

This document is the Accepted Manuscript version of a Published Work that appeared in final form in **JOURNAL OF PHYSICAL CHEMISTRY A**, copyright 2010 American Chemical Society after peer review and technical editing by the publisher. To access the final edited and published work see <https://pubs.acs.org/doi/full/10.1021/jp907031x>

Postprint of: Smalara K., Giędoń Ł., Bobrowski M., Rybicki J., Czaplewski C., Theoretical study of polymerization mechanism of p-xylylene based polymers, JOURNAL OF PHYSICAL CHEMISTRY A, Vol. 114, Iss. 12 (2010), pp. 4296–4303, DOI: [10.1021/jp907031x](https://doi.org/10.1021/jp907031x)

Theoretical Study of Polymerization Mechanism of p-xylylene Based Polymers

Journal:	<i>The Journal of Physical Chemistry</i>
Manuscript ID:	jp-2009-07031x.R1
Manuscript Type:	Article
Date Submitted by the Author:	04-Dec-2009
Complete List of Authors:	Smalara, Krzysztof; University of Gdansk, Faculty of Chemistry Giędoń, Artur; University of Gdansk, Faculty of Chemistry Bobrowski, Maciej; Technical University of Gdansk, Faculty of Technical Physics and Applied Mathematics Rybicki, Jaroslaw; Technical University of Gdansk, Faculty of Technical Physics and Applied Mathematics Czaplewski, Cezary; University of Gdansk, Faculty of Chemistry



Theoretical study of polymerization mechanism of *p*-xylylene based polymers

*Krzysztof Smalara*¹, *Artur Giełdoń*¹, *Maciej Bobrowski*², *Jarostaw Rybicki*²,

Cezary Czaplewski^{1,*}

¹Faculty of Chemistry, University of Gdańsk, Sobieskiego 18, 80-952 Gdańsk, Poland

²Faculty of Technical Physics and Applied Mathematics, Technical University of Gdańsk,

Naturowicza 11/12, 80-233 Gdańsk, Poland

ABSTRACT

The mechanism of polymerization of *p*-xylylene and its derivatives is analyzed at the theoretical level. The polymerization reaction takes place in vacuo without any catalyst. The first step is a pyrolytic decomposition of starting material for polymerization, paracyclophane, a cyclic dimer of *p*-xylylene, into biradical linear dimer and finally into two quinonoid monomeric molecules of *p*-xylylene. The quinonoid monomer is diamagnetic, i.e., it has a singlet ground state. The monomers after pyrolysis, when temperature is lowered, do not form back cyclic dimers but instead polymerize into long chain molecules. The initiation of polymerization requires dimerization of two monomers leading to formation of a genuine non-coupled biradical dimer. The chain molecules grow through the propagation reaction only one unit at a time, by the attachment of a monomer to a radical chain end. In this work the pyrolysis

* Corresponding author. E-mail: czarek@chem.univ.gda.pl

1 reaction, the initiation reaction and the first propagation steps of parylene polymerization (up to
2 pentamer) are studied in details using different quantum chemical methods: AM1 and PM6
3 semiempirical methods and density functional theory (DFT) approach using B3LYP functional with two
4 basis sets of different size (SVP and TZVP).
5
6
7
8
9

10
11 **KEYWORDS** parylene, poly-p-xylylene, chemical vapor deposition, radical polymerization, density
12 functional theory, semiempirical methods.
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

INTRODUCTION

Members of poly(*p*-xylylene) family of polymers, also known as parylenes, are polymers that can be deposited in thin film form at room temperature by chemical vapor deposition.¹ The discovery of the poly(*p*-xylylene) was first reported by Szwarc in 1947 when he found a polymer as one of the products formed in the vacuum thermal decomposition (pyrolysis) of *p*-xylene.² However, the yields of polymer film were only a few percent even at very high pyrolysis temperature. It was not until 1966 when Gorham found a much more effective process starting with the vacuum pyrolysis of di-*p*-xylylene ([2.2]paracyclophane).³ Parylenes become technically important materials for use in electronics, medical applications, and optical devices. Today the parylene polymer is widely used for the coating of printed circuits, for barrier coatings, in corrosion control and as a dry lubricant.^{4, 5} Parylene based polymers are hydrophobic and offer an attractive low dielectric permittivity. These polymers exhibit excellent thermal and mechanical properties, good solvent resistance, bulk barrier properties that are among the best of organic coatings. The chemical vapor deposition is able to produce the desired film thickness and uniformity over the coating area, which is essential in many applications in the biotechnology and microelectronics industries. Three commercially most popular members of parylene family are shown on Figure 1.

Figure 1.

Parylene N, is poly-*p*-xylylene, a completely linear, highly crystalline material. Parylene C, the second commercially available member of the series, is produced from similar monomer modified only by the substitution of a chlorine atom for one of the aromatic hydrogen atom. Parylene D is produced from the monomer modified by the substitution of the chlorine atoms for two of the aromatic hydrogen atoms. Recent introduction of novel substituents into parylene broaden its applications. **Variable degrees of substitution and functionalities including hydroxy, methoxy, amino, triflate, or trifluoroacetyl groups are used to prepare thin films of poly(*p*-xylylenes) with distinct chemical and optical properties.**^{6, 7} Parylene

1 based chemically functionalized polymer coatings have potential biomedical applications.⁸ Various
2 acetylenic [2.2]paracyclophanes such as 4-ethynyl-[2.2]paracyclophane were subjected to gas phase
3 vacuum pyrolysis and the resulting polymer was then treated with biotinazide to covalently attach biotin
4 molecule to the polymer surface.⁹ Biotin is known to form a noncovalent complex with streptavidin
5 protein thus allowing preparation of bioactive surfaces that could be employed as novel biosensors and
6 microarrays. Chemical vapor deposition of the germanium derivative of [2.2]paracyclophane and
7 subsequent annealing produces germanium grains embedded in the parylene matrix.¹⁰ Traditional metal-
8 polymer systems can be obtained by the treatment of parylene coating with metal vapors or by the
9 reduction of metal salts in solution in the presence of polymers.⁵

10 In spite of wide industrial application of the polymerization of p-xylylene and its substituents leading
11 to parylene family of polymers, the polymerization reaction has not been studied by computational
12 methods extensively. The fact that no solvents or catalysts take part in polymerization of p-xylylene
13 makes this process very interesting from a theoretical point of view. Over the several decades only a few
14 articles regarding the mechanism of formation of poly(p-xylylene) from the vapor phase have been
15 published since Errede and Szwarc prepared their review article in 1958.¹¹ Their qualitative picture of
16 the polymerization mechanism still seems valid. Parylene polymerization is of the chain growth type
17 except that the chains are not terminated during growth.¹² In the chain growth polymerization polymer
18 chain grows only one unit at a time, by the attachment of a monomer to the chain end. In general the
19 chain ends could be a radical, cation or anion, and in case of parylene the chain ends are radical. Chain
20 growth polymerization takes place in three common steps: initiation, propagation and termination. In
21 case of parylene polymerization there is no termination step and unreacted chain ends are buried in the
22 film as it grows. Subsequent termination of the radical chain ends can occur post-deposition via
23 reactions with atmospheric oxygen that has diffused into the polymer film¹³.

24 Beach worked on quantitative understanding of p-xylylene vapor deposition polymerization.¹⁴ He
25 compared results from his kinetic model with the activation energy for the propagation, 8.7 kcal/mol, as
26 measured by Errede in solution.¹⁵ At the time of Beach publication no measure of the activation energy
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53

1 for initiation reaction existed, but Errede¹⁵ suggested earlier that it should be considerably larger than
2 the activation energy for the propagation. A simple estimation of the heat of formation from bond and
3 resonance energies carried out by Kubo's¹⁶ gives 16.1 kcal/mole difference between the heat of
4 formation for the biradical dimer and the heat of formation of two starting monomers and -2.3 kcal/mol
5 difference between the heat of formation for the biradical trimer and the heat of formation of three
6 starting monomers. From this it can be roughly estimated that the activation energy for initiation
7 (according to Beach¹⁴ this is the highest potential energy during the reaction forming the trimer,
8 assuming that the activation energy for reaction between two monomers is smaller than the activation
9 for reaction between monomer and biradical dimer) is $16.1 + 8.7 = 24.8$ kcal/mol. In his review Szwarc¹²
10 defined initiation reaction not as the formation of the trimer but of the dimer. He criticized earlier kinetic
11 experiment in solution performed by Errede¹⁵. In his opinion the measured propagation activation
12 energy of 8.7 kcal/mol may have substantial error. The measured value depends on the concentration of
13 monomer in the swollen polymer particles (where polymerization in solution takes place), which may be
14 different from its bulk concentration.¹² Most of the recent studies of polymerization of p-xylylene were
15 focused on modeling physical process of deposition of polymer¹⁷⁻²⁰, together with chain growth, but not
16 the chemical reactions during polymerization. Recently an analytical kinetic model for the chemical
17 vapor deposition of poly(p-xylylene) was modeled as multistep process that includes both physisorption
18 of monomer on the surface and subsequent chemisorption.²¹ The best fit parameters from this kinetic
19 model to experimental data gives 9.41 kcal/mol as the difference between the activation energy for
20 desorption and the activation energy for chemisorption. Monte Carlo simulation of vapor deposition
21 polymerization using a simple two-dimensional model shows that the polymer chain length, the polymer
22 film thickness and density, and polymer structure depends on the ration of diffusion coefficient to
23 deposition rate.²²

24 The thermolysis of the [2.2]-paracyclophane has been studied experimentally by kinetic measurements
25 in the presence of NO or O₂.²³ The enthalpy and entropy of transition state for the reaction of the ring
26 opening was determined from the temperature dependence of trapping rates of the intermediate
27

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

biradicals by NO or O₂.²³ These values were compared with the heats of formation for reactants, products and transition state calculated with the empirical forcefield making use of the EVBH method,²³ which allows to calculate radical stabilization energies with high accuracy. The experimental activation barrier for the opening of [2.2]-p-cyclophane ring was measured as 37.7±0.5 kcal/mol, and the barrier for the reverse reaction was 11.8±1.0 kcal/mol. Together with experimental heat of formation of [2.2]-p-cyclophane equal 58.5±0.5 kcal/mol²⁴ or more commonly known value 59.9±1.9 kcal/mol²⁵ this allows estimation of the heat of formation of the biradical dimer as 84.4 or 85.8 kcal/mol. Experimental heat of formation for p-xylylene is 50±4 kcal/mol,²⁶ so the heat of formation for two monomers is around 15 kcal/mol higher than the heat of formation the biradical dimer. The initiation reaction of formation of the biradical dimer is an exothermic process. This is in disagreement with simple estimation of the heat of formation from bond and resonance energies carried out by Kubo's¹⁶ and later used by Beach.¹⁴

Thermal isomerization of disubstituted [2.2]-p-cyclophane was also studied experimentally and only the diradical mechanism of the ring opening is consistent with the measured equilibrium and the rate constants.²⁷ The quantitative conversion of dimer to monomer as a function of the pyrolysis furnace temperature was studied by mass spectroscopy.²⁸ Cracking of the dimer begins at 385°C and by 565°C one hundred percent of dimer flowing through the pyrolysis zone is cracked into monomer. The experiment was performed in non equilibrium conditions, the residence time of the dimer in the pyrolysis zone effected the conversion, and therefore authors did not try to estimate the activation energy for the pyrolysis reaction.²⁸

Alexandrova and Salcedo studied the chemical reaction of decomposition of the unsubstituted [2.2]-p-cyclophane, chloro-p-cyclophane and cyano-p-cyclophane in the pyrolytic zone into the intermediate quinoid monomer molecules using AM1 semiempirical method²⁹. They calculated the total energies, ionization potentials and analyzed frontier orbitals for both [2.2]-p-cyclophane and p-quinodimethane with and without substitutions and discussed the influence of the substituents on the polymerization reactions on the basis of the Taft and Topson rules for aromatic compounds. Authors did not studied polymerization reaction in details but concluded that the intermediate molecule p-quinodimethane is

1 very important in starting polymerization process and can exist in two forms: a closed shell tetraolefin
2 and an aromatic biradical which has the higher energy but is accessible in the environment of reaction.
3 Alexandrova and Salcedo postulated that during the polymerization the monomer must take a polar form
4 in order to join with another monomer or continue in propagation but they did not present any results
5 supporting this statement. In opposition to the mechanism presented by Alexandrova and Salcedo the
6 generally accepted mechanism of polymerization of para-xylylene based polymers is radical not ionic.¹¹
7 In this work the pyrolysis reaction, the initiation and the first propagation steps of parylene
8 polymerization are studied in details using different quantum chemistry methods: AM1 and PM6
9 semiempirical methods and density functional theory (DFT) approach using B3LYP functional with two
10 basis sets of different size.
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25

26 METHODS.

27
28 The polymerization of parylene was modeled using semiempirical AM1 and PM6 methods as
29 implemented in Mopac 2007,³⁰ and the density functional theory (DFT) with B3LYP functional using
30 single zeta basis set with polarization (def2-SVP) and triple zeta basis set with polarization (def2-TZVP)
31 as implemented in Turbomole.³¹ Two selected semiempirical methods represent evolution of this class
32 of computational methods over last 30 years. The classical AM1 method was parameterized in 1985 to
33 reproduce molecular properties of around 200 compounds.³² Experimental and ab initio data from over
34 9000 compounds were used to develop the new PM6 method.³³ In the case of semiempirical calculations
35 for molecules with biradical character the lowest singlet energy state, resulting from the mixing of four
36 microstates using configuration interaction (CI) method, was optimized. These microstates included the
37 microstate arising from a one electron excitation from the HOMO to the LUMO; the microstate resulting
38 from the time-reversal operator acting on the parent microstate; the microstate resulting from de-
39 excitation from the formal LUMO to the HOMO; and the microstate resulting from the single electron in
40 the formal HOMO being excited into the LUMO. The lowest singlet energy state in configuration
41 interaction model describes correctly both closed shell and open shell biradical molecules. This allows
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

1 the use of standard methods for a search of the transitions state of each reaction. Energy profiles for
2 breaking of the bond in the paracyclophane molecule and in the linear biradical di-para-xylylene dimer
3 molecule calculated using semiempirical PM6 method with RHF and CI (singlet and triplet state)
4 wavefunctions are compared in Figure 2.
5
6
7
8
9
10

11
12 Figure 2.
13
14
15
16

17 Both closed shell systems: paracyclophane molecule (a minimum for short distance in Fig. 2a) and two
18 monomer xylylene molecules (a minimum for large distance in Fig. 2b) have almost the same heat of
19 formation calculated using RHF and singlet CI model. Open shell biradical di-para-xylylene dimer (a
20 minimum for large distances in Fig 2a and a minimum for short distances in Fig 2b) has the same heat of
21 formation in singlet and triplet state calculated using CI method. Equal energy of singlet and triplet state
22 can be explained by large distance between atomic centers where the single electrons are located in this
23 molecule. RHF model can describe only closed shell paracyclophane and two monomer xylylene
24 molecules. Triplet CI model can describe only the ground state of open shell di-para-xylylene dimer.
25
26 Transition state points for both reactions estimated from maxima on singlet CI profiles are close to the
27 crossing points between RHF and triplet CI profiles. For the first reaction of breaking of the bond in
28 paracyclophane the crossing point between RHF and triplet CI profiles is 8 kcal/mol higher than the
29 maximum on singlet CI profile but appears at the same distance of around 2.5 Å. For the second reaction
30 of breaking bond in biradical di-para-xylylene dimer the crossing point between RHF and triplet CI
31 profiles is 3 kcal/mol lower than the maximum on singlet CI profile and appears at the distance shorter
32 by 0.1 Å.
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50

51 DFT method was selected for this work because it includes dynamic correlation energy without the
52 additional computational overhead as in post-Hartree–Fock methods. B3LYP is the commonly used
53 hybrid density functional which offers a good compromise between computational cost, coverage, and
54 accuracy of results. It has become a standard method used to study organic chemistry in the gas phase.³⁴
55
56
57
58
59
60

1 In the DFT calculations biradical molecules were treated as triplets with UHF method. In the case of
2 reactants and products of different multiplicity, the chemical reaction was modeled using both standard
3 restricted density functional theory (RDFT) and unrestricted density functional theory (UDFT). The
4 transition state energy was estimated from the crossing between two calculated potential energy profiles
5 as shown on Figure 3.
6
7
8
9
10

11
12
13
14 Figure 3.
15
16
17
18

19 Unrestricted density functional theory can be used for the description of open-shell biradicals³⁵
20 especially when overlap between the open-shell orbitals is small and the single electrons are located at
21 different atomic centers as in the case of all molecules studied in this work.
22
23
24
25
26
27

28 **RESULTS AND DISSCUSSION.**

29

30 The first modeled reaction was the pyrolysis reaction of cracking the cyclo-di-para-xylylene dimer
31 ([2.2]paracyclophane) into monomers as shown on Figure 4.
32
33
34
35
36
37

38 Figure 4.
39
40
41
42

43 In this process the system changes multiplicity twice, both a reactant, a cyclic dimer cyclo-di-para-
44 xylylene, and the final product, two monomer para-xylylene molecules, are a close shell molecules. The
45 intermediate product, linear dimer, di-para-xylylene, has biradical character. The results of both
46 semiempirical AM1 and PM6 methods and DFT B3LYP/SVP and B3LYP/TZVP calculations are
47 gathered in Table 1 as energies in kcal/mol relative to the reactant. The absolute values of the heat of
48 formation in kcal/mol and total energies in hartree as calculated for the reactant using semiempirical and
49 DFT methods, respectively, are also show in Table 1. Calculations using DFT method give lower values
50 of both the differences between reactant and product energies and the transition state energies.
51
52
53
54
55
56
57
58
59
60

Table 1

The results of calculations are in a good agreement with the experimental data available for thermolysis reaction of the unsubstituted [2.2]-p-cyclophane (parylene N).²³ As shown in Table1 cyclic dimer (cyclo-di-para-xylylene or [2.2]paracyclophane, DI) is the most stable compound but in high enough temperature can be decomposed into monomers of p-xylylene (M). The highest energy barrier for pyrolysis, necessary to break the first bond in cyclic dimer, is about 50 kcal/mol using both AM1 and PM6 methods and about 43 kcal/mol using DFT B3LYP method with smaller SVP basis set and 40 kcal/mol with larger TZVP basis set. The last value is with a good agreement with the experimental value of 37.7 ± 0.5 kcal/mol. Breaking the second bond in biradical linear dimer (MM) is easier, with energetic barrier of about 42 kcal/mol from AM1, 38 kcal/mol from PM6 methods and about 29 and 28 kcal/mol from DFT calculations with SVP and TZVP basis sets, respectively. The experimental barrier for this reaction is not available. The total enthalpy of the pyrolysis reaction is overestimated by both semiempirical methods, 60 kcal/mol from AM1 and 56 kcal/mol from PM6, and underestimated by DFT B3LYP method using larger TZVP basis set which gives value of 31 kcal/mol. The results from DFT B3LYP method using smaller SVP basis set give perfect agreement with the experimental value of 41.5 kcal/mol. Experimental data are available only for parylene N, and our calculations show only small differences for parylene C and parylene D caused by the substitution of the chlorine atom for one or two of the aromatic hydrogen atoms. The activation energy barriers, the energies of intermediate biradical dimer and the total energy changes during the reaction are on average slightly higher for parylene C and slightly lower for parylene D in comparison to parylene N for both semiempirical and DFT methods. The pyrolysis reaction is also driven by entropy factor (higher entropy of two monomer molecules compared to one dimer molecule), which we did not consider in our modeling.

The monomers after pyrolysis, when temperature is lowered, do not form back cyclic dimer (DI) but instead polymerize into long chain molecules.¹¹ The schematic reaction is show on Figure 5 and results

1 of semiempirical AM1 and PM6 and DFT B3LYP/SVP and B3LYP/TZVP calculations are presented in
2
3 Tables 2-5.
4
5
6

7
8 Figure 5, Table 2
9

10
11 The barrier for reaction between two monomers (Table 2) is around 16 kcal/mol using AM1, and around
12
13 20 kcal/mol using PM6 methods. DFT B3LYP calculations give smaller barrier, around 10 kcal/mol
14
15 using smaller SVP basis set and around 15 kcal/mol using larger TZVP basis set. All computational
16
17 methods show that this is an exothermic reaction, with biradical dimer having lower energy compared to
18
19 two monomers. There is no experimental measurement for the activation barrier of this reaction. The
20
21 experimental energetic effect of the biradical dimer formation starting from two monomers is around 14
22
23 kcal/mol, but this value has a substantial uncertainty. Both semiempirical methods and the DFT
24
25 calculations with smaller SVP basis set overestimate this value, while the DFT calculations with larger
26
27 TZVP basis set underestimate it. Results obtained for this reaction are similar for all types of parylene.
28
29
30
31
32
33
34

35
36 Table 3
37
38
39

40 The data for next reaction, between monomer (M) and biradical linear dimer (MM) forming biradical
41
42 trimer (MMM), are presented in Table 3. The barrier in this reaction is around 7 kcal/mol using AM1
43
44 and 9 kcal/mol using PM6 methods, and only around 1-3 kcal/mol from DFT calculations depending on
45
46 the basis set. This is a much lower barrier than the barrier of forming cyclic dimer (DI), which is around
47
48 15 kcal/mol using DFT method with larger basis set or AM1 semiempirical method, around 10 kcal/mol
49
50 using DFT with smaller basis set, and around 20 kcal/mol using PM6 semiempirical method (a reaction
51
52 reverse to this is shown in Table 1). The difference between energy barrier of the reaction of two
53
54 monomers and monomer with biradical dimer explains why existing chain molecules are growing faster
55
56 in comparison to forming of a new chain, which must be initiated by creating the new linear biradical
57
58
59
60

1 dimer. We have also modeled reactions between a monomer and tri- and tetramer to form tetramer and
2 pentamer, respectively. As shown in Tables 4 and 5 barriers and energetic effects for these reactions are
3 similar to reaction between a monomer and biradical dimer.
4
5
6
7
8

9
10 Table 4, Table 5
11

12
13
14 Both semiempirical methods, AM1 and PM6, give worse agreement with available experimental data
15 compared to DFT B3LYP calculations. Correct description of biradical molecules is very important for
16 current study, however parameterization of AM1 and PM6 methods is focused on close shell molecules.
17 The DFT method gives better agreement but surprisingly in some cases larger basis set, TZVP, gives
18 worse agreement with experiment than smaller basis set SVP. The possible explanation of this result is
19 an error cancellation for smaller basis set. An approximation of height of barrier of reactions calculated
20 by DFT method from the crossing between two calculated potential energy profiles can produce large
21 errors.
22
23
24
25
26
27
28
29
30
31
32
33
34

35 CONCLUSION

36
37 The three reactions modeled: pyrolytic decomposition of paracyclophane (a cyclic dimer of p-
38 xylylene); the initiation reaction between two p-xylylene monomers; and the first propagation step of
39 parylene polymerization, formation of the trimer are summarized on Fig.6.
40
41
42
43
44
45
46

47 Figure 6
48
49
50
51

52 The pyrolytic decomposition of paracyclophane into two monomers is an endothermic reaction with
53 the total calculated barrier around 45 kcal/mol. The calculated values are in moderate agreement with
54 available experimental data. The initiation reaction of formation of biradical linear dimer from two
55 monomers is an exothermic reaction with the activation barrier around 15 kcal/mol. There are no direct
56
57
58
59
60

1 experimental data to compare with this value. The reaction of propagation of parylene polymerization is
2 also exothermic with much smaller calculated activation barrier of around 3 kcal/mol. The experimental
3 value of the activation energy for propagation, 8.7 kcal/mol, comes from measurement in solution not in
4 vacuo, and there is no standard deviation available and this value.¹⁵ The results of our calculations
5 confirm the generally accepted mechanism of polymerization of para-xylylene based polymers: a high
6 activation barrier for paracyclophane decomposition, a moderate activation barrier for initiation reaction
7 between two monomer p-xylylene molecules, and a low activation barrier for propagation reaction
8 between a monomer p-xylylene molecule and a biradical chain molecule.

9
10
11
12
13
14
15
16
17
18
19 The details of calculated energy profiles provide a new physical insight into reaction mechanism of
20 polymerization of p-xylylene based polymers. To date, there are no experimental data for all details of
21 both profiles, but a good agreement between our theoretical values and available experimental data can
22 prove the reliability of our modeling. Our calculations show that a high activation barrier for
23 paracyclophane decomposition is not a result of the high energy of intermediate product, biradical
24 dimer, and that the highest potential energy during the [2.2]paracyclophane decomposition into two
25 monomers is the transition state for breaking the second bond between two monomers in the biradical
26 dimer. Theoretical modeling proves that the initiation reaction for polymerization of para-xylylene is the
27 reaction between two monomers. The reaction for forming the biradical trimer has the same energy
28 profile as any reaction between biradical oligomer and monomer (we calculated formations of oligomers
29 up to pentamer). This result support the model of polymerization mechanism proposed by Szwarc¹² but
30 is in disagreement with many proposed mechanisms assuming that initiation reaction is the formation of
31 the trimer and not the dimer. Our results show that the low activation barrier for propagation reaction is
32 due to reactivity of biradical chain molecule. Biradical chain molecule is more reactive than closed shell
33 monomer. This is a good starting point for modeling of mechanism of copolymerization or reactions of
34 parylene with suitable substrate during the CVD polymerization leading to modified layer of parylene
35 over the reactive substrate.³⁶ This research is in progress in our laboratory.

ACKNOWLEDGMENT

1
2
3
4 This work was supported by the MULTIPOL project STREP n°033201 funded by the European
5
6 Commission under the 6th Framework Program, and by a grant from the Polish Ministry of Science and
7
8 Education (399/6PRUE/2007/7). This research was conducted using the resources of the Informatics
9
10 Center of the Metropolitan Academic Network (IC MAN) in Gdańsk, and our own Linux cluster at the
11
12 Faculty of Chemistry, University of Gdańsk.
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

References

- 1
2
3 (1) Fortin, J. B.; Lu, T. M. *Chemical vapor deposition polymerization : the growth and properties of*
4 *parylene thin films*; Kluwer: Boston, 2004.
- 5
6 (2) Szwarc, M. Some Remarks on the $\text{CH}_2=\text{C}_6\text{H}_4=\text{CH}_2$ Molecule. *Discuss. Faraday Soc.* **1947**, 2, 46-49.
- 7
8 (3) Gorham, W. F. A New General Synthetic Method for Preparation of Linear Poly-P-Xylylenes. *J.*
9 *Polym. Sci. Pol. Chem.* **1966**, 4, 3027-3039.
- 10
11 (4) Tracton, A. A. *Coatings technology handbook*; CRC Press: Boca Raton, 2005.
- 12
13 (5) Hopf, H. [2.2]Paracyclophanes in Polymer Chemistry and Materials Science. *Angew. Chemie - Int.*
14 *Ed.* **2008**, 47, 9808-9812.
- 15
16 (6) Lahann, J.; Klee, D.; Hocker, H. Chemical Vapour Deposition Polymerization of Substituted
17 [2.2]Paracyclophanes. *Macromol. Rapid Commun.* **1998**, 19, 441-444.
- 18
19 (7) Lahann, J.; Langer, R. Novel Poly(p-Xylylenes): Thin Films with Tailored Chemical and Optical
20 Properties. *Macromolecules* **2002**, 35, 4380-4386.
- 21
22 (8) Lahann, J. Vapor-Based Polymer Coatings for Potential Biomedical Applications. *Polym. Int.* **2006**,
23 55, 1361-1370.
- 24
25 (9) Bondarenko, L.; Dix, I.; Hinrichs, H.; Hopf, H. Cyclophanes. Part LII: Ethynyl[2.2]Paracyclophanes
26 - New Building Blocks for Molecular Scaffolding. *Synthesis* **2004**, 16, 2751-2759.
- 27
28 (10) Hopf, H.; Gerasimov, G. N.; Chvalun, S. N.; Rozenberg, V. I.; Popova, E. L.; Nikolaeva, E. V.;
29 Grigoriev, E. I.; Zavjalov, S. A.; Trakhtenberg, L. I. Metal-Containing Poly(p-Xylylene) Films by
30 CVD: Poly(p-Xylylene) with Germanium Crystals. *Chem. Vap. Deposition* **1997**, 3, 197-200.
- 31
32 (11) Errede, L. A.; Szwarc, M. Chemistry of P-Xylylene, its Analogues, and Polymers. *Quarterly*
33 *Reviews* **1958**, 12, 301-320.
- 34
35 (12) Szwarc, M. Poly-Para-Xylelene - its Chemistry and Application in Coating Technology. *Polym.*
36 *Eng. Sci.* **1976**, 16, 473-479.
- 37
38 (13) Beach, W. F.; Lee, C.; Bassett, D. R.; Austin, T. M.; Olson, R. In *Xylylene polymers*; Encyclopedia
39 of polymer science and engineering; Wiley: New York, 1988; .
- 40
41 (14) Beach, W. F. A Model for Vapor-Deposition Polymerization of Para-Xylylene. *Macromolecules*
42 **1978**, 11, 72-76.
- 43
44 (15) Errede, L. A.; Gregorian, R. S.; Hoyt, J. M. The Chemistry of Xylylenes .6. the Polymerization of
45 Para-Xylylene. *J. Am. Chem. Soc.* **1960**, 82, 5218-5223.
- 46
47 (16) Kubo, S.; Wunderli.B Crystallization during Polymerization of Poly-P-Xylylene. *Journal of*
48 *Polymer Science Part B-Polymer Physics* **1972**, 10, 1949-1966.
- 49
50 (17) Kramer, P.; Sharma, A. K.; Hennecke, E. E.; Yasuda, H. Polymerization of Para-Xylylene
51 Derivatives (Parylene Polymerization) .1. Deposition Kinetics for Parylene-N and Parylene-C. *J.*
52 *Polym. Sci. Pol. Chem.* **1984**, 22, 475-491.
- 53
54 (18) Greiner, A.; Mang, S.; Schafer, O.; Simon, P. Poly(p-Xylylene)s: Synthesis, Polymer Analogous
55 Reactions, and Perspectives on Structure-Property Relationships. *Acta Polym.* **1997**, 48, 1-15.
- 56
57
58
59
60

- 1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
- (19) Gazicki, M.; Surendran, G.; James, W.; Yasuda, H. Polymerization of Para-Xylylene Derivatives (Parylene Polymerization) .3. Heat-Effects during Deposition of Parylene-N at Different Temperatures. *J. Polym. Sci. Pol. Chem.* **1986**, *24*, 215-240.
- (20) Lee, T.; Lee, J.; Park, C. Characterization of Parylene Deposition Process for the Passivation of Organic Light Emitting Diodes. *Korean J. Chem. Eng.* **2002**, *19*, 722-727.
- (21) Fortin, J. B.; Lu, T. M. A Model for the Chemical Vapor Deposition of Poly(Para-Xylylene) (Parylene) Thin Films. *Chem. Mater.* **2002**, *14*, 1945-1949.
- (22) Bowie, W.; Zhao, Y. P. Monte Carlo Simulation of Vapor Deposition Polymerization. *Surf. Sci.* **2004**, *563*, L245-L250.
- (23) Roth, W. R.; Hopf, H.; deMeijere, A.; Hunold, F.; Borner, S.; Neumann, M.; Wasser, T.; Szurowski, J.; Mlynek, C. Radical Recombination Enthalpy. Thermochemistry of the Ringopening of Cyclophanes. *Liebigs Annalen* **1996**, , 2141-2154.
- (24) Nishiyama, K.; Sakiyama, N.; Seki, S.; Horita, H.; Otsubo, T.; Misumi, S. Thermochemical Studies on Double-Layered and Triple-Layered [2.2]Paracyclophanes - Estimation of Molecular Strain Energies. *Bull. Chem. Soc. Jpn.* **1980**, *53*, 869-877.
- (25) Boyd, R. H. Heat of Combustion and Strain Energy of 2,2-Paracyclophane. *Tetrahedron* **1966**, *22*, 119-122.
- (26) Pollack, S. K.; Raine, B. C.; Hehre, W. J. Determination of the Heats of Formation of the Isomeric Xylylenes by Ion-Cyclotron Double-Resonance Spectroscopy. *J. Am. Chem. Soc.* **1981**, *103*, 6308-6313.
- (27) Reich, H. J.; Cram, D. J. Macro Rings .36. Ring Expansion Racemization and Isomer Interconversions in [2.2]Paracyclophane System through a Diradical Intermediate. *J. Am. Chem. Soc.* **1969**, *91*, 3517-&.
- (28) Fortin, J. B.; Lu, T. M. Mass Spectrometry Study during the Vapor Deposition of Poly-Para-Xylylene Thin Films. *J. Vac. Sci. Technol. A* **2000**, *18*, 2459-2465.
- (29) Alexandrova, L.; Salcedo, R. Pathway for Polymerization of P-Xylylenes. *Polymer* **1994**, *35*, 4656-4658.
- (30) Stewart, J. J. P. *MOPAC2007*; Stewary Computational Chemistry: Colorado Springs, 2007; <http://OpenMOPAC.new>.
- (31) Von Arnim, M.; Ahlrichs, R. Performance of Parallel TURBOMOLE for Density Functional Calculations. *J. Comput. Chem.* **1998**, *19*, 1746-1757.
- (32) Dewar, M. J. S.; Zoebisch, E. G.; Healy, E. F.; Stewart, J. J. P. The Development and use of Quantum-Mechanical Molecular-Models .76. Am1 - a New General-Purpose Quantum-Mechanical Molecular-Model. *J. Am. Chem. Soc.* **1985**, *107*, 3902-3909.
- (33) Stewart, J. J. P. Optimization of Parameters for Semiempirical Methods V: Modification of NDDO Approximations and Application to 70 Elements. *J. Mol. Model.* **2007**, *13*, 1173-1213.
- (34) Tirado-Rives, J.; Jorgensen, W. L. Performance of B3LYP Density Functional Methods for a Large Set of Organic Molecules. *J. Chem. Theory Comput.* **2008**, *4*, 297-306.

- 1 (35) Grafenstein, J.; Kraka, E.; Filatov, M.; Cremer, D. Can Unrestricted Density-Functional Theory
2 Describe Open Shell Singlet Biradicals? *Int. J. Mol. Sci.* **2002**, *3*, 360-394.
- 3 (36) Bolognesi, A.; Botta, C.; Andicsova, A.; Giovanella, U.; Arnautov, S.; Charmet, J.; Laux, E.;
4 Keppner, H. Chemical Binding of Unsaturated Fluorenes to Poly(2-Chloroxylylene) Thin Films.
5 *Macromol. Chem. Phys.* **2009**, *210*, 2052-2057.
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

FIGURE CAPTIONS

Fig 1. The structures of three commercially most popular p-xylylene based polymers.

Fig 2. Energy profiles for breaking of the bond in paracyclophane molecule **(a)** and in a linear biradical di-para-xylylene dimer molecule **(b)** calculated using semiempirical PM6 method. Changes in heat of formation calculated using closed shell model (RHF, solid line) are compared with those calculated using configuration interaction (CI) method and singlet (dashed line) or triplet (dotted line) state. Singlet CI model describes correctly both closed shell systems: paracyclophane for short distance in **(a)** and two monomer xylylene molecules for larger distance in **(b)**, and an open shell biradical di-para-xylylene dimer for the larger distances in **(a)** and shorter distances in **(b)**. For the mixing of four microstates triplet CI model gives the same energy as singlet CI for the biradical linear di-para-xylylene dimer. Transition state energies for both reactions estimated from maxima on singlet CI profiles are compared to the crossing points between RHF and triplet CI profiles.

Fig 3. (a) Energy profiles for breaking of the bond in paracyclophane molecule calculated using closed shell model (RHF) and open shell model (UHF) with B3LYP/SVP and B3LYP/TZVP method. Energies of closed shell dimer were used as zero energy baselines for both methods. The cyclic dimer, paracyclophane molecule, is a closed shell molecule (RHF, solid line, gives the lowest energy for the ground state with short distance and the intact bond) but the first step of decomposition reaction produces open shell biradical product, the linear dimer (UHF, dashed line, gives lower energies for larger distances with the broken bond). **(b)** Energy profiles for breaking of the bond in a linear biradical di-para-xylylene dimer molecule calculated using closed shell model (RHF) and open shell model (UHF) with B3LYP/SVP and B3LYP/TZVP method. As in Fig 2a, energies of closed shell paracyclophane dimer were used as zero energy baselines for both methods. The linear di-para-xylylene dimer is an open shell molecule (UHF, dashed line, gives the lowest energy for the ground state with short distance and the intact bond) but the second step of decomposition reaction produces close shell

1 products, two monomeric para-xylylene molecules (RHF, solid line, gives lower energies for larger
2 distances with the broken bond). Transition state energies for both reactions were estimated from
3
4 crossing between RHF and UHF profiles. In case of larger basis set B3LYP/TZVP method only points
5
6 around the transition state and for stable reactants and products were calculated.
7
8

9
10 **Fig 4.** Scheme of cracking of the cyclo-di-para-xylylene dimer into monomers in the pyrolysis reaction.
11

12
13 **Fig 5.** Schemes of the initiation reaction of polymerization of parylene and the first propagation step of
14 the biradical di-para-xylylene dimer reaction with the monomer forming the biradical trimer.
15
16

17
18 **Fig.6.** Energy profiles from the DFT B3LYP/TZVP calculations for the pyrolysis reaction of cracking
19 the cyclo-di-para-xylylene dimer ([2.2]paracyclophane) into monomers (top); and the initiation reaction
20 and the first propagation step of parylene polymerization (bottom). The energy scale on the left uses the
21 energy of cyclo-di-para-xylylene as zero, the available experimental values are shown in parenthesis for
22 comparison.
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

Table 1. Relative to the reactant energies (kcal/mol) for various species in the reaction of cracking of the cyclic dimer (DI^a) into two monomers (M^c) calculated at different levels of theory for parylene N, C and D. For the reactants (DI) the absolute values of calculated energies are shown. Experimental reference data are available only for parylene N.

	DI ^a	DI/MM ^b	MM ^c	MM/M+M ^d	M+M ^e
parylene N					
AM1	59.839 ^f	51.887	34.621	76.581	59.955
PM6	50.963 ^f	50.657	39.663	77.302	56.584
B3LYP SVP//SVP	-618.4482598990 ^g	43.062	23.364	52.207	41.595
B3LYP SVP//TZVP	-619.1065393245 ^g	39.565	18.493	46.606	31.304
B3LYP TZVP//TZVP	-619.1083035010 ^g	39.821	18.434	46.481	31.133
Exp. ^{23, 24, 26}	58.5±0.5 ^f	37.7±0.5	25.7±1.5	n/a	41.5±4.5
Parylene C					
AM1	47.035 ^f	51.808	35.193	76.768	56.424
PM6	29.214 ^f	51.172	41.228	78.442	56.348
B3LYP SVP//SVP	-1537.260995702 ^g	43.588	25.060	54.302	44.822
B3LYP SVP//TZVP	-1538.235887620 ^g	40.059	20.471	46.095	33.609
B3LYP TZVP//TZVP	-1538.237685220 ^g	39.941	20.424	48.375	33.482
Parylene D					
AM1	36.000 ^f	51.268	34.829	75.930	55.901
PM6	12.936 ^f	50.824	38.981	75.744	53.907
B3LYP SVP//SVP	-2456.061840702 ^g	43.114	21.215	50.523	40.858
B3LYP SVP//TZVP	-2457.353619613 ^g	39.621	16.446	44.444	29.932
B3LYP TZVP//TZVP	-2457.354993232 ^g	38.639	16.169	44.071	29.451

^a reactant, paracyclophane molecule; ^b transition state for the reaction of breaking the first bond in paracyclophane; ^c biradical dimer; ^d transition state for the reaction of breaking the second bond, ^e product, two p-xylylene monomer molecules; ^f heat of formation of the reactant in kcal/mol; ^g absolute total energy in Hartree for the reactant

Table 2. Relative to the reactant energies (kcal/mol) for transition state and product for the reaction of two monomers forming biradical dimer calculated at different levels of theory for parylene N, C and D. For the reactants (M+M) the absolute values of calculated energies are shown. Experimental reference data are available only for parylene N.

	M+M ^a	M+M/MM ^b	MM ^c
parylene N			
AM1	119.794 ^d	16.625	-25.335
PM6	107.548 ^d	20.718	-16.921
B3LYP SVP//SVP	-618.3819744756 ^e	10.613	-18.230
B3LYP SVP//TZVP	-619.0566527226 ^e	15.302	-12.811
B3LYP TZVP//TZVP	-619.0586905636 ^e	15.348	-12.698
Exp. ^{23, 26}	100±8 ^d	n/a	-14.2±5.0
parylene C			
AM1	103.459 ^d	20.350	-21.231
PM6	85.562 ^d	22.095	-15.120
B3LYP SVP//SVP	-1537.189567172 ^e	9.481	-19.762
B3LYP SVP//TZVP	-1538.182327324 ^e	12.486	-13.138
B3LYP TZVP//TZVP	-1538.184327261 ^e	14.892	-13.058
parylene D			
AM1	91.901 ^d	20.032	-21.072
PM6	66.844 ^d	21.836	-14.926
B3LYP SVP//SVP	-2455.996728480 ^e	9.664	-19.643
B3LYP SVP//TZVP	-2457.305919033 ^e	14.511	-13.486
B3LYP TZVP//TZVP	-2457.308059982 ^e	14.620	-13.282

^a reactants, two p-xylylene molecules; ^b transition state for the initiation reaction of forming the biradical dimer; ^c biradical dimer; ^d heat of formation of the reactants in kcal/mol; ^e absolute total energy in Hartree for the reactants

Table 3. Relative to the reactants energies (kcal/mol) for transition state and products for the first step of propagation reaction of a monomer with biradical dimer forming biradical trimer calculated at different levels of theory for parylene N, C and D. For the reactants (MM+M) the absolute values of calculated energies are shown.

	MM+M ^a	MM+M/MMM ^b	MMM ^c
parylene N			
AM1	154.268 ^d	7.467	-47.165
PM6	143.265 ^d	9.710	-40.483
B3LYP SVP//SVP	-928.6083741428 ^e	1.760	-40.183
B3LYP SVP//TZVP	-928.6054064264 ^e	3.137	-35.438
B3LYP TZVP/TZVP	-928.6083741428 ^e	3.374	-35.213
parylene C			
AM1	135.813 ^d	7.251	-46.983
PM6	113.362 ^d	8.593	-41.262
B3LYP SVP//SVP	-2305.815947413 ^e	1.145	-41.065
B3LYP SVP//TZVP	-2307.294556202 ^e	2.862	-35.808
B3LYP TZVP/TZVP	-2307.297341500 ^e	2.896	-35.814
parylene D			
AM1	118.426 ^d	7.267	-46.603
PM6	84.757 ^d	9.124	-40.588
B3LYP SVP//SVP	-3684.027265700 ^e	1.317	-40.871
B3LYP SVP//TZVP	-3685.980417783 ^e	2.456	-36.236
B3LYP TZVP/TZVP	-3685.983376906 ^e	2.461	-36.027

^a reactants, biradical dimer and a p-xylylene molecule; ^b transition state for the propagation reaction of forming the biradical trimer; ^c biradical trimer; ^d heat of formation of the reactants in kcal/mol; ^e absolute total energy in Hartree for the reactants

Table 4. Relative to the reactants energies (kcal/mol) for transition state and products for the second step of propagation reaction of a monomer with biradical trimer forming biradical tetramer calculated at different levels of theory for parylene N, C and D. For the reactants (MMM+M) the absolute values of calculated energies are shown.

	MMM+M ^a	MMM+M/MMMM ^b	MMMM ^c
parylene N			
AM1	166.356 ^d	7.953	-46.713
PM6	155.209 ^d	9.891	-40.384
B3LYP SVP//SVP	-1236.921990671 ^e	2.117	-39.812
B3LYP SVP//TZVP	-1238.190328402 ^e	3.230	-35.327
B3LYP TZVP/TZVP	-1238.194063441 ^e	3.228	-35.429
parylene C			
AM1	142.377 ^d	7.161	-47.034
PM6	114.572 ^d	8.960	-40.928
B3LYP SVP//SVP	-3074.478126195 ^e	2.205	-39.806
B3LYP SVP//TZVP	-3076.442992874 ^e	2.967	-35.625
B3LYP TZVP/TZVP	-3076.446859126 ^e	3.024	-35.564
parylene D			
AM1	119.379 ^d	7.183	-46.763
PM6	77.002 ^d	9.054	-40.691
B3LYP SVP//SVP	-4912.090459006 ^e	0.760	-41.591
B3LYP SVP//TZVP	-4914.691215035 ^e	2.586	-36.059
B3LYP TZVP/TZVP	-4914.694916713 ^e	2.656	-35.956

^a reactants, biradical trimer and a p-xylylene molecule; ^b transition state for the propagation reaction of forming the biradical tetramer; ^c biradical tetramer; ^d heat of formation of the reactants in kcal/mol; ^e absolute total energy in Hartree for the reactants

Table 5. Relative to the reactants energies (kcal/mol) for transition state and products for the third step of propagation reaction of a monomer with biradical tetramer forming biradical pentamer calculated at different levels of theory for parylene N, C and D. For the reactants (MMMM+M) the absolute values of calculated energies are shown.

	MMMM+M ^a	MMMM+M/MMMMMM ^b	MMMMM ^c
parylene N			
AM1	179.450 ^d	7.402	-47.264
PM6	167.455 ^d	9.658	-40.575
B3LYP SVP//SVP	-1546.113187153 ^e	1.829	-40.143
B3LYP SVP//TZVP	-1547.775140025 ^e	3.205	-35.434
B3LYP TZVP/TZVP	-1547.779530559 ^e	3.402	-35.218
parylene C			
AM1	148.594 ^d	7.382	-46.756
PM6	116.210 ^d	8.865	-41.005
B3LYP SVP//SVP	-3843.136479708 ^e	1.024	-41.063
B3LYP SVP//TZVP	-3845.590988954 ^e	2.818	-35.850
B3LYP TZVP/TZVP	-3845.595564644 ^e	2.826	-35.854
parylene D			
AM1	120.139 ^d	7.248	-46.615
PM6	69.210 ^d	8.988	-40.760
B3LYP SVP//SVP	-6140.154488006 ^e	0.581	-41.643
B3LYP SVP//TZVP	-6143.401762053 ^e	2.591	-36.008
B3LYP TZVP/TZVP	-6143.406218852 ^e	2.462	-35.976

^a reactants, biradical tetramer and a p-xylylene molecule; ^b transition state for the propagation reaction of forming the biradical pentamer; ^c biradical pentamer; ^d heat of formation of the reactants in kcal/mol; ^e absolute total energy in Hartree for the reactants

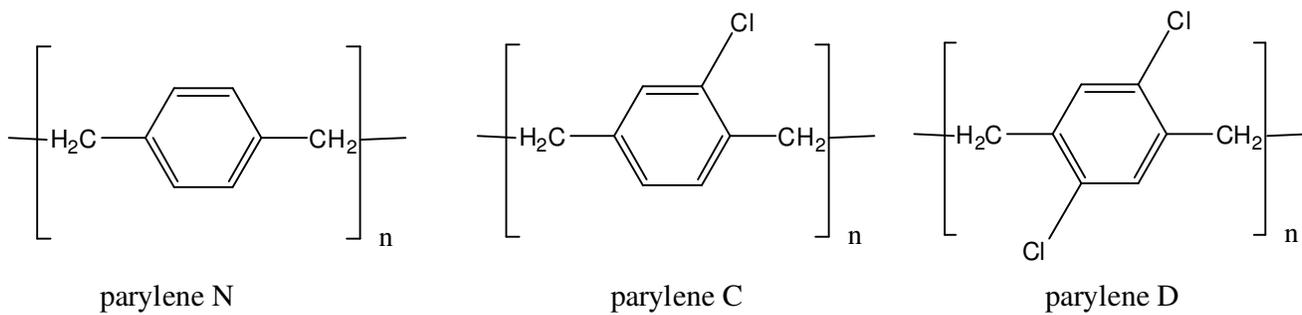


Figure 1.

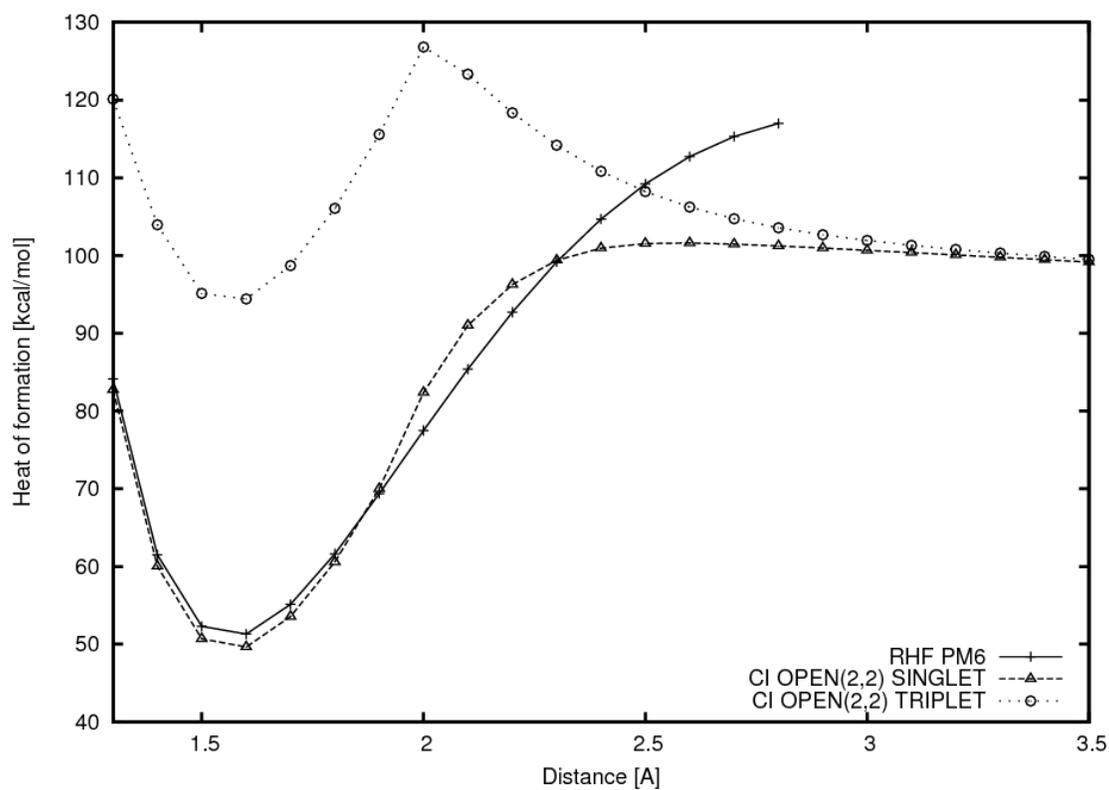


Figure 2a.

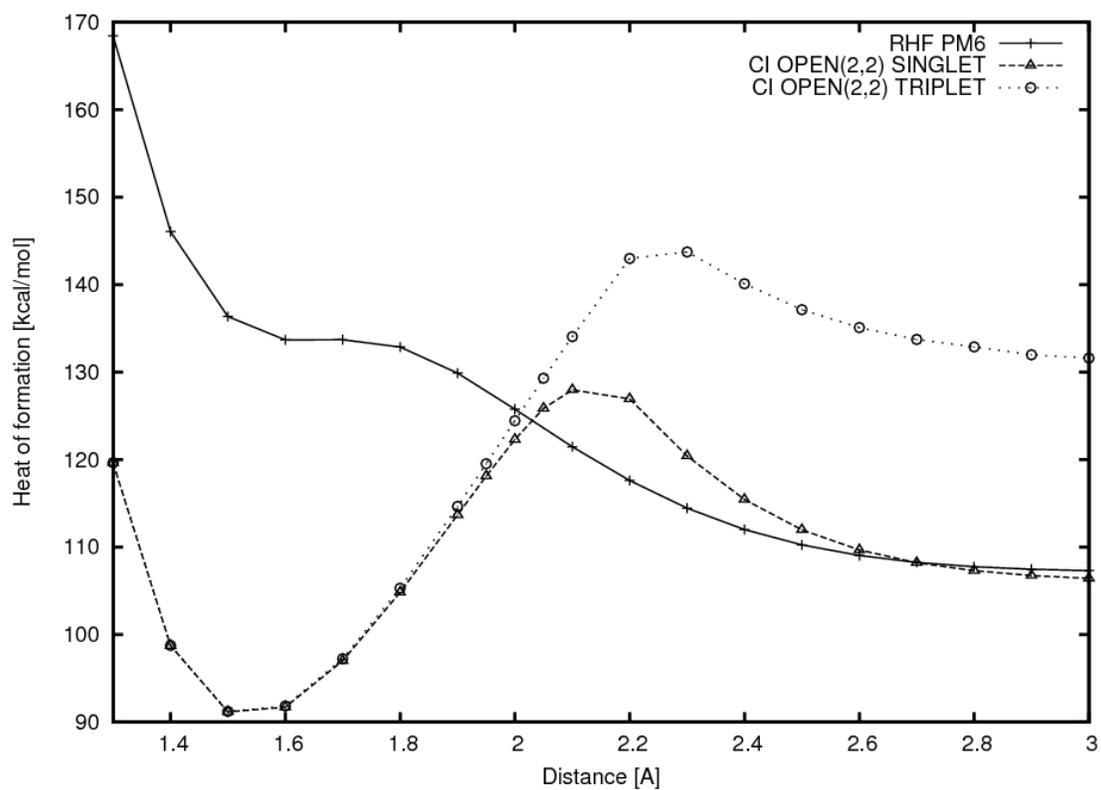


Figure 2b.

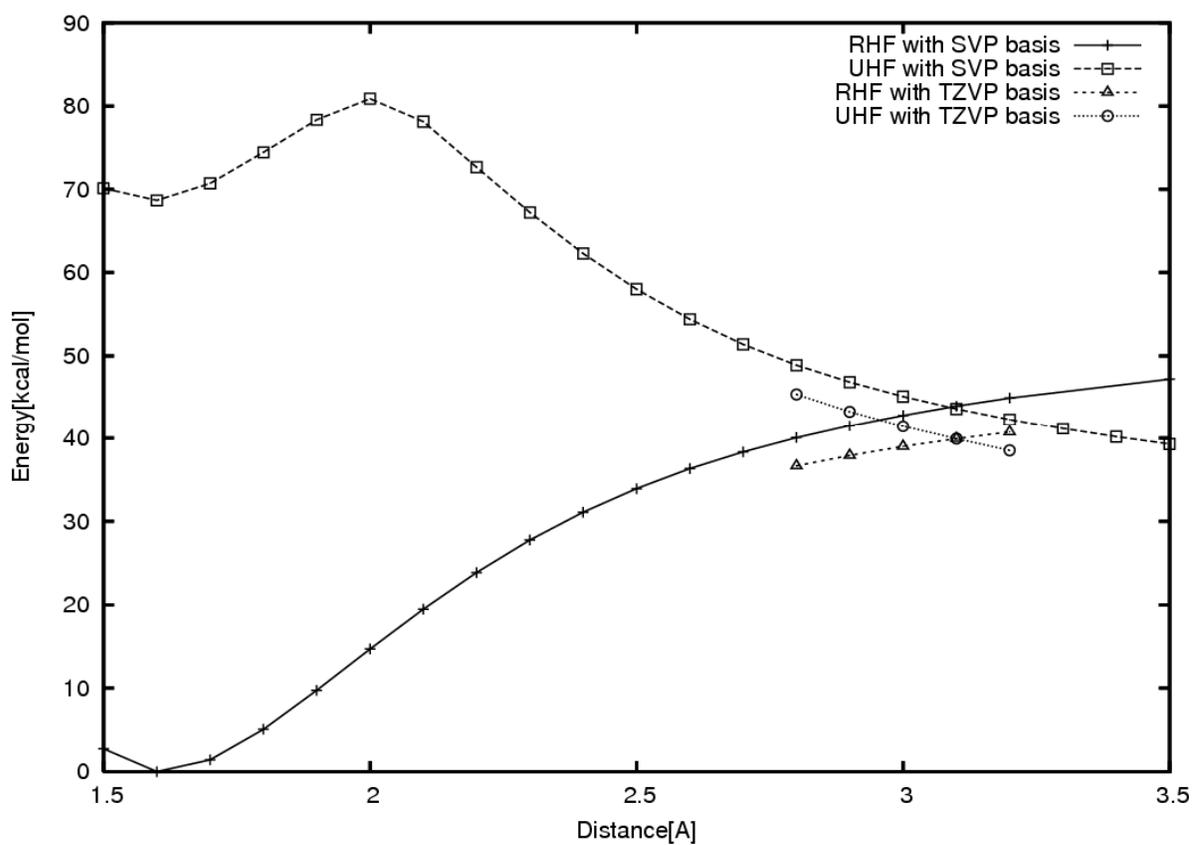


Figure 3a.

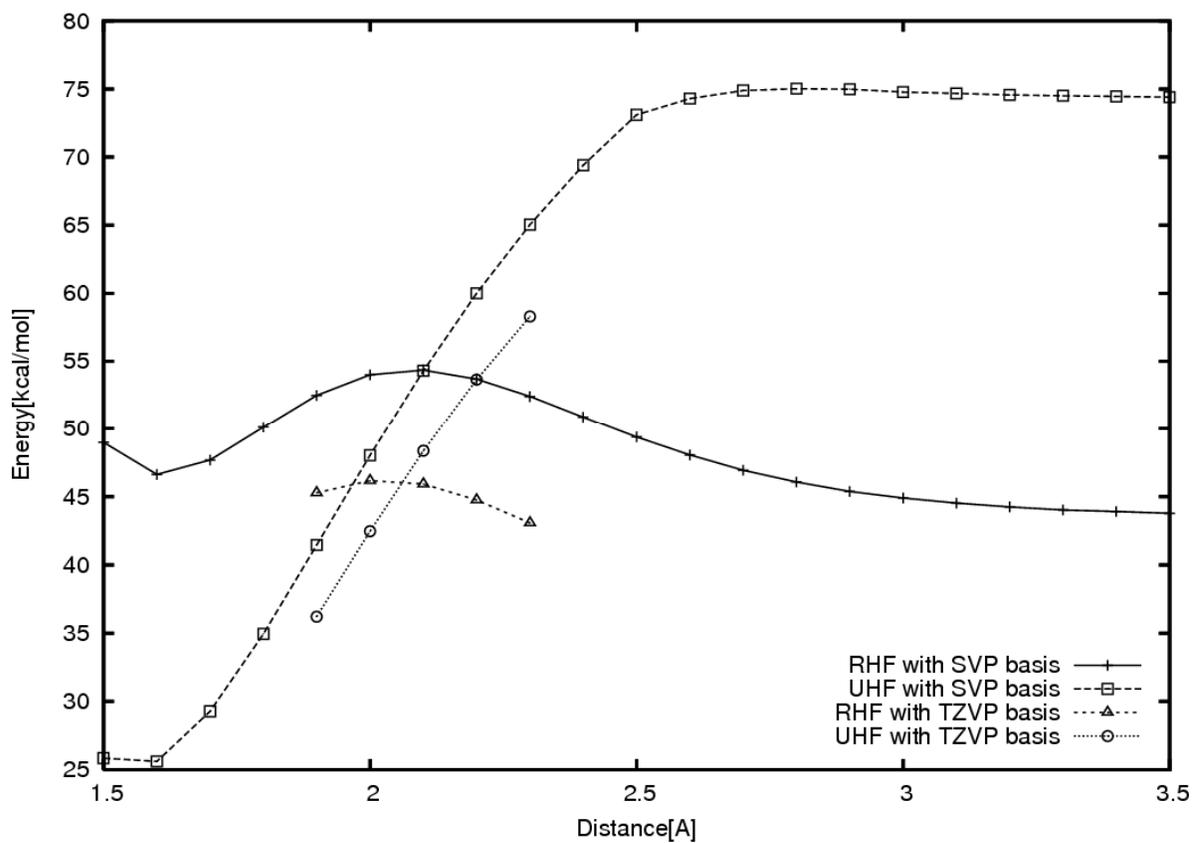


Figure 3b.

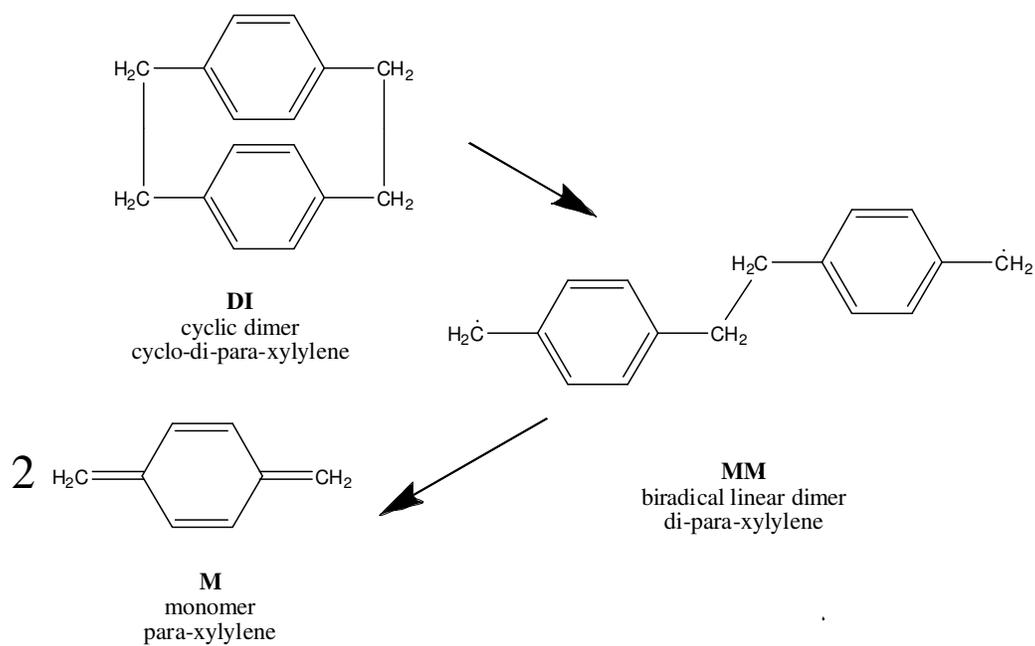


Figure 4.

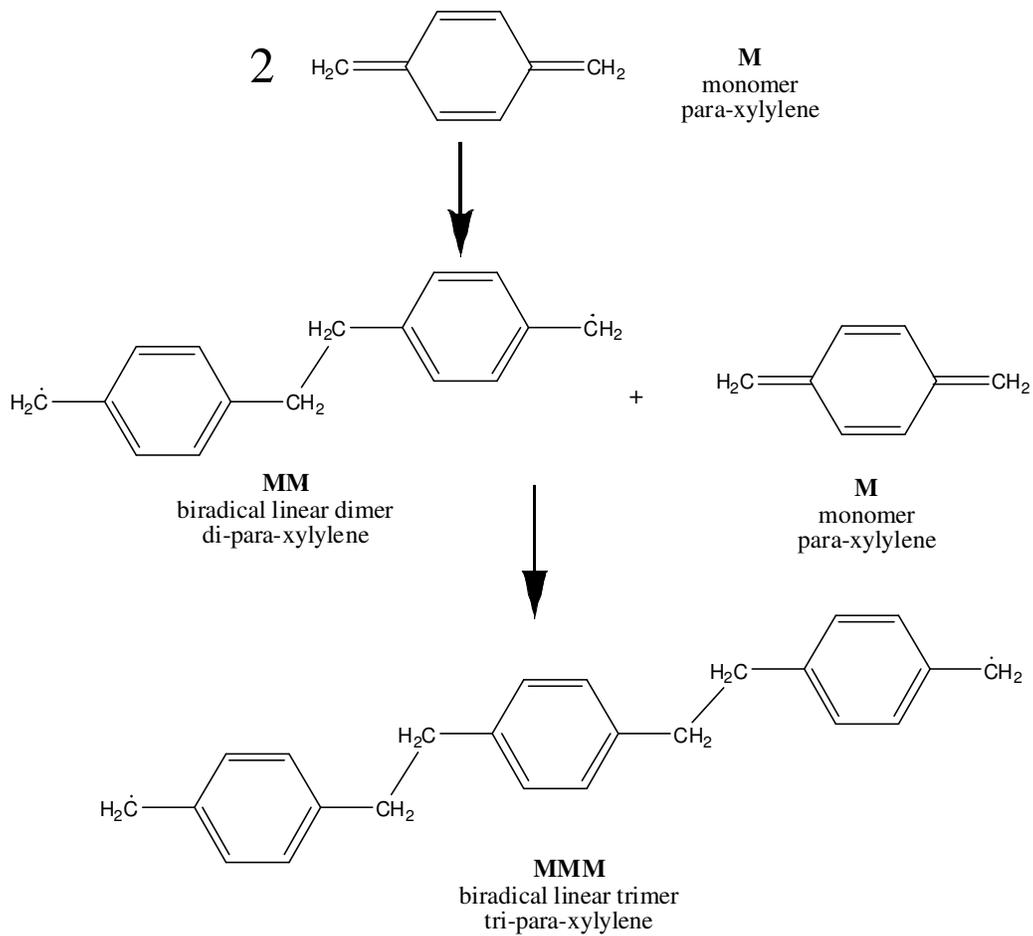


Figure 5.

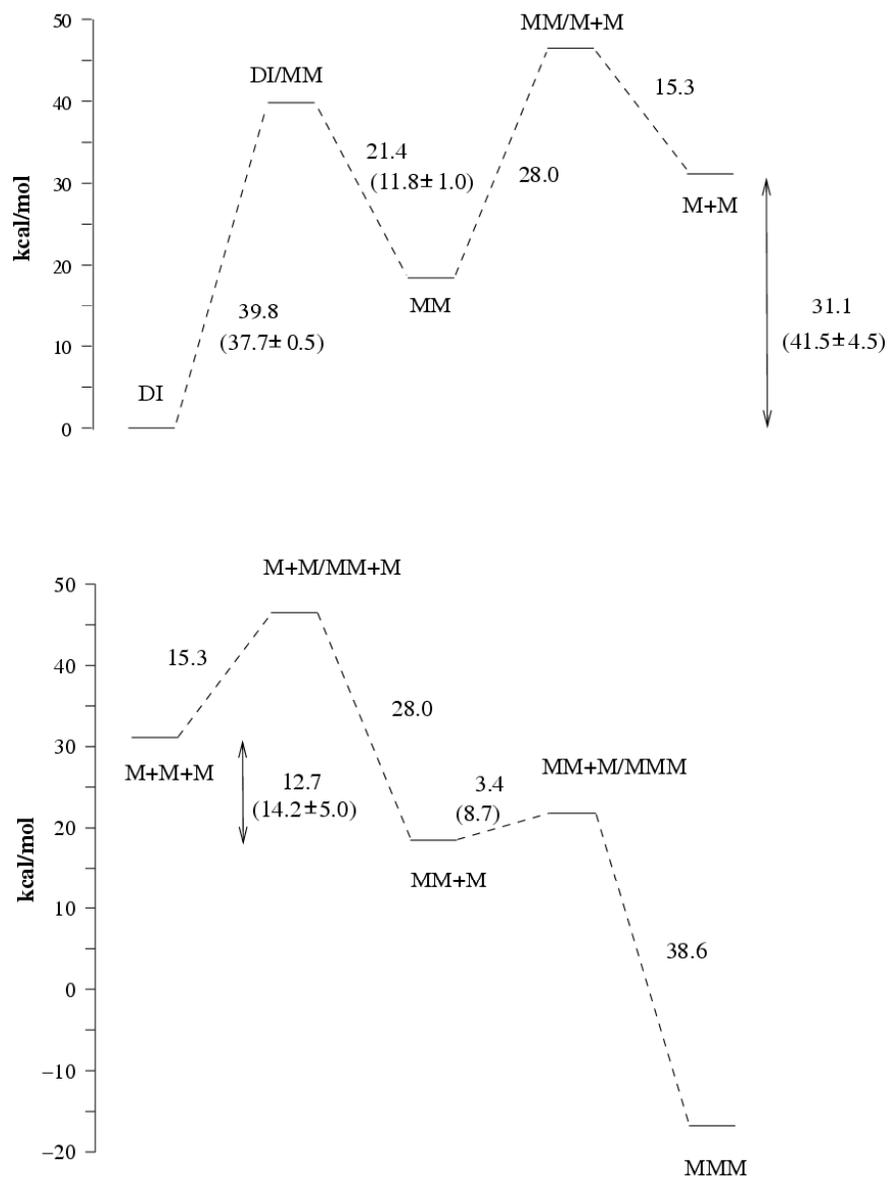
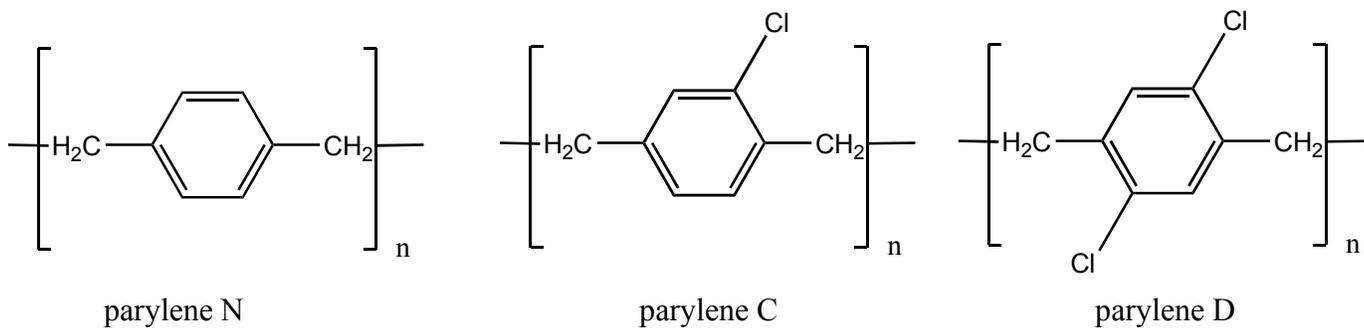
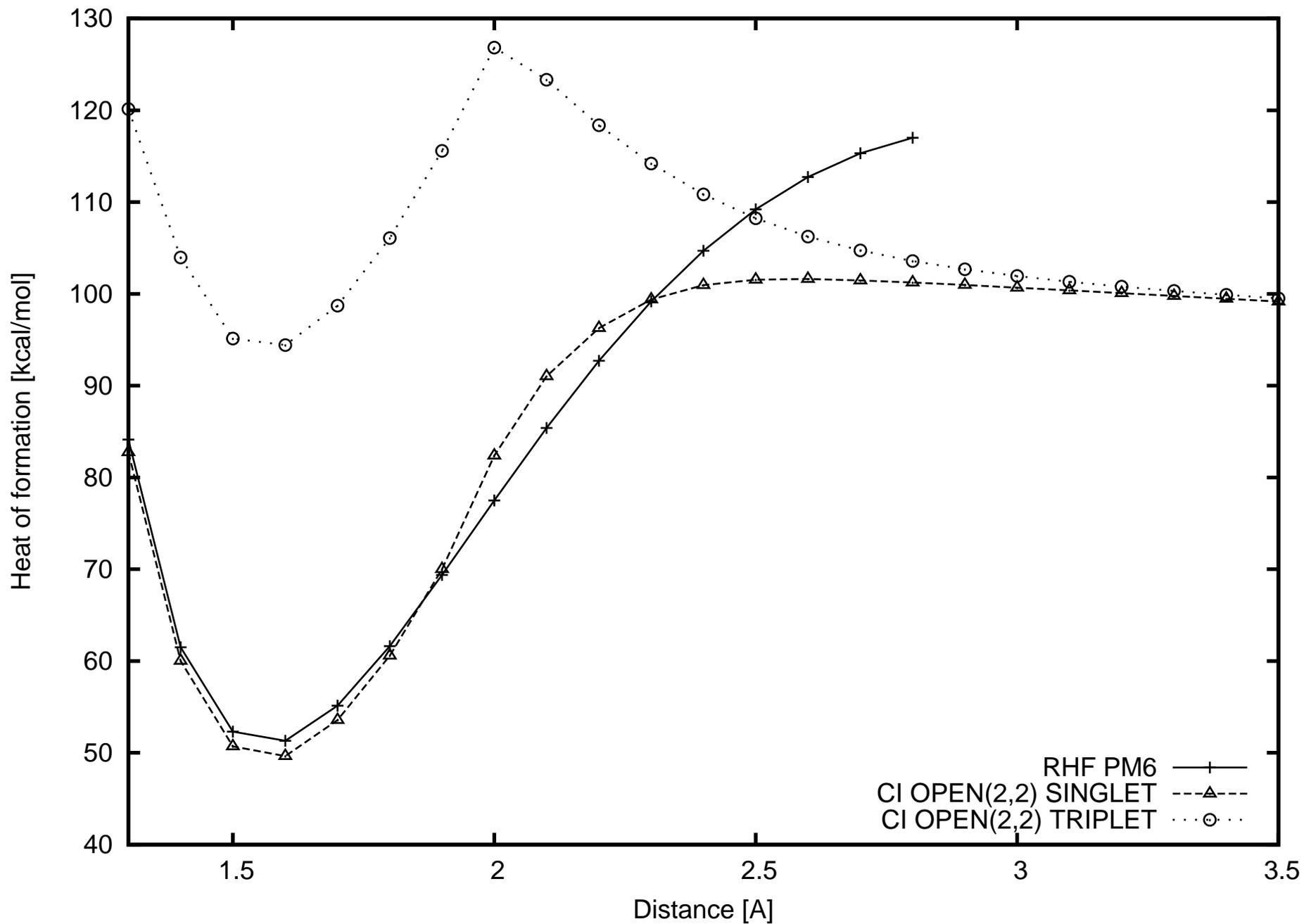
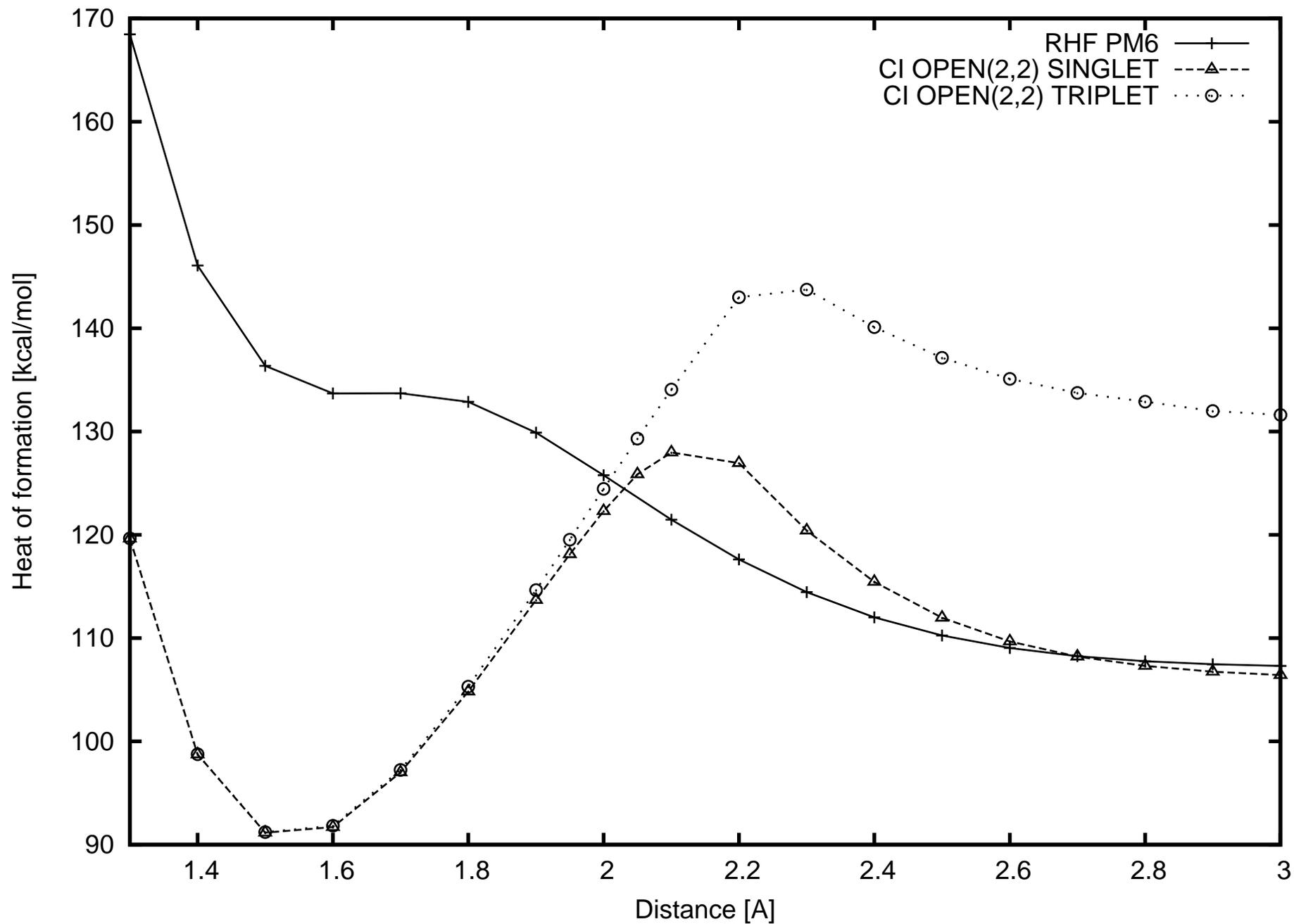
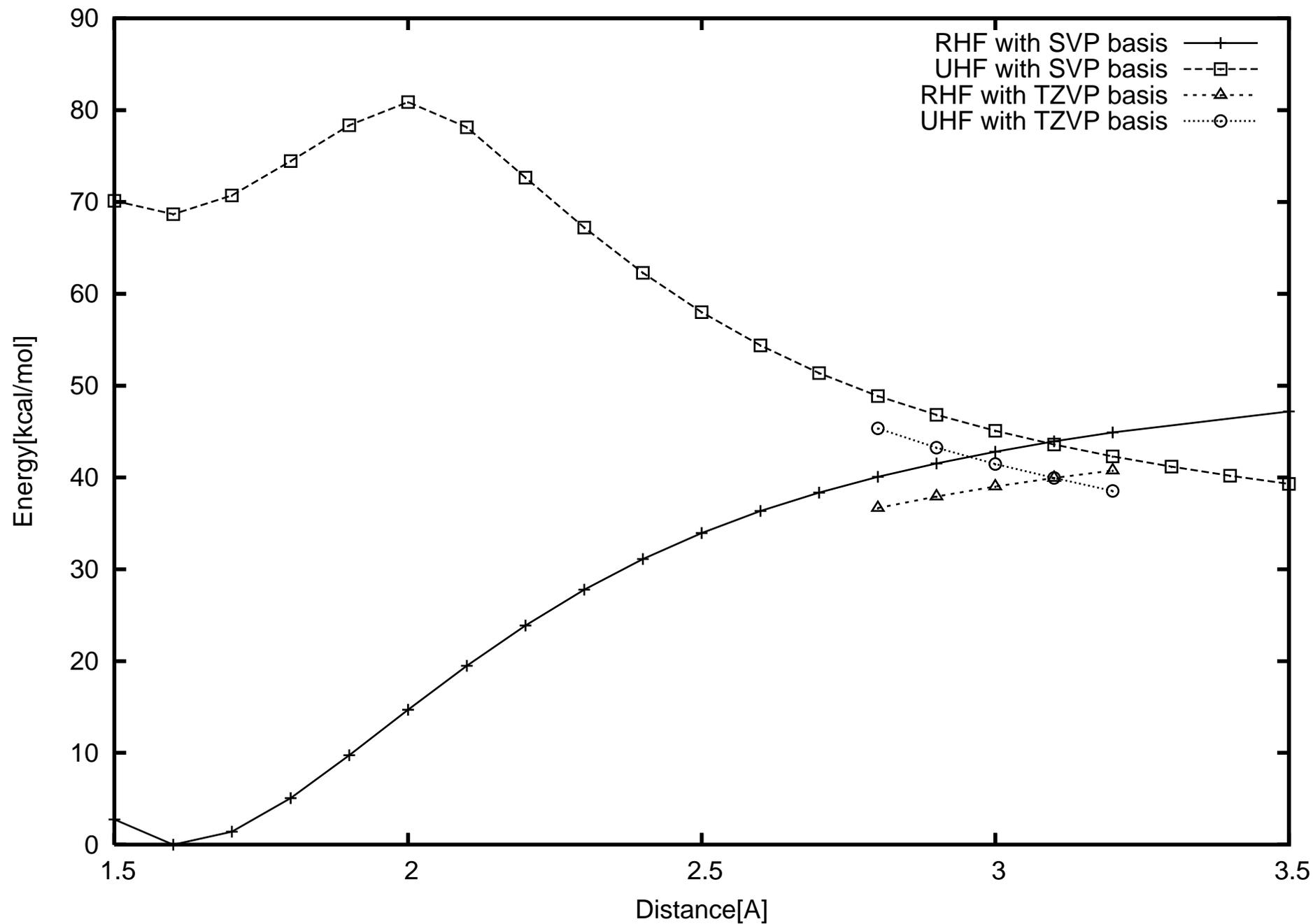


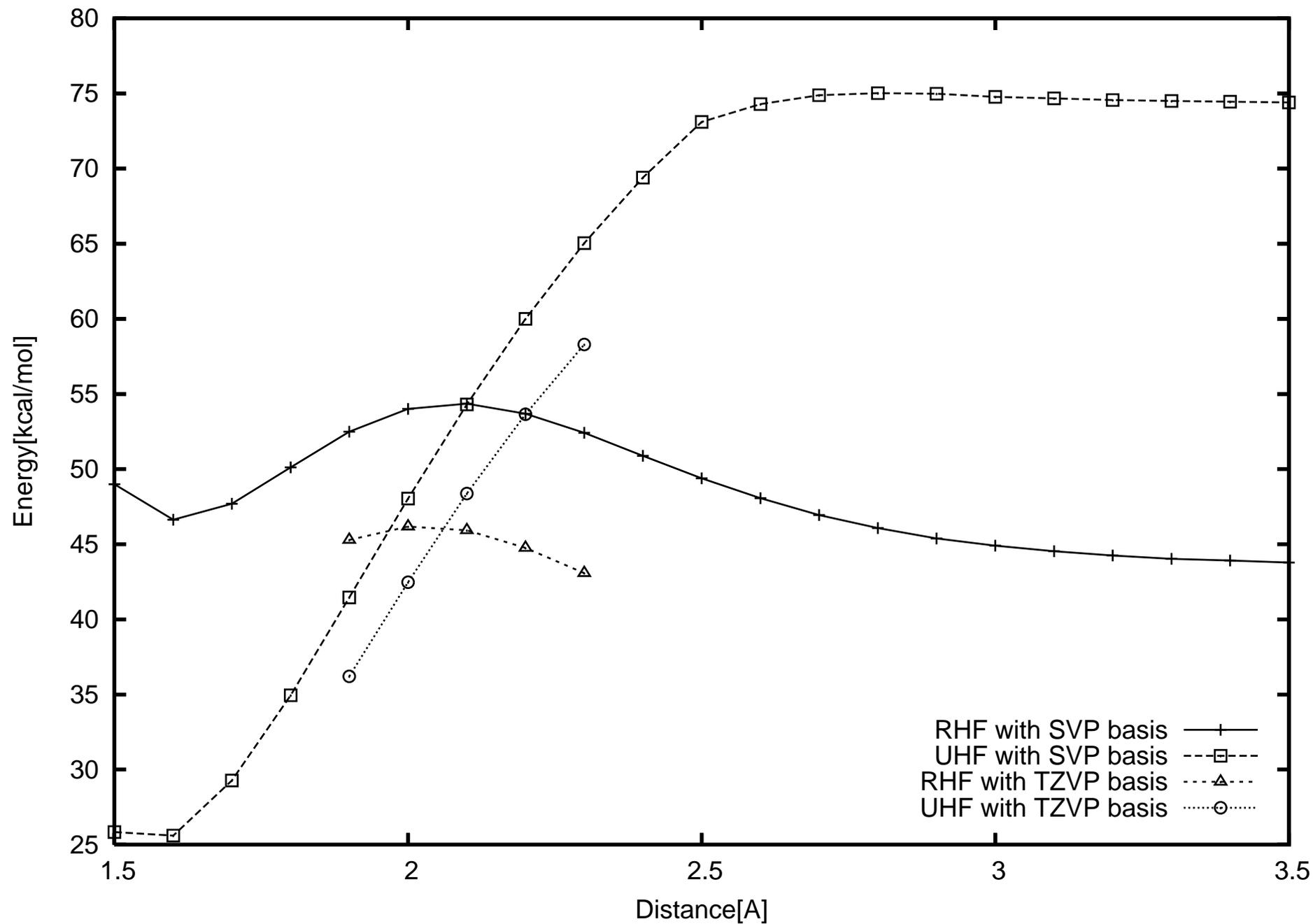
Figure 6.

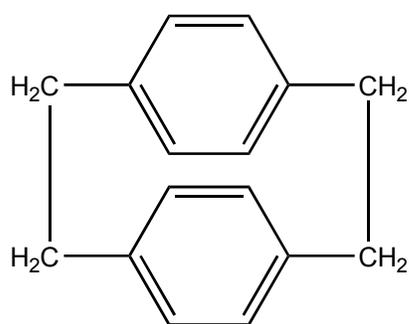




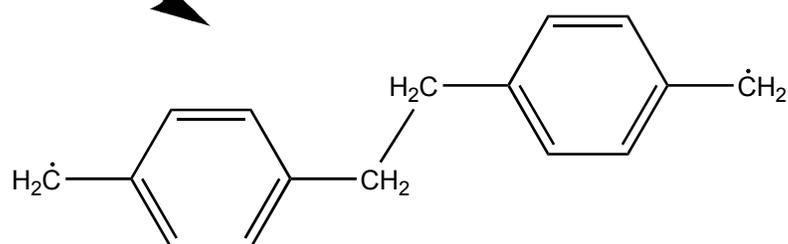




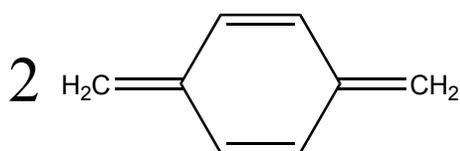




DI
cyclic dimer
cyclo-di-para-xylylene



MM
biradical linear dimer
di-para-xylylene



M
monomer
para-xylylene

