	U	0.666666667	0.666666667	0.0000000000	0	0	0
79	U	0.666666667	0.333333333	0.0000000000	0	0	0
80	U	0.333333333	0.666666667	0.0000000000	0	0	0
81	U	0.151218039	0.506822556	0.548576738			
82	U	0.146390108	0.829542179	0.788362872			
83	U	0.185174494	0.843342696	0.464715498			
84	U	0.143670888	0.494112883	0.870258462			
85	U	0.521448430	0.133334423	0.501328591			
86	U	0.833500163	0.136787016	0.798434778			
87	U	0.495145627	0.121151838	0.844025002			
88	U	0.863545497	0.168786689	0.469156772			
89	U	0.509274324	0.548329765	0.145881356			
90	U	0.825440636	0.779984312	0.192980330			
91	U	0.842423236	0.466015059	0.136756583			
92	U	0.534458472	0.865141497	0.169291879			
93	U	0.310602920	0.323532531	0.315012292			
94	Mo	0.328606490	0.314883686	0.687255302			
95	Mo	0.674009341	0.305267841	0.662448637			
96	U	0.326631011	0.679870122	0.331479707			
97	U	0.371644890	0.679274954	0.665208460			
98	Mo	0.672193000	0.303810812	0.317212538			
99	U	0.820847752	0.816237464	0.833790833			
100	U	0.780071628	0.836705518	0.490628528			
101	U	0.493041587	0.450284430	0.842990907			
102	U	0.818302670	0.476570581	0.798002061			
103	U	0.497363584	0.801441831	0.487806684			
104	U	0.478662001	0.802952159	0.852807185			
105	U	0.852755368	0.505332549	0.451217549			
106	U	0.687902994	0.670557165	0.683653268			
107	Xe	0.536400212	0.492947199	0.459667944			
108	LAST_IMAGE						
109	ATOMIC_POSITIONS (crystal)						
110	U	0.0000000000	0.0000000000	0.0000000000	0	0	0
111	U	0.211003121	0.204403180	0.229059646			
112	U	0.0000000000	0.0000000000	0.333333333	0	0	0
113	U	0.0000000000	0.0000000000	0.666666667	0	0	0
114	U	0.333333333	0.0000000000	0.0000000000	0	0	0

```

115 U      0.666666667  0.000000000  0.000000000  0  0  0
116 U      0.000000000  0.333333333  0.000000000  0  0  0
117 U      0.000000000  0.666666667  0.000000000  0  0  0
118 U      0.137157542  0.154100490  0.530986252
119 U      0.174212597  0.129079723  0.860099413
120 U      0.526361077  0.134914785  0.159501081
121 U      0.862023067  0.133697598  0.175888456
122 U      0.158401680  0.524202200  0.202384340
123 U      0.148244066  0.848143594  0.127034040
124 U      0.000000000  0.333333333  0.333333333  0  0  0
125 U      0.000000000  0.666666667  0.666666667  0  0  0
126 U      0.000000000  0.666666667  0.333333333  0  0  0
127 U      0.000000000  0.333333333  0.666666667  0  0  0
128 U      0.333333333  0.000000000  0.333333333  0  0  0
129 U      0.666666667  0.000000000  0.666666667  0  0  0
130 U      0.333333333  0.000000000  0.666666667  0  0  0
131 U      0.666666667  0.000000000  0.333333333  0  0  0
132 U      0.333333333  0.333333333  0.000000000  0  0  0
133 U      0.666666667  0.666666667  0.000000000  0  0  0
134 U      0.666666667  0.333333333  0.000000000  0  0  0
135 U      0.333333333  0.666666667  0.000000000  0  0  0
136 U      0.178710377  0.490990744  0.516187076
137 U      0.211424168  0.769055779  0.787371675
138 U      0.175042054  0.807911917  0.455992431
139 U      0.138797282  0.465117394  0.842521779
140 U      0.460172734  0.148226288  0.492431541
141 U      0.853214362  0.204001135  0.813615314
142 U      0.517320360  0.155236389  0.808583066
143 U      0.796831649  0.141536092  0.504982369
144 U      0.472082596  0.445170387  0.165199942
145 U      0.797246556  0.819083198  0.205717103
146 U      0.848947010  0.446752941  0.157261389
147 U      0.477337922  0.823974130  0.198045419
148 U      0.357415253  0.358227015  0.377748970
149 Mo     0.316993580  0.314763082  0.680421155
150 Mo     0.607201462  0.351778562  0.642719282
151 U      0.340550068  0.659420403  0.325593019
152 U      0.361166032  0.621614060  0.637522343
153 Mo     0.660553429  0.302407475  0.343460369
154 U      0.864645732  0.824012823  0.866480839
155 U      0.857095779  0.828386743  0.537288219
156 U      0.459295873  0.501704484  0.851504670
157 U      0.787396737  0.503369090  0.850267568
158 U      0.483789070  0.821735869  0.546285283
159 U      0.525937071  0.834449910  0.872642503
160 U      0.803265518  0.439297450  0.559004083
161 U      0.678713059  0.684639768  0.648649342
162 Xe     0.649346200  0.596837093  0.354823657
163 END_POSITIONS
164 K_POINTS automatic
165 4 4 4 0 0 0
166 CELL_PARAMETERS {alat}
167 1.00 0.00 0.00
168 0.00 1.00 0.00
169 0.00 0.00 1.00
170 END_ENGINE_INPUT
171 END

```


F.3.4 A sample code to run distorted lattice in quantum espresso

The following code sample is valid for bcc lattice only.

```
1 import os, subprocess
2 from glob import glob
3 import re
4 import matplotlib.pyplot as plt
5 import numpy as np
6
7 def matprintf(x):
8     for i in range(len(x)):
9         print ('{:16.13f} {:16.13f} {:16.13f}'.format(x[i][0],x[i]
10                ][1],x[i][2]))
11
12 #d = np.array([3.42, 3.43, 3.44, 3.455, 3.45, 3.465, 3.46, 3.475,
13               3.47, 3.48, 3.445, 3.4425])
14 d = np.array
15     ([0,0.01,-0.01,0.005,-0.005,0.0075,-0.0075,0.00625,-0.00625,0.0025,-0.0025,0.0025])
16
17 # Run with different ecutwfc
18 for i in range(len(d)):
19     dd = d[i]
20     A12 = dd
21     A21 = dd
22     A33 = np.float128(1/((1-dd**2)))
23     #crystal axis for bcc
24     R = np.array([[ -0.5,0.5,0.5],[0.5,-0.5,0.5],[0.5,0.5,-0.5]],dtype=
25                 np.float128)
26     #distortion matrix for monoclinic distortion
27     Dmono = np.array([[1,A12,0.0],[A21,1,0.0],[0.0,0.0,A33]],dtype=np.
28                      float128)
29     Rprime = np.matmul(R,Dmono)
30
31     filename = 'U_qepp_gamma.scf'
32     pseudo = '/home/scruffy/rafi/Desktop/rafi/quantum_espresso/
33             supercell_study/pp_dir'
34     with open(filename + str(d[i]) + '.in','w') as f:
35         f.write("&control\n")
36         f.write("title = 'U_gamma'\n")
37         f.write("calculation = 'relax'\n")
38         f.write("restart_mode = 'from_scratch'\n")
39         f.write("pseudo_dir = '{:s}'\n".format(pseudo))
40         f.write("outdir = '{:s}'\n".format(pseudo))
41         f.write("prefix = 'gammaU'\n")
42         f.write("etot_conv_thr = 1.0e-8\n")
43         f.write("forc_conv_thr = 1.0e-8\n")
44         #f.write("tstress = .true.\n")
45         #f.write("tprnfor = .true.\n")
46         f.write("/\n")
47         f.write(" ")
48         f.write("&system\n")
49         f.write("ibrav = 0\n")
50         f.write("A = 3.459\n")
51         #f.write("A = {:3.10f}\n".format(d[i]))
52         f.write("nat = 1\n")
53         f.write("ntyp = 1\n")
54         f.write("ecutwfc = 50\n")
```

```

50     f.write("      ecutrho = 250 \n")
51     f.write("      smearing = 'methfessel-paxton'\n")
52         #f.write("      smearing = 'gauss'\n")
53         #f.write("      degauss = 0.01\n")
54     f.write("/\n")
55     f.write(" ")
56     f.write("&electrons\n")
57     f.write("      diagonalization = 'david'\n")
58         #f.write("      conv_thr = 1.0e-8\n")
59         #f.write("      mixing_beta = 0.7\n")
60     f.write("/\n")
61     f.write(" ")
62     f.write("&IONS\n")
63     f.write("/\n")
64     f.write(" ")
65     f.write("&CELL\n")
66     f.write("/\n")
67     f.write("CELL_PARAMETERS {alat} \n")
68     #f.write("      -0.5      0.5      0.5 \n")
69     #f.write("      0.5      -0.5      0.5 \n")
70     #f.write("      0.5      0.5      -0.5 \n")
71
72     for j in range (len(Rprime)) :
73         f.write ('{:16.13f} {:16.13f} {:16.13f} \n'.format(
Rprime[j][0],Rprime[j][1],Rprime[j][2]))
74
75     f.write(" \n")
76     f.write("ATOMIC_SPECIES\n")
77     f.write("U 238.029  U.GGA-PBE-paw.UPF\n")
78     f.write(" \n")
79     f.write("ATOMIC_POSITIONS {crystal}\n")
80     f.write("U  0.000  0.000  0.000\n")
81     f.write(" \n")
82     f.write("K_POINTS automatic\n")
83     f.write("35 35 35 0 0 0\n")
84     command = ('mpiexec -n 8 pw.x -i ' + filename + str(d[i]) + '.in >
' + filename + str(d[i]) + '.out' )
85     print(command)
86     p = subprocess.Popen(command, shell=True)
87     p.wait()

```

BIBLIOGRAPHY

- IAEA, *Management of High Enriched Uranium for Peaceful Purposes: Status and Trends*, TECDOC Series No. 1452 (INTERNATIONAL ATOMIC ENERGY AGENCY, Vienna, 2005)
- R. Serber, *The Los Alamos primer: The first lectures on how to build an atomic bomb* (Univ of California Press, 1992)
- A. Travelli, *Current status of the RERTR program*, Tech. Rep. (Argonne National Lab., IL (USA), 1980)
- J. L. Snelgrove, G. L. Hofman, M. K. Meyer, C. L. Trybus, and T. C. Wiencek, *Nuclear Engineering and Design* **178**, 119 (1997)
- D. E. Burkes, I. J. Schwerdt, T. K. Huber, H. Breitzkreutz, C. Reiter, W. Petry, J. L. Schulthess, A. M. Casella, A. J. Casella, E. C. Buck, *et al.*, *Journal of Nuclear Materials* **547**, 152823 (2021)
- E. Wilson, A. Bergeron, J. Stillman, T. Heltemes, D. Jaluvka, and L. Jamison, in *Proceedings of the 2017 European Research Reactor Conference* (RRFM Rotterdam, Netherlands, 2017)
- National Academies of Sciences, Engineering, and Medicine, *Reducing the Use of Highly Enriched Uranium in Civilian Research Reactors* (National Academies Press, Washington, DC, 2016)
- National Research Council, *Progress, Challenges, and Opportunities for Converting U.S. and Russian Research Reactors: A Workshop Report* (National Academies Press, Washington, DC, 2012)
- A. R. Kaufmann, *Nuclear Reactor Fuel Elements: Metallurgy and Fabrication* (Interscience Publishers, New York, 1962)
- M. K. Meyer, J. Gan, J. F. Jue, D. D. Keiser, E. Perez, A. Robinson, D. M. Wachs, N. Woolstenhulme, G. L. Hofman, and Y. S. Kim, *Nuclear Engineering and Technology* **46**, 169 (2014)
- S. Pugh, *Journal of Nuclear Materials* **4**, 177 (1961)

- B. Loomis and D. Pracht, *Swelling of uranium and uranium alloys on postirradiation annealing*, Tech. Rep. (Argonne National Lab., Ill., 1962)
- H. H. Chiswik, A. E. Dwight, L. T. Lloyd, M. V. Nevitt, and S. T. Zegler, Second Un. Nat. In. Conf. on the Peaceful Uses of Atomic Energy (1958), 10.2172/4322509
- K. Farrell, in *Comprehensive Nuclear Materials*, edited by R. J. Konings (Elsevier, Oxford, 2012) pp. 143–175
- D. W. White, A. P. Beard, and A. H. Willis (General Electric Company, 1957)
- H. A. Saller, R. F. Dickerson, F. A. Rough, E. L. Foster, A. A. Bauer, and J. R. Lulay, *A Study of Aluminum-Uranium Alloys*, Tech. Rep. (Battelle Memorial Inst., Columbus, Ohio, 1956)
- L. Sannen, S. van den Berghe, and A. Leenaers, in *6th Forum on New Materials - Part B*, Advances in Science and Technology, Vol. 94 (Trans Tech Publications Ltd, 2014) pp. 43–54
- M. K. Meyer, T. C. Wiencek, S. L. Hayes, and G. L. Hofman, *Journal of Nuclear Materials* **278**, 358 (2000)
- G. L. Hofman, R. F. Domagala, and G. L. Copeland, *Journal of Nuclear Materials* **150**, 238 (1987)
- S. van den Berghe, A. Leenaers, E. Koonen, and L. Sannen, in *5th FORUM ON NEW MATERIALS PART B*, Advances in Science and Technology, Vol. 73 (Trans Tech Publications Ltd, 2011) pp. 78–90
- G. Donzé and G. Cabane, *Journal of Nuclear Materials* **1**, 364 (1959)
- F. Giraud-Heraud and J. Guillaumin, *Acta Metallurgica* **21**, 1243 (1973)
- D. A. Lopes, T. A. G. Restivo, and A. F. Padilha, *Journal of Nuclear Materials* **440**, 304 (2013)
- H. A. Saller, F. Rough, and A. Bauer, *Transformation kinetics of uranium-molybdenum alloys*, Tech. Rep. (Battelle Memorial Inst., Columbus, Ohio, 1954)
- W. A. Bostrom and E. K. Halteman, *THE METASTABLE GAMMA PHASE IN URANIUM BASE MOLYBDENUM ALLOYS*, Tech. Rep. (Westinghouse Electric Corp. Bettis Plant, Pittsburgh, 1956)
- R. Prabhakaran, *JOM* **69**, 2529 (2017)
- W. Williams, A. Robinson, and B. Rabin, *JOM* **69**, 2546 (2017)
- H. Okamoto, *Journal of Phase Equilibria and Diffusion* **33**, 497 (2012)

- J. A. Horak, J. A. Reuscher, and D. J. Sasmor, *Operating experience with uranium–molybdenum fuel in pulsed reactors*, Tech. Rep. (Sandia Labs., Albuquerque, N. Mex.(USA), 1973)
- S. A. Cottrell, E. Edmonds, P. Higginson, and W. Oldfield, *Development and performance of Dounreay fast reactor metal fuel*, Tech. Rep. (United Kingdom Atomic Energy Authority. Industrial Group. Dounreay, 1964)
- I. A. E. Agency, Nuclear Fuel Cycle and Material Section (2003)
- A. Leenaers, S. Van den Berghe, E. Koonen, C. Jarousse, F. Huet, M. Trotabas, M. Boyard, S. Guillot, L. Sannen, and M. Verwerft, *Journal of Nuclear Materials* **335**, 39 (2004)
- J.-F. Jue, D. D. Keiser, C. R. Breckenridge, G. A. Moore, and M. K. Meyer, *Journal of Nuclear Materials* **448**, 250 (2014)
- S. Van den Berghe, W. Van Renterghem, and A. Leenaers, *Journal of Nuclear Materials* **375**, 340 (2008)
- D. Olander, *Journal of Nuclear Materials* **383**, 201 (2009)
- A. E. Guay, “Uranium swelling in N-Reactor (PT-NR-4, Sup. A, Report No. 1),” United States. <https://www.osti.gov/biblio/10163384> (1965)
- B. D. Miller, J. Gan, J. Madden, J.-F. Jue, A. Robinson, and D. D. Keiser, *Journal of Nuclear Materials* **424**, 38 (2012)
- J. Gan, D. D. Keiser, D. M. Wachs, A. B. Robinson, B. D. Miller, and T. R. Allen, *Journal of Nuclear Materials* **396**, 234 (2010)
- D. R. Hartree, *Mat. Proc. Cambridge Philos. Soc.* **24**, 89 (1928)
- V. Fock, *Zeitschrift für Physik* **61**, 126 (1930)
- L. H. Thomas, in *Mathematical Proceedings of the Cambridge Philosophical Society*, Vol. 23 (Cambridge University Press, 1927) pp. 542–548
- E. Fermi, *Rend. Accad. Naz. Lincei* **6**, 32 (1927)
- P. Hohenberg and W. Kohn, *Physical Review* **136**, B864 (1964)
- C. Herring, *Physical Review* **57**, 1169 (1940)
- J. C. Phillips and L. Kleinman, *Physical Review* **116**, 287 (1959)
- D. R. Hamann, M. Schlüter, and C. Chiang, *Physical Review Letters* **43**, 1494 (1979)
- N. Troullier and J. L. Martins, *Physical Review B: Condensed Matter and Materials Physics* **43**, 1993 (1991)

- D. Vanderbilt, Physical Review B: Condensed Matter and Materials Physics **41**, 7892 (1990)
- G. Kresse and D. Joubert, Physical Review B: Condensed Matter and Materials Physics **59**, 1758 (1999)
- P. E. Blöchl, Physical Review B: Condensed Matter and Materials Physics **50**, 17953 (1994)
- D. E. Burkes, A. M. Casella, A. J. Casella, E. C. Buck, K. N. Pool, P. J. MacFarlan, M. K. Edwards, and F. N. Smith, Journal of Nuclear Materials **464**, 331 (2015)
- V. V. Rondinella and T. Wiss, Materials Today **13**, 24 (2010)
- A. T. Blades, W. H. Fleming, and H. G. Thode, Canadian Journal of Chemistry **34**, 233 (1956)
- J. A. Petruska, H. G. Thode, and R. H. Tomlinson, Canadian Journal of Physics **33**, 693 (1955)
- Y. S. Kim and G. L. Hofman, Journal of Nuclear Materials **419**, 291 (2011)
- B. D. Miller, J. Gan, D. D. Keiser, Jr, A. B. Robinson, J. F. Jue, J. W. Madden, and P. G. Medvedev, Journal of Nuclear Materials **458**, 115 (2015)
- J. Gan, D. D. Keiser, B. D. Miller, A. B. Robinson, J.-F. Jue, P. Medvedev, and D. M. Wachs, Journal of Nuclear Materials **424**, 43 (2012)
- P. B. Johnson and D. J. Mazey, Journal of Nuclear Materials **93–94**, 721 (1980)
- P. B. Johnson and D. J. Mazey, Journal of Nuclear Materials **91**, 41 (1980)
- J. H. Evans, Journal of Nuclear Materials **119**, 180 (1983)
- D. J. Mazey and J. H. Evans, Journal of Nuclear Materials **138**, 16 (1986)
- J. H. Evans and D. J. Mazey, Journal of Nuclear Materials **138**, 176 (1986)
- P. B. Johnson, K. J. Stevens, and R. W. Thomson, Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms **62**, 218 (1991)
- P. B. Johnson and D. J. Mazey, Journal of Nuclear Materials **218**, 273 (1995)
- F. E. Lawson and P. B. Johnson, Journal of Nuclear Materials **252**, 34 (1998)
- N. M. Ghoniem, D. Walgraef, and S. J. Zinkle, **8**, 1 (2001)
- P. B. Johnson and F. Lawson, Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms **243**, 325 (2006)

- J. Gan, D. D. Keiser, Jr., B. D. Miller, A. B. Robinson, D. M. Wachs, and M. K. Meyer, *Journal of Nuclear Materials* **464**, 1 (2015)
- K. Bakker, *International Journal of Heat and Mass Transfer* **40**, 3503 (1997)
- J. C. Maxwell, *A Treatise on Electricity and Magnetism*, Vol. 1 (Clarendon Press, Oxford, 1881)
- J. B. MacEwan, R. L. Stoute, and M. J. F. Notley, *Journal of Nuclear Materials* **24**, 109 (1967)
- L. A. Goldsmith and J. A. M. Douglas, *Journal of Nuclear Materials* **47**, 31 (1973)
- M. F. DeVries, *Journal of Heat Transfer* **111**, 281 (1989)
- A. L. Loeb, *Journal of the American Ceramic Society* **37**, 96 (1954)
- M. E. Cunningham and K. L. Peddicord, *International Journal of Heat and Mass Transfer* **24**, 1081 (1981)
- D. Y. Tzou, *International Journal of Heat and Mass Transfer* **34**, 1839 (1991)
- T. H. Bauer, *International Journal of Heat and Mass Transfer* **36**, 4181 (1993)
- S. Hu, A. M. Casella, C. A. Lavender, D. J. Senor, and D. E. Burkes, *Journal of Nuclear Materials* **462**, 64 (2015)
- Trellis Pro (csimsoft, LLC., American Fork, Utah, 2012–2017)
- V. A. Rabinovich, A. A. Vasserman, V. I. Nedostup, and L. S. Veksler, *Thermophysical Properties of Neon, Argon, Krypton, and Xenon* (Hemisphere Publishing Corporation, New York, NY, 1987)
- D. E. Burkes, C. A. Papesch, A. P. Maddison, T. Hartmann, and F. J. Rice, *Journal of Nuclear Materials* **403**, 160 (2010)
- G. W. Greenwood, A. J. E. Foreman, and D. E. Rimmer, *Journal of Nuclear Materials* **1**, 305 (1959)
- H. Trinkaus, *Radiation Effects* **78**, 189 (1983)
- H. Xiao, C. Long, X. Tian, and S. Li, *Materials and Design* **74**, 55 (2015)
- L. E. Thomas, in *Fundamental Aspects of Inert Gases in Solids* (Springer, New York, 1991) pp. 431–441
- M. Ross and A. K. McMahan, *Physical Review B: Condensed Matter and Materials Physics* **21**, 1658 (1980)
- J. Zheng, Q. F. Chen, Y. J. Gu, Z. Y. Chen, and C. J. Li, *Journal of Chemical Physics* **141**, 124 (2014)

- D. Gaston, C. Newman, G. Hansen, and D. Lebrun-Grandie, *Nuclear Engineering and Design* **239**, 1768 (2009)
- C. R. Clark, G. C. Knighton, M. K. Meyer, and G. L. Hofman, in *2003 International Meeting on Reduced Enrichment for Research and Test Reactors*, Vol. 1 (Chicago, Illinois, 2003)
- D. S. Smith, A. Alzina, J. Bourret, B. Nait-Ali, F. Pennec, N. Tessier-Doyen, K. Otsu, H. Matsubara, P. Elser, and U. T. Gonzenbach, *Journal of Materials Research* **28**, 2260 (2013)
- Z. Hashin and S. Shtrikman, *Journal of Applied Physics* **33**, 3125 (1962)
- B. Schulz, *High Temperatures – High Pressures* **13**, 649 (1981)
- Y. S. Kim, G. Hofman, and J. S. Cheon, *Journal of Nuclear Materials* **436**, 14 (2013)
- T. H. Bauer and J. W. Holland, *Nuclear Technology* **110**, 407 (1995)
- K. L. Peddicord, M. E. Cunningham, and A. Tripathi, *Transactions of the American Nuclear Society* **28**, 548 (1978)
- K. Bakker, H. Kwast, and E. H. P. Cordfunke, *Journal of Nuclear Materials* **226**, 128 (1995)
- A. C. Lawson, C. E. Olsen, J. W. Richardson, M. H. Mueller, and G. H. Lander, *Acta Crystallographica B: Structural Science* **44**, 89 (1988)
- J. Akella, S. Weir, J. M. Wills, and P. Söderlind, *Journal of Physics: Condensed Matter* **9**, L549 (1997)
- G. H. Lander, *Science* **301**, 1057 (2003)
- A. J. Freeman and G. H. Lander, *Handbook on the Physics and Chemistry of the Actinides*, Vol. 1,2 (North-Holland, Amsterdam, 1984)
- J. M. Wills and O. Eriksson, *Physical Review B: Condensed Matter and Materials Physics* **45**, 13879 (1992)
- O. Eriksson, P. Söderlind, J. M. Wills, and A. M. Boring, *Physica C: Superconductivity* **190**, 5 (1993)
- J. P. Crocombette, F. Jollet, L. Thien Nga, and T. Petit, *Physical Review B: Condensed Matter and Materials Physics* **64**, 104107 (2001)
- P. Söderlind, *Physical Review B: Condensed Matter and Materials Physics* **66**, 085113 (2002)
- A. C. Lawson, B. M. Artinez, J. A. Roberts, B. I. Bennett, and J. W. Richardson, Jr., *Philosophical Magazine B* **80**, 53 (2000)

- M. D. Jones, J. C. Boettger, R. C. Albers, and D. J. Singh, *Physical Review B: Condensed Matter and Materials Physics* **61**, 4644 (2000)
- C. D. Taylor, *Physical Review B: Condensed Matter and Materials Physics* **77**, 094119 (2008)
- J. P. Perdew, J. A. Chevary, S. H. Vosko, K. A. Jackson, M. R. Pederson, D. J. Singh, and C. Fiolhais, *Physical Review B: Condensed Matter and Materials Physics* **46**, 6671 (1992)
- J. P. Perdew, J. A. Chevary, S. H. Vosko, K. A. Jackson, M. R. Pederson, D. J. Singh, and C. Fiolhais, *Physical Review B: Condensed Matter and Materials Physics* **48**, 4978 (1993)
- C. S. Barrett, M. H. Mueller, and R. L. Hitterman, *Physical Review* **129**, 625 (1963)
- S. Xiang, H. Huang, and L. M. Hsiung, *Journal of Nuclear Materials* **375**, 113 (2008)
- J. P. Perdew, K. Burke, and M. Ernzerhof, *Physical Review Letters* **77**, 3865 (1996)
- J. P. Perdew, K. Burke, and M. Ernzerhof, *Physical Review Letters* **78**, 1396 (1997)
- J. H. Li, Q. B. Ren, C. H. Lu, L. Lu, Y. Dai, and B. X. Liu, *Journal of Alloys and Compounds* **516**, 139 (2012)
- B. Beeler, C. Deo, M. Baskes, and M. Okuniewski, *Journal of Nuclear Materials* **433**, 143 (2013)
- P. Giannozzi, S. Baroni, N. Bonini, M. Calandra, R. Car, C. Cavazzoni, D. Ceresoli, G. L. Chiarotti, M. Cococcioni, I. Dabo, A. Dal Corso, S. de Gironcoli, S. Fabris, G. Fratesi, R. Gebauer, U. Gerstmann, C. Gougoussis, A. Kokalj, M. Lazzeri, L. Martin-Samos, N. Marzari, F. Mauri, R. Mazzarello, S. Paolini, A. Pasquarello, L. Paulatto, C. Sbraccia, S. Scandolo, G. Sclauzero, A. P. Seitsonen, A. Smogunov, P. Umari, and R. M. Wentzcovitch, *Journal of Physics: Condensed Matter* **21**, 395502 (2009)
- N. A. W. Holzwarth, A. R. Tackett, and G. E. Matthews, *Computer Physics Communications* **135**, 329 (2001)
- A. R. Tackett, N. A. W. Holzwarth, and G. E. Matthews, *Computer Physics Communications* **135**, 348 (2001)
- N. Iché-Tarrat and C. J. Marsden, *The Journal of Physical Chemistry A* **112**, 7632 (2008)
- A. M. Rappe, K. M. Rabe, E. Kaxiras, and J. D. Joannopoulos, *Physical Review B: Condensed Matter and Materials Physics* **41**, 1227 (1990)
- Naval Research Laboratories, “Structure of Crystals,” <http://aflowlib.duke.edu/users/egossett/lattice/> (2015)

- J. D. Pack and H. J. Monkhorst, *Physical Review B: Condensed Matter and Materials Physics* **16**, 1748 (1977)
- M. Methfessel and A. T. Paxton, *Physical Review B: Condensed Matter and Materials Physics* **40**, 3616 (1989)
- P. Ravindran, L. Fast, P. A. Korzhavyi, B. Johansson, J. Wills, and O. Eriksson, *Journal of Applied Physics* **84**, 4891 (1998)
- O. Beckstein, J. E. Klepeis, G. L. W. Hart, and O. Pankratov, *Physical Review B: Condensed Matter and Materials Physics* **63**, 134112 (2001)
- G. H. Lander, E. S. Fisher, and S. D. Bader, *Advances in Physics* **43**, 1 (1994)
- T. Le Bihan, S. Heathman, M. Idiri, G. H. Lander, J. M. Wills, A. C. Lawson, and A. Lindbaum, *Physical Review B: Condensed Matter and Materials Physics* **67**, 134102 (2003)
- F. D. Murnaghan, *Proceedings of the National Academy of Sciences of the United States of America* **30**, 244 (1944)
- R. Q. Hood, L. H. Yang, and J. A. Moriarty, *Physical Review B: Condensed Matter and Materials Physics* **78**, 024116 (2008)
- C.-S. Yoo, H. Cynn, and P. Söderlind, *Physical Review B: Condensed Matter and Materials Physics* **57**, 10359 (1998)
- E. S. Fisher and H. J. McSkimin, *Journal of Applied Physics* **29**, 1473 (1958)
- A. S. Wilson and R. E. Rundle, *Acta Crystallographica* **2**, 126 (1949)
- H. L. Yakel, *Review of X-ray Diffraction Studies in Uranium Alloys*, Tech. Rep. (Oak Ridge National Laboratory, Tennessee (USA), 1973)
- I. Grenthe, J. Drozdzyński, T. Fujino, E. C. Buck, T. E. Albrecht-Schmitt, and S. F. Wolf, *The Chemistry of the Actinide and Transactinide Elements*, Vol. 1 (Springer, Dordrecht, 2006) pp. 253–698
- J. H. Kittel, B. R. T. Frost, J. P. Mustelier, K. Q. Bagley, G. C. Crittenden, and J. Van Dievoet, *Journal of Nuclear Materials* **204**, 1 (1993)
- N.-T. H. Kim-Ngan and L. Havela, *Journal of Science: Advanced Materials and Devices* **1**, 121 (2016)
- M. Born, *Proceedings of the Cambridge Philosophical Society* **36**, 160 (1940)
- M. Born and K. Huang, *Dynamical Theory of Crystal Lattices* (Clarendon Press, 1954)
- F. Mouhat and F.-X. Coudert, *Physical Review B: Condensed Matter and Materials Physics* **90**, 224104 (2014)
- P. Söderlind, *Advances in Physics* **47**, 959 (1998)

- C. W. Tucker, Jr., *An Approximate Crystal Structure for the Beta Phase of Uranium*, Tech. Rep. KAPL-388 (Knolls Atomic Power Laboratory, 1950)
- C. W. Tucker, *Acta Crystallographica* **4**, 425 (1951)
- J. Donohue and H. Einspahr, *Acta Crystallographica B: Structural Science* **27**, 1740 (1971)
- J. Donohue, *Structures of the Elements* (John Wiley and Sons, 1974) pp. 134–148
- D. C. Wallace, *Thermodynamics of Crystals* (Courier Corporation, 1998)
- A. R. M. Iasir and K. D. Hammond, *Computational Materials Science* **171**, 109221 (2020)
- A. Dal Corso, *Computational Materials Science* **95**, 337 (2014)
- Quantum Espresso, “PS library,” <http://www.quantum-espresso.org/pseudopotentials> (2019)
- V. P. Sinha, P. V. Hegde, G. J. Prasad, G. K. Dey, and H. S. Kamath, *Journal of Alloys and Compounds* **506**, 253 (2010)
- H. L. Yakel, *Journal of Nuclear Materials* **33**, 286 (1969)
- V. P. Sinha, P. V. Hegde, G. J. Prasad, G. K. Dey, and H. S. Kamath, *Journal of Alloys and Compounds* **491**, 753 (2010)
- H. Okamoto, M. E. Schlesinger, and E. M. Mueller, eds., “Mo (molybdenum) binary alloy phase diagrams,” in *Alloy Phase Diagrams*, ASM Handbook, Vol. 3 (ASM International, 2016) pp. 489–498
- A. Berche, N. Dupin, C. Guénau, C. Rado, B. Sundman, and J. C. Dumas, *Journal of Nuclear Materials* **411**, 131 (2011)
- A. E. Dwight, *Journal of Nuclear Materials* **2**, 81 (1960)
- K. Tangri and G. Williams, *Journal of Nuclear Materials* **4**, 226 (1961)
- A. Berche, N. Dupin, C. Guéneau, C. Rado, B. Sundman, and J. C. Dumas, *Journal of Nuclear Materials* **411**, 131 (2011)
- X. Zhang, Y. F. Cui, G. L. Xu, W. J. Zhu, H. S. Liu, B. Y. Yin, and Z. P. Jin, *Journal of Nuclear Materials* **402**, 15 (2010)
- E. L. Losada and J. E. Garcés, *Journal of Nuclear Materials* **518**, 380 (2019)
- A. Landa, P. Söderlind, and P. E. A. Turchi, *Journal of Nuclear Materials* **414**, 132 (2011)
- P. R. Alonso and G. H. Rubiolo, *Modelling and Simulation in Materials Science and Engineering* **15**, 263 (2007)
- A. Castellano, F. Bottin, B. Dorado, and J. Bouchet, *Physical Review B: Condensed Matter and Materials Physics* **101**, 184111 (2020)

- A. R. M. Iasir, N. J. Peters, and K. D. Hammond, *Journal of Nuclear Materials* **508**, 159 (2018)
- J. Rest, Y. S. Kim, G. L. Hofman, M. K. Meyer, and S. L. Hayes, *U–Mo fuels handbook. Version 1.0*, Tech. Rep. (Argonne National Lab.(ANL), Argonne, IL (United States), 2006)
- R. W. Grimes and C. R. A. Catlow, *Philosophical Transactions of the Royal Society A: Mathematical, Physical, and Engineering Sciences* **335**, 609 (1991)
- D. A. Andersson, B. P. Uberuaga, P. V. Nerikar, C. Unal, and C. R. Stanek, *Physical Review B: Condensed Matter and Materials Physics* **84**, 054105 (2011)
- Y. Yun, H. Kim, H. Kim, and K. Park, *Journal of Nuclear Materials* **378**, 40 (2008)
- J. C. Carter, E. J. Driscoll, and T. S. Elleman, *Physica Status Solidi A: Applications and Materials Science* **14**, 673 (1972)
- H. Matzke, *Nuclear Applications* **2**, 131 (1966)
- J. R. MacEwan and W. H. Stevens, *Journal of Nuclear Materials* **11**, 77 (1964)
- K. Une, I. Tanabe, and M. Oguma, *Journal of Nuclear Materials* **150**, 93 (1987)
- C. R. A. Catlow, *Proceedings of the Royal Society of London Series A, Mathematical and Physical Sciences* **364**, 473 (1978)
- R. A. Jackson, A. D. Murray, J. H. Harding, and C. R. A. Catlow, *Philosophical Magazine A* **53**, 27 (1986)
- R. W. Grimes, C. R. A. Catlow, and A. M. Stoneham, *Journal of the American Ceramic Society* **72**, 1856 (1989)
- R. G. J. Ball and R. W. Grimes, *Journal of the Chemical Society, Faraday Transactions* **86**, 1257 (1990)
- T. Petit, G. Jomard, C. Lemaignan, B. Bigot, and A. Pasturel, *Journal of Nuclear Materials* **275**, 119 (1999)
- J.-P. Crocombette, *Journal of Nuclear Materials* **305**, 29 (2002)
- M. Freyss, N. Vergnet, and T. Petit, *Journal of Nuclear Materials* **352**, 144 (2006)
- Y. Adda and A. Kirianenko, *Journal of Nuclear Materials* **1**, 120 (1959)
- N. L. Peterson and S. J. Rothman, *Physical Review* **136**, A842 (1964)
- S. J. Rothman, L. T. Lloyd, R. Weil, and A. L. Harkness, *Self-Diffusion in gamma Uranium*, Tech. Rep. (Argonne National Lab., Lemont, Ill., 1959)
- S. J. Rothman, *Journal of Nuclear Materials* **3**, 77 (1961)

- Y. Adda and A. Kirianenko, *Journal of Nuclear Materials* **6**, 130 (1962)
- R. Resnick and L. L. Seigle, *Journal of Nuclear Materials* **5**, 5 (1962)
- S. J. Rothman, J. Gray, Jr, J. P. Hughes, and A. L. Harkness, *Journal of Nuclear Materials* **3**, 72 (1961)
- Y. Liu, D. Yu, Y. Du, G. Sheng, Z. Long, J. Wang, and L. Zhang, *Calphad* **37**, 49 (2012)
- D. E. Smirnova, A. Y. Kuksin, S. V. Starikov, and V. V. Stegailov, *Physics of Metals and Metallography* **116**, 445 (2015)
- J. B. Adams, S. M. Foiles, and W. G. Wolfer, *Journal of Materials Research* **4**, 102 (1989)
- P. E. Blöchl, E. Smargiassi, R. Car, D. B. Laks, W. Andreoni, and S. T. Pantelides, *Physical Review Letters* **70**, 2435 (1993)
- P. E. Blöchl, C. G. Van de Walle, and S. T. Pantelides, *Physical Review Letters* **64**, 1401 (1990)
- W. Frank, U. Breier, C. Elsässer, and M. Fähnle, *Physical Review Letters* **77**, 518 (1996)
- A. Janotti, M. Krčmar, C. L. Fu, and R. C. Reed, *Physical Review Letters* **92**, 085901 (2004)
- M. Krčmar, C. L. Fu, A. Janotti, and R. C. Reed, *Acta Materialia* **53**, 2369 (2005)
- V. Milman, M. C. Payne, V. Heine, R. J. Needs, J. S. Lin, and M. H. Lee, *Physical Review Letters* **70**, 2928 (1993)
- N. Sandberg, B. Magyari-Köpe, and T. R. Mattsson, *Physical Review Letters* **89**, 065901 (2002)
- A. B. Lidiard, *Philosophical Magazine Series 7* **46**, 1218 (1955)
- A. B. Lidiard, *Philosophical Magazine A* **5**, 1171 (1960)
- A. D. Leclaire and A. B. Lidiard, *Philosophical Magazine A* **1**, 518 (1956)
- A. D. Le Claire, *Philosophical Magazine A* **21**, 819 (1970)
- H. Mehrer, *Diffusion in Solids: Fundamentals, Methods, Materials, Diffusion-Controlled Processes*, Vol. 155 (Springer Science & Business Media, 2007) pp. 116–122
- G. H. Vineyard and G. J. Dienes, *Physical Review* **93**, 265 (1954)
- G. H. Vineyard, *Journal of Physics and Chemistry of Solids* **3**, 121 (1957)
- H. Eyring, *Journal of Chemical Physics* **3**, 107 (1935)
- M. G. Evans and M. Polanyi, *Transactions of the Faraday Society* **31**, 875 (1935)

- K. Heinola and T. Ahlgren, Journal of Applied Physics **107**, 113531 (2010)
- R. W. Balluffi and P. S. Ho, “Diffusion,” (American Society for Metals, Metals Park, Ohio, 1973) p. 83
- C. Wolverton, Acta Materialia **55**, 5867 (2007)
- P. Soderlind, Advances in Physics **47**, 959 (1998)
- Y.-Y. Ye, Y. Chen, K.-M. Ho, B. N. Harmon, and P.-A. Lindgrd, Physical Review Letters **58**, 1769 (1987)
- J. M. Sanchez and D. De Fontaine, Physical Review Letters **35**, 227 (1975)
- B. Beeler, B. Good, S. Rashkeev, C. Deo, M. Baskes, and M. Okuniewski, Journal of Physics: Condensed Matter **22**, 505703 (2010)
- G. Henkelman, B. P. Uberuaga, and H. Jónsson, Journal of Chemical Physics **113**, 9901 (2000)
- G. Henkelman and H. Jónsson, Journal of Chemical Physics **113**, 9978 (2000)
- H. Matter, J. Winter, and W. Triftshäuser, Journal of Nuclear Materials **88**, 273 (1980)
- K. R. Lund, K. G. Lynn, M. H. Weber, and M. A. Okuniewski, Journal of Physics: Conference Series **443**, 012021 (2013)
- D. Shin and C. Wolverton, Acta Materialia **58**, 531 (2010)
- J. E. Saal and C. Wolverton, Acta Materialia **60**, 5151 (2012)
- J. Burke, Journal of the Less-Common Metals **28**, 441 (1972)
- X.-S. Kong, X. Wu, Y.-W. You, C. Liu, Q. Fang, J.-L. Chen, G.-N. Luo, and Z. Wang, Acta Materialia **66**, 172 (2014)
- T. Ohnuma, N. Soneda, and M. Iwasawa, Acta Materialia **57**, 5947 (2009)
- M. Bell, H. Kugel, R. Kaita, L. Zakharov, H. Schneider, B. LeBlanc, D. Mansfield, R. Bell, R. Maingi, S. Ding, *et al.*, Plasma Physics and Controlled Fusion **51**, 124054 (2009)
- S. Mirnov, V. Lazarev, S. Sotnikov, V. Evtikhin, I. Lyublinski, A. Vertkov, *et al.*, Fusion Engineering and Design **65**, 455 (2003)
- J. Sánchez, F. Tabarés, D. Tafalla, J. Ferreira, I. García-Cortés, C. Hidalgo, F. Medina, M. Ochando, M. Pedrosa, and T.-I. The, Journal of nuclear materials **390**, 852 (2009)
- A. Tuccillo, A. Alekseyev, B. Angelini, S. V. Annibaldi, M. Apicella, G. Apruzzese, J. Berrino, E. Barbato, A. Bertocchi, A. Biancalani, *et al.*, Nuclear Fusion **49**, 104013 (2009)

- G. Xu, B. Wan, J. Li, X. Gong, J. Hu, J. Shan, H. Li, D. Mansfield, D. Humphreys, V. Naulin, *et al.*, *Nuclear Fusion* **51**, 072001 (2011)
- S. Munaretto, S. Dal Bello, P. Innocente, M. Agostini, F. Auriemma, S. Barison, A. Canton, L. Carraro, G. De Masi, S. Fiameni, *et al.*, *Nuclear Fusion* **52**, 023012 (2012)
- S. Erents, G. McCracken, and P. Goldsmith, *Journal of Physics D: Applied Physics* **4**, 672 (1971)
- J. Hartley, B. Gore, and J. Young, *Lithium Needs and Resources*, 337 (1978)
- J. P. Allain and C. N. Taylor, *Physics of Plasmas* **19**, 056126 (2012)
- P. E. Blöchl, *Physical Review B: Condensed Matter and Materials Physics* **50**, 17953 (1994)
- P.-W. Ma and S. Dudarev, *Physical Review Materials* **3**, 063601 (2019)
- P. Ehrnhar, P. Jung, H. Schultz, and H. Ullmaier, in *Atomic Defects in Metals*, Vol. 25, edited by H. Ullmaier (Springer-Verlag Berlin Heidelberg, 1991)
- P.-W. Ma and S. L. Dudarev, *Physical Review Materials* **3**, 013605 (2019)
- R. Benedek, L. Yang, C. Woodward, and B. Min, *Physical Review B: Condensed Matter and Materials Physics* **45**, 2607 (1992)
- R. Pawellek, M. Fahnle, C. Elsasser, K. M. Ho, and C. T. Chan, *Journal of Physics: Condensed Matter* **3**, 2451 (1991)
- W. Frank, U. Breier, C. Elsässer, and M. Fahnle, *Physical Review B: Condensed Matter and Materials Physics* **48**, 7676 (1993)
- C. Becquart and C. Domain, *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* **255**, 23 (2007)
- T. Seletskaya, Y. Osetsky, R. E. Stoller, and G. M. Stocks, *Physical Review Letters* **94**, 046403 (2005)
- C.-C. Fu and F. Willaime, *Physical Review B: Condensed Matter and Materials Physics* **72**, 064117 (2005).

VITA

Abu Rafi Mohammad Iasir was born in Chattagram (Chittagong), Bangladesh. He received his BSc. in Chemical Engineering from Bangladesh University of Engineering and Technology in 2012. In 2013, he moved to Mizzou and received an M.S. in Nuclear Engineering under the supervision of Dr. Gary Solbrekken.