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Diels-Alder Synthesis of Novel Heterocyclic Compounds, Including Inverse-Electron-Demand and Microwave Promotion

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DIELS-ALDER SYNTHESES OF NOVEL HETEROCYCLIC COMPOUNDS, INCLUDING INVERSE-

ELECTRON-DEMAND AND MICROWAVE PROMOTION

By

Kristen Richey

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BACHELOR OF SCIENCE

in

Biochemistry

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Honors Council Chair (printed)	Signature	Date
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To God and to my parents

ACKNOWLEDGEMENTS

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ABSTRACT

One of the main subjects of this research is to compare "inverse-electron-demand" Diels-Alder (IED-DA) reactions with the classical, or "normal-electron-demand" (NED), DA reactions in an attempt to further define the line between the two. The other main focus is to compare methods using conventional heat with using microwave promotion. In both cases, the goal was to produce novel heterocyclic compounds.

Keywords: Diels-Alder, inverse-electron-demand, benzofurazan, vinylene carbonate, 4,5-diphenyl-1,3-dioxol-2-one, anthranil, diphenylacetylene, 5-nitro-2-furaldehyde, 4-chloro-7-nitro-2,1,3-benzoxadiazole (NBD-Cl)

INTRODUCTION

In 1950, the Nobel Prize was awarded to Otto Diels and Kurt Alder for their development of an important cycloaddition reaction involving a diene, a 4-π electron system with two conjugated double bonds, and a dienophile, a 2-π electron system with a double or triple bond, producing a six-membered ring containing one or two double bonds called an adduct (Solomons & Fryhle, 2011, shown in Figure 1).

Figure 1. Diels-Alder Reaction Mechanism
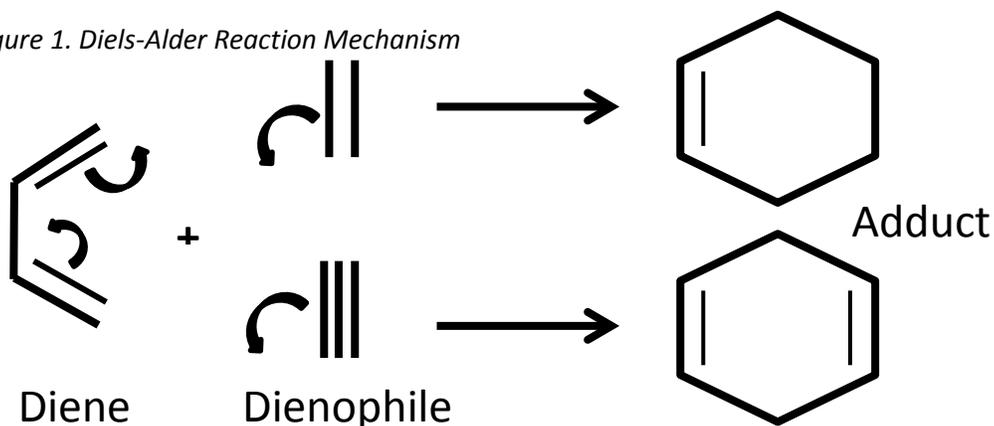
Although the Diels-Alder (DA) reaction has been around for a long time, it holds much promise for the future, both in the theoretical development of organic chemistry, and as a very powerful method for synthesizing novel compounds with several potential uses. Classical, or "normal-electron-demand" (NED), DA reactions involve electron-rich dienes and electron-poor dienophiles. The main subject of this research, however, involves just the opposite electronic distribution, called "inverse-electron-demand" (IED) DA reactions. Such reactions have been investigated to a much lesser extent than

have the NED-DA reactions, and therefore the IED reactions deserve more attention, so as to further the usefulness of DA reactions in general.

The electron deficiency or the electron richness (as the case may be) of the bonds in dienes and dienophiles results from the association of electron-withdrawing and -donating groups. The electron-withdrawing groups work primarily by resonance effect but might also include the inductive effect. Electron-withdrawing groups usually contain an element that is more electronegative than carbon – such as nitrogen, oxygen, etc., including nitro   ($-NO_2$), cyano (-CN), carboxyl (-COOH), ester   (-COOR) and other such groups containing a double bond to oxygen. Electron-donating groups are typically those with a single bond to an electronegative element bearing one or more pairs of nonbonding electrons. Well-known electron-donating groups are amine ($-NR_2$), hydroxyl (-OH), ether (-OR), and phenyl (-C6H5) groups (Solomons & Fryhle, 2011).

In addition to studying IED-DA reactions, microwave assistance was explored versus conventional heating methods. Conventional methods use an external heat source, such as a sand or oil bath, for thermal conducting, which can be a slower and inefficient technique for energy transfer in comparison to microwave irradiation because it depends on the thermal conductivity of the oil or sand bath. Since the conductivity must be carried through the materials being used, the temperature of the vessel in which the reaction is being carried out ends up higher than the reaction mixture. On the other hand, microwave irradiation works by internal heating, which can

be a much more effective means of heating provided that the solvent being used

absorbs the energy effectually (Dallinger & Kappe, 2007).

REVIEW OF LITERATURE

Because the IED-DA reactions are a developing unit of organic synthesis, work

still needs to be done to define the line between the two classes of DA reactions.

Studies that have been done to shed light on IED have discovered different aspects that

contribute to the inverse character of these reactions, including a compound's

substituents and the nature of reactivity of the other reactant.

The reactivity of some compounds is dependent upon the electronic character of

the substituents of the compound as is evidenced in studies by many research groups. In

the research reported by Oakdale and Boger (2010), it was found that the aryl groups

determined the behavior of the 1,2-diarylacetylene derivatives under study in that they

acted in an electrophilic manner. Substituents also play a key role in the magnitude of

electrophilic or nucleophilic reactivity. For example, nitro groups enhance the

electrophilic quality of neutral heteroaromatic 10-π electron systems, such as 4,6-

dinitrobenzofurazan (Goumont, Sebban, Marrot, & Terrier, 2004) or 2,1,3-

benzoxadiazoles (Sebban et al., 2012) and 6-π electron systems, for example benzenoid

aromatic compounds (Terrier, Dust, & Buncel, 2011).

Another significant player in how a compound reacts in a Diels-Alder reaction is

the other reactant being used. There are dienes or dienophiles that can react in either

IED-DA reactions or NED-DA reactions. The versatility of a compound that has this ability

is typically seen where it acts as the diene or dienophile in an NED-DA reaction and a
dienophile or diene in an IED-DA reaction, respectively, depending on the reaction
partner (Goumont, Sebban, Marrot, & Terrier, 2004). An example of this relationship
can be observed in which dienes, such as cyclopentadieneones, that are very reactive in
an inverse-demand fashion are required to provoke [4+2] cycloadditions with
diphenylacetylene (Collins, Yap, & Falles, 2001). Other compounds have a different sort
of flexibility as they can be used in the same manner for both normal- and inverse-
electron-demand reactions and can change because of a reactant that has the opposite
demand (Butler & Coyne, 2015).

Microwave promotion in reactions has only recently become a popular method
in organic synthesis and will mostly likely continue being so. Many reactions can take
place under conventional heating, but the use of a microwave instrument can result in
shorter reaction times, sometimes lower reaction temperatures, and can increase
product yield and purity (Dallinger & Kappe, 2007). Moreover, this can largely been
done without much change to the designed reaction conditions (Baar, Fakone, &
Gordon, 2010). Microwave assistance can accomplish these beneficial feats by
improving the efficiency and, therefore, minimizing the energy content as reported by
Dong et al. (2011) when investigating the Retro-Diels-Alder reaction, the reverse of a
Diels-Alder reaction, and Diels-Alder cascades of *o*-quinol dimers. The effectiveness of
microwave irradiation has also been discovered to simplify multistep methods and use
of hazardous solvents in the interest of green chemistry (Bhuyan, Sarmah, Dommaraju,

& Prajapati, 2014). Some studies have even found that using the effects of a microwave can lead to solvent-free reactions, such as those reported by Ramesh and Raghunathan (2008) and Della Rosa et al. (2015), which takes this exciting feature to another level as green chemistry becomes a greater concern among organic chemists.

RESULTS AND DISCUSSION

For all structures described herein, the reaction mixture was stirred via a magnetic stir bar, and in all cases the solvent was refluxed. All structures of products are tentative, pending further investigation.

The first trial run was a 1:1 molar ratio of benzofurazan to vinylene carbonate in toluene shown below in Scheme 1. Toluene, which boils at around 110 degrees Celsius, was chosen as the starting solvent for almost all reactions observed because of its common use in organic synthesis, and it can provide energy for the reaction without excessive heating. Benzofurazan **1** was selected as the electron-deficient diene, though only previously used as an electron-deficient dienophile in NED-DA reactions (Goumont, Sebban, Marrot, & Terrier, 2004; Sebban et al., 2012; Butler & Coyne, 2015). It was supposed that the conjugated double bond book-ended by the nitrogen atoms would aid in the deficiency of the double bonds and result in that pair being the one with which a dienophile would react. The dienophile chosen was vinylene carbonate **2** because it has previously been found to react as a dienophile in an IED-DA reaction (Arjona et al., 2004). When no reaction was seen to take place with an analysis done by thin-layer chromatography (TLC), it was concluded that either the toluene did not reach

a high enough boiling point to provide the energy needed for this reaction to take place

or perhaps the dienophile double bond was not electron-rich enough.

Scheme 1. Benzofurazan + Vinylene Carbonate
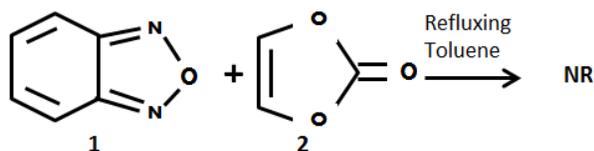
Next, benzofurazan was reacted with 4,5-diphenyl-1,3-dioxol-2-one **3** in toluene

(Scheme 2) following the thought that vinylene carbonate did not have a sufficient

electron-richness. 4,5-diphenyl-1,3-dioxol-2-one is very similar to vinylene carbonate

but has two phenyl groups conjugated to the double bond that would donate electron

density. Again, no reaction was detected by TLC analysis. With this run, it was decided

that toluene was most likely the limiting constituent in the reaction and that a higher

boiling solvent should be used.

Scheme 2. Benzofurazan + 4,5-diphenyl-1,3-dioxol-2-one (in toluene)
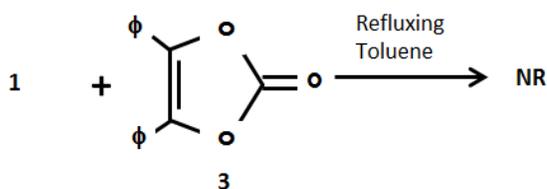
The next trial, shown in Scheme 3, implements the previous two reactants and

the solvent mesitylene, which has a boiling point of around 163 degrees Celsius. A TLC

analysis indicated a product **4** was formed, but both reactants were still present in the

reaction mixture. Another experiment with these conditions was run with a 30% excess

of benzofurazan to attempt reacting all of the 4,5-diphenyl-1,3-dioxol-2-one. However,

an analysis of this reaction mixture showed the same results. A longer reflux of this run

resulted in multiple products showing up on the TLC. In a final endeavor to push this

reaction to completion with a single product, the solvent 5-*tert*-butyl-*m*-xylene with a

still higher boiling point of 203 to 205 degrees Celsius was selected. The TLC revealed

two products in the reaction mixture along with the two reactants.

Scheme 3. Benzofurazan + 4,5-diphenyl-1,3-dioxol-2-one
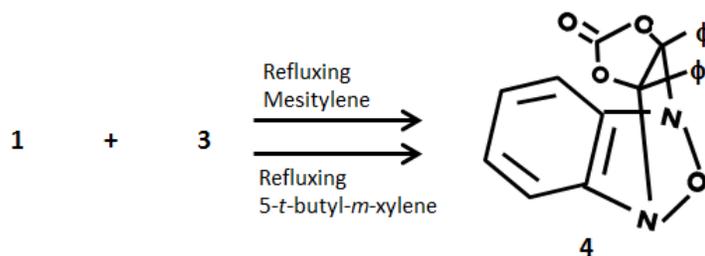
A reaction mixture from these trials with a single product was chosen for infrared (IR)

analysis. After the solvent was evaporated off, the product was a yellow semi-solid.

Figure 2 shows the spectrum obtained for product **4** and Table 1 lists the peaks and the

most likely interpretation for each.
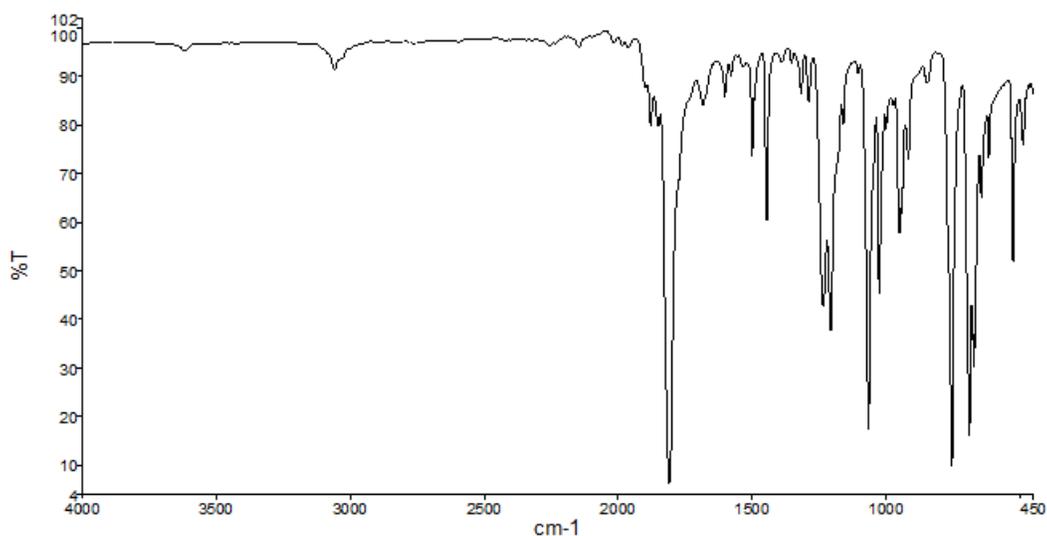
Figure 2. IR Spectrum for **4**

Table 1. IR Analysis for Product 4		
Functional Group	**Peak (cm^{-1})**	**Page***
Disubstituted φ	754.24	227 (1)
O-C-O	1159.41	248 (1)
C=O	1809.44	240 (1)
	1682.91	240 (1)
N-O	949.77	51 (2)
	916.74	51 (2)
	1234.55	248-249,272 (1)
C-O-C	1206.39	248-249,272 (1)
	1065.48	272 (1)
	3059.49	418-420,375 (1)
Mono-substituted φ	1602.54	418 (1)
	1025.42	418 (1)
	754.24	226 (1)
	1500.08	225 (1)
φ	1445.54	26 (2)
	688.43	27 (2)
	670.71	27 (2)

*(#) following page number denotes from which source it was acquired
1: Colthup, Daly, & Wiberley (1964)
2: Nakanishi (1962)

The structure for product **4** shown in Scheme 3 is that which would result from an IED-DA reaction and is believed to be consistent with the results presented in Figure 2 and Table 1.

Because of the lack of a complete reaction, another avenue to consider was the electron-deficiency of the diene. For the next experiment, anthranil **5** was chosen for the diene reactant because it is similar to benzofurazan as it contains only one nitrogen in the ringed structure and therefore would be less electron-deficient. 4,5-diphenyl-1,3-dioxol-2-one **3** was kept for the dienophile and mesitylene as the reaction solvent so that only one reaction variable was changed. A product (**6**) was indicated by the TLC with a similar R_f value to that of product **4**, so a similar structure was assumed to have been produced. However, also present were both reactants, impying another incomplete reaction. The antranil itself gave three separate spots for R_f values on the TLC, suggesting that the anthranil was not as pure as one would prefer a compound to be in research. Thus, there was no further analyses done with the anthranil compound.
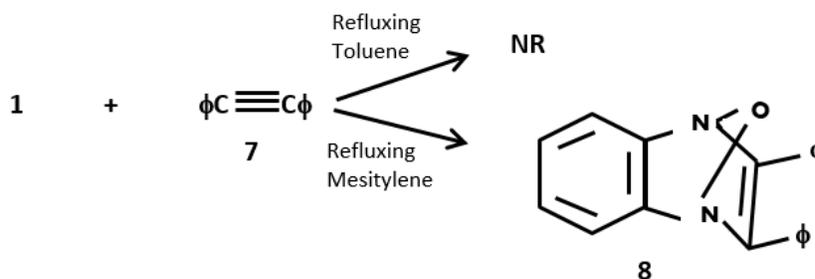

Scheme 4. Anthranil + 4,5-diphenyl-1,3-dioxol-2-one
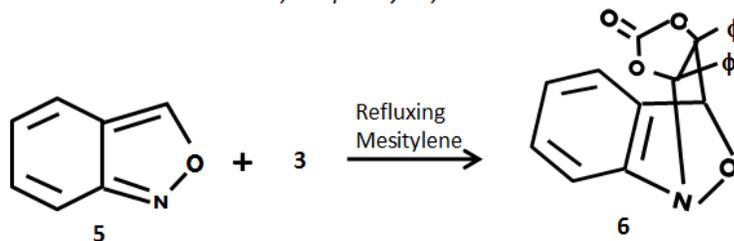
Benzofurazan **1** was returned to for use as the diene in Scheme 5 and reacted with diphenylacetylene **7**. Diphenylacetylene was chosen to observe IED-DA reactions

with a triple bonded dienophile. The first trial employed toluene as the reaction solvent, and no reaction was indicated by TLC to have taken place. In mesitylene, however, three products and both reactants were observed. The structure of one of the products **8**, depicted in Scheme 5, is that of the sought after product and is proposed by the spot on the TLC analysis having a similar R_f value to previous product spots. Because three compounds were observed to have been produced by these reactions conditions, no further analyses of this trial were done at this time.

Scheme 5. Benzofurazan + Diphenylacetylene

Scheme 6 shows the trials that followed those with diphenylacetylene. 4,5-dipenyl-1,3-dioxol-2-one **3** was revisited as the dienophile with 5-nitro-2-furaldehyde **9** as the diene. The nitro group ($-NO_2$) and the aldehyde group (-CHO) conjugated to the conjugated double bonds should provide the desired electron-deficiency by drawing electron density away from the diene by resonance. Again, no reaction was observed to occur in toluene, but in mesitylene, the TLC analysis of the reaction mixture showed a single product **10** and both reactants present.

Scheme 6. 5-nitro-2-furaldehyde + 4,5-diphenyl-1,3-dioxol-2-one
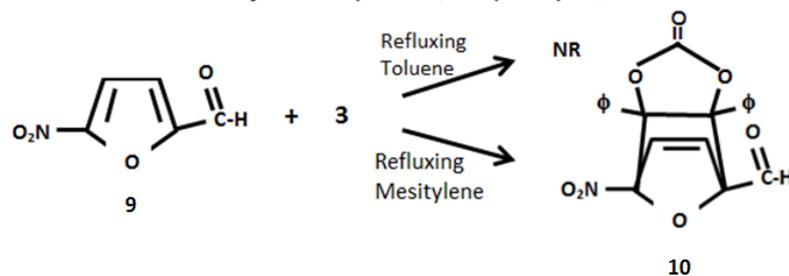
The solvent was evaporated off leaving behind a brown, semi-solid sample that was tested by IR. Figure 3 shows the spectrum obtained for product **10** and Table 2 lists each of the significant peaks and the most probable interpretation.
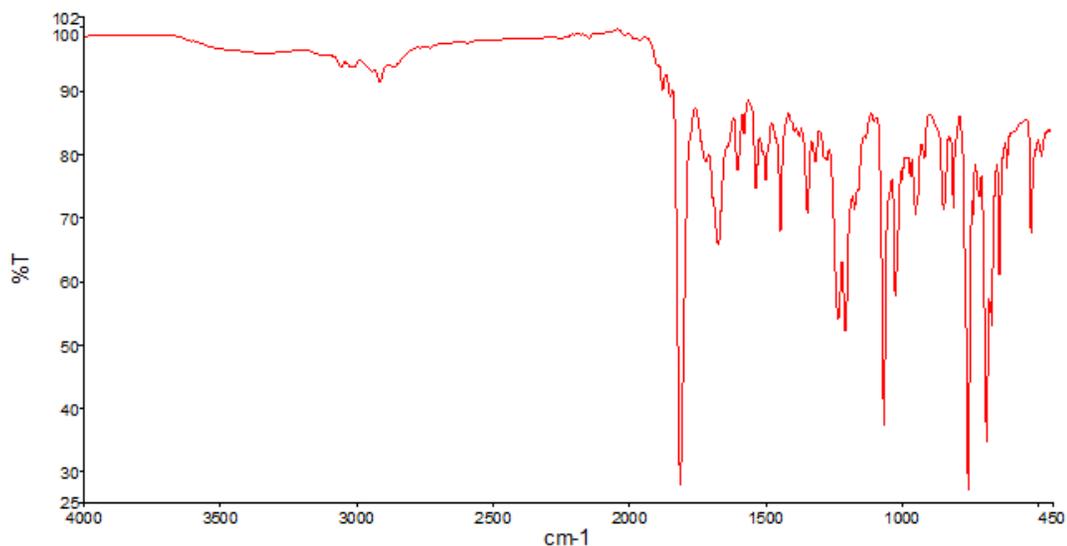
Figure 3. IR Spectrum for **10**

Table 2. IR Analysis for Product 10		
Functional Group	**Peak (cm^{-1})**	**Page***
C=O	1879.65	240 (1)
HC=CH	847.76	382,385 (1)
N-O	950.44	51 (2)
NO$_2$	1536.31	286 (1)
	1500.35	286 (1)
O=C-H	2917.34	397 (1)
	1676.66	248 (1)

Mono-substituted φ	1605.13	418 (1)
	757.22	226 (1)
O-C-O	1174.62	379,380 (1)
	1067.04	379,380 (1)
C-O-C	1235.12	248-249,272 (1)
	1208.28	248-249,272 (1)
	1025.14	380 (1)
φ	1500.35	225 (1)
	1446.82	26 (2)
	689.93	226 (1)

(#) following page number denotes from which source it was acquired

The structure depicted for product **10** in Scheme 6 is that which would result from an IED-DA reaction and is highly probable according to the results presented in Figure 3 and Table 2. The peak at 847.76 cm^{-1} is important for suggesting the structure found in Scheme 6 as it represents the presence of a HC=CH group, which is found only in the adduct after the rearrangement of bonds and not in either of the reactants.

The next experiment, shown in Scheme 7, continued the use of 4,5-diphenyl-1,3-dioxol-2-one **3** as the dienophile, which was reacted with yet another diene 4-chloro-7-nitro-2,1,3-benzoxadiozole (NBD-Cl) **11**. NBD-Cl is comparable to benzofurazan, but in addition to the two nitrogen atoms present within the ringed structure, there are two electron withdrawing groups – a nitro group ($-NO_2$) and a chlorine (-Cl) – conjugated to the diene bonds, resulting in a more electron deficient diene. This reaction was not observed with toluene because of the lack of success in the preceding trials. In mesitylene, an incomplete reaction was observed producing a single product but with both reactants still present.

Scheme 7. NBD-Cl + 4,5-diphenyl-1,3-dioxol-2-one
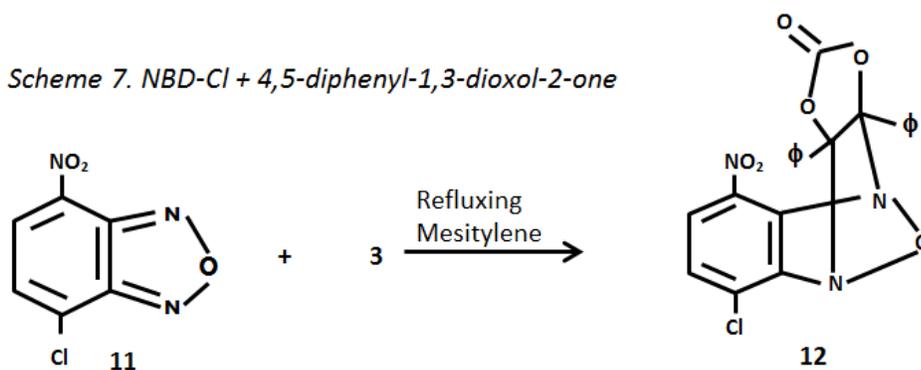
The solvent was evaporated off, leaving behind a yellow semi-solid. The sample was

analyzed by IR, and the results can be seen in Figure 4 and Table 3 below.
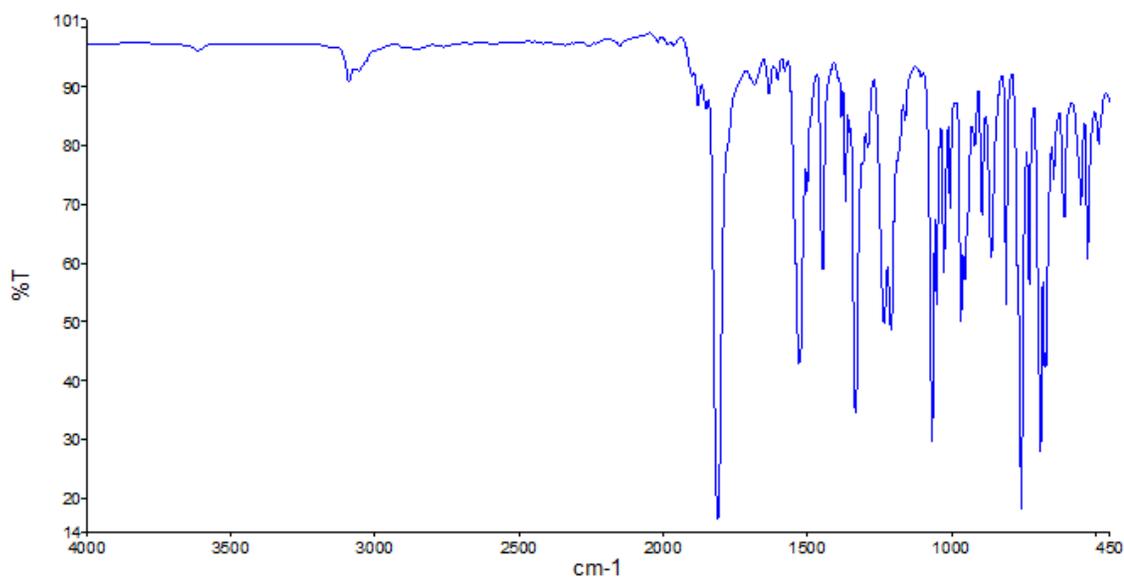
Figure 4. IR Spectrum for 12

Table 3. IR Analysis for Product 12		
Functional Group	**Peak (cm^{-1})**	**Page***
Polysubstituted ϕ	860.90	27 (2)
C=O	1810.57	240 (1)
Mono-substituted	756.90	226,227 (1)
N-O	966.06	51 (2)
	953.50	51 (2)

C-O-C/C-O	1233.79	248-249,272 (1)
	1209.07	248-249,272 (1)
C-O-C	1066.43	272 (1)
	1050.91	272 (1)
	1025.91	36 (2)
Cl	809.82	315-316 (1)
	729.68	315-316 (1)
	607.50	57 (2)
NO$_2$	1530.00	285 (1)
	1500.55	285 (1)
	1331.22	285 (1)
φ	3091.45	375 (1)
	1447.02	26 (2)
	893.28	27 (2)
	690.25	27 (2)
	607.50	57 (2)

(#) following page number denotes from which source it was acquired

The peaks in Figure 4 suggest (though do not conclusively prove) the structure shown in Scheme 7 for product **12**.

In Scheme 8, the reaction of benzofurazan **1** with vinylene carbonate **2** was revisited with higher boiling solvents. The trial using mesitylene as the solvent showed a product **13** made with a similar R_f value to those aforementioned but still contained reactants. This reaction was repeated using 5-*t*-butyl-*m*-xylene as the solvent and resulted in two compounds produced. The TLC spots with the same R_f value, which are similar to other products yielded earlier, suggest the presence of the anticipated product **13**.

Scheme 8. Benzofurazan + Vinylene Carbonate

$$1 + 2 \xrightarrow[\text{5-t-butyl-m-xylene}]{\text{Refluxing}} \xrightarrow{\text{Refluxing Mesitylene}}$$

13
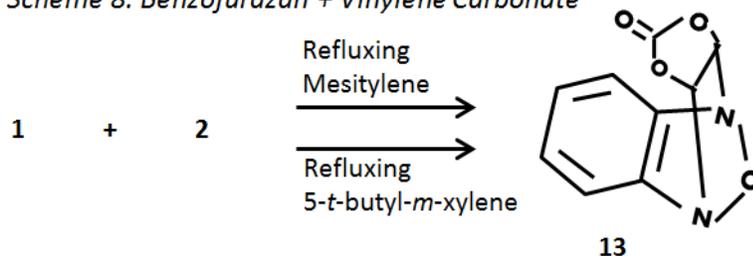
The diene 5-nitro-2-furaldehyde **9** was returned to in Scheme 9 being reacted with vinylene carbonate **2** in the solvent mesitylene. This reaction mixture produced a single product **14** with a similar R_f value to those of the prior products obtained. The reactants were also present in the reaction mixture. Due to difficulties observing the vinylene carbonate on TLC plates, no further analyses have yet been carried out with the reaction mixtures containing this compound.

Scheme 9. 5-nitro-2-furaldehyde + Vinylene Carbonate

$$9 + 2 \xrightarrow{\text{Refluxing Mesitylene}}$$

14
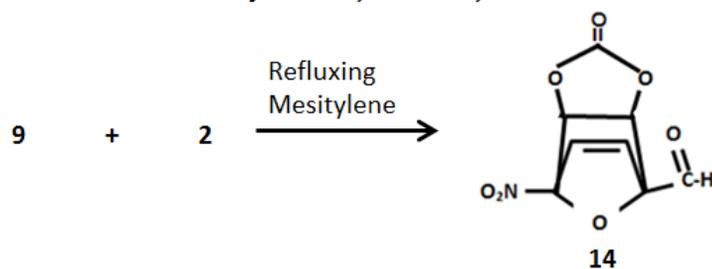
With no complete reactions yet observed using conventional heat sources, microwave heating was implemented in Scheme 10. 5-nitro-2-furaldehyde **9** and 4,5-diphenyl-1,3-dioxol-2-one **3**, which make a product with a more distinguishable product, were chosen for a microwave trial. The solvent used was *o*-dichlorobenzene and resulted in an incomplete reaction producing compound **10**.

Scheme 10. 5-nitro-2-furaldehyde + 4,5-diphenyl-1,3-dioxol-2-one (MW)

9   +   3 $\xrightarrow[\substack{\text{5 min. @ 100°C +}\\\text{3 min. @ 160°C}}]{\text{MW}}$ 10

Because not all of the results were definitive nor produced a desired complete reaction, more research is still to be done involving these reaction combinations. Further analyses, such as nuclear magnetic resonance (NMR), can help support the suggested structures of the products obtained. Recrystallization and column chromatography could be implemented also in purifying the products for more accurate analyses. Future endeavors regarding IED-DA reactions such as these can and should include different combinations and different reactants. Moreover, the use of catalysts for these reactions could facilitate complete reactions.

EXPERIMENTAL

The following equipment was used and provided by the Chemistry Department of Olivet Nazarene University: 50-mL boiling flasks, condensers, magnetic stir bars, sand baths, hot plates, Spectroline® Model CM-10 for the UV light source, Perkin Elmer FT–IR Spectrum Two spectrometer, Biotage® Initiator Classic microwave instrument with Biotage® tubes and caps.

All reagents were used as received from vendors. Most reagents were purchased from Sigma Aldrich with the exceptions of benzofurazan from Alfa Aesar and 4-chloro-7-nitro-2,1,3-benzoxadiazole from Tokyo Chemical Industry Co., LTD. (NEED SOLVENTS)

Designations starting with CA-2 refer to sample numbers in the research notebook. All TLC's (thin-layer chromatography) were run using slides of polyester backing, coated with silica gel that fluoresces at 254 nm.

1:1 Benzofurazan and Vinylene Carbonate (Scheme 1). 72 mg of vinylene carbonate was added to 100 mg of benzofurazan dissolved in 10 mL of toluene. This solution was refluxed with stirring via a magnetic stir bar for 30 minutes in a 100-mL boiling flask by a hot plate and sand bath (CA-2-4-1). Thin layer chromatography (TLC) #1 was run using a solvent (for development) consisting of 75% hexanes and 25% ethyl acetate. A small amount of benzofurazan was dissolved in 1 mL of ethyl acetate; the same was done with vinylene carbonate. These two solutions were used as the knowns for this TLC run against the reaction mixture. The TLC showed one spot show R_f value was the same as that of benzofurazan and one spot with an appreciably larger R_f value. Vinylene carbonate did not appear on the plate. Refluxing was continued for another hour because benzofurazan was still present (CA-2-4-2), and TLC #2 was carried out. The same results were seen on TLC #2.

1:1 Benzofurazan and 4,5-diphenyl-1,3-dioxol-2-one (Scheme 2). 100 mg of 4,5-diphenyl-1,3-dioxol-2-one and 51 mg of benzofurazan was dissolved in 5 mL of toluene and refluxed for 30 minutes (CA-2-5-1). TLC #3 was run with the previously stated conditions with the exception that the product of this run was diluted for use on the TLC plate. The dilution was made with one drop of toluene, the solvent used for the reaction, and one drop of product. This dilution technique became the standard

preparation of the product sample being used on the TLC plate. The results indicated that no reaction had taken place. Refluxing was continued for an additional 6 hours and 10 minutes (CA-2-5-2). TLC #5 analysis was run with the same conditions and also showed no reaction had occurred.

1:1 Benzofurazan and 4,5-diphenyl-1,3-dioxol-2-one (Scheme 3). 100 mg of 4,5-diphenyl-1,3-dioxol-2-one and 51 mg of benzofurazan was dissolved in 5 mL of mesitylene and refluxed for 30 minutes (CA-2-7-1). TLC #4 was run with the previously stated conditions. TLC #4 indicated a new product was formed. However, both reactants were still present in the product solution. Refluxing was continued for an additional 1 hour (CA-2-7-2). TLC #6 analysis was run with the same conditions and gave the same results as TLC #4. Another 16 hours and 20 minutes of refluxing followed (CA-2-7-3) with TLC #8. The results showed both reactant still present and now 3 products. Under suspicion that the vial was contaminated a new sample from the CA-2-7-3 product was made, and TLC #9 was run with the same conditions. TLC #9 showed the same results.

1:1 Anthranil and 4,5-diphenyl-1,3-dioxol-2-one (Scheme 4). 100 mg of anthranil and 200 mg of 4,5-diphenyl-1,3-dioxol-2-one were dissolved in 5 mL of mesitylene and refluxed with stirring for 30 minutes (CA-2-9-1). TLC #7 was run with the previous conditions; the results revealed the anthranil to be impure (with 3 R_f values). The product was seen to contain a new product and both reactants.

1.3:1 Benzofurazan and 4,5-diphenyl-1,3-dioxol-2-one (Scheme 3). 100 mg of 4,5-diphenyl-1,3-dioxol-2-one and 65.5 mg of benzofurazan (30% excess) was dissolved

in 5 mL of mesitylene. The solution was refluxed for 1 hour and 5 minutes (CA-2-10-1). TLC #10 was run with previously stated conditions. The results showed both reactants still present along with a new product.

1:1 Benzofurazan and Diphenylacetylene (Scheme 5). 100 mg of benzofurazan and 148 mg of diphenylacetylene was dissolved in 5 mL of toluene and refluxed for 45 minutes (CA-2-11-1). TLC #11 was run with the same conditions as previously stated. TLC#11 indicated that no reaction occurred.

1:1 Benzofurazan and Diphenylacetylene (Scheme 5). 100 mg of benzofurazan and 148 mg of diphenylacetylene was dissolved in 5 mL of mesitylene and refluxed for 2 hours (CA-2-12-1). TLC #12 was run with the same conditions as previous analyses. The results showed a product with both reactants still present and two other compounds.

1:1 5-nitro-2-furaldehyde and 4,5-diphenyl-1,3-dioxol-2-one (Scheme 6). 100 mg of 5-nitro-2-furaldehyde and 169 mg of 4,5-diphenyl-1,3-dioxol-2-one was dissolved in 5 mL of toluene and refluxed for 42 minutes with stir bar (CA-2-13-1). TLC #13 was run with 60% hexanes and 40% ethyl acetate solution. The reactant and product solutions for TLC were made up as previously stated. TLC #13 showed no reaction.

1:1 5-nitro-2-furaldehyde and 4,5-diphenyl-1,3-dioxol-2-one (Scheme 6). 100 mg of 5-nitro-2-furaldehyde and 169 mg of 4,5-diphenyl-1,3-dioxol-2-one was dissolved in 5 mL of mesitylene and refluxed for 1 hour and 32 minutes with stir bar (CA-2-14-1). TLC #14 was run with the same conditions as Scheme 8. No reaction was

indicated. The solution was then refluxed for an additional 3 hours and 25 minutes (CA-2-14-2). TLC #15 was run in the same manner and gave the same outcome as TLC #14.

1:1 4-chloro-7-nitro-2,1,3-benzoxadiazole (NBD-Cl) and 4,5-diphenyl-1,3-dioxol-2-one (Scheme 7). 84 mg of NBD-Cl and 100 mg of 4,5-diphenyl-1,3-dioxol-2-one was dissolved in 10 mL of mesitylene and refluxed for 30 minutes (CA-2-15-1). TLC #16 was run under the same conditions as Scheme 8. A new product was formed, and both reactants were still present in the product mixture.

1:1 Benzofurazan and Vinylene Carbonate (Scheme 8). 100 mg of benzofurazan and 72 mg of vinylene carbonate was dissolved in 5 mL of mesitylene and refluxed with magnetic stirring for 30 minutes, resulting in CA-2-16-1. TLC #17 was run in 75% hexanes and 25% ethyl acetate. Undiluted vinylene carbonate and diluted benzofurazan were used as the knowns. A product was indicated by TLC #17, and at least one of the reactants (benzofurazan) was still present. Only benzofurazan is reported with certainty because diluted vinylene carbonate does not as readily appear on TLC.

1:1 Benzofurazan and 4,5-diphenyl-1,3-dioxol-2-one (Scheme 3). 50.4 mg of benzofurazan and 100 mg of 4,5-diphenyl-1,3-dioxol-2-one was dissolved in 5 mL of 1-*tert*-butyl-3,5-dimethyl-benzene (also called 5-*tert*-butyl-*m*-xylene) and refluxed with magnetic stirring for 30 minutes, resulting in CA-2-17-1. TLC #18was run with the same conditions as stated in Scheme 11. The results showed two products and the reactant present in the product solution, though benzofurazan was very faint. The product was

refluxed for another 2 hours and 5 minutes (CA-2-17-2). TLC #19 was run with the same conditions and had the same outcome.

1:1 Benzofurazan and Vinylene Carbonate (Scheme 8). 100 mg of benzofurazan and 72 mg of Vinylene carbonate was dissolved in 5 mL of 5-*t*-butyl-*m*-xylene and refluxed with magnetic stirring for 30 minutes (CA-2-18-1). TLC #20 was run with the previously stated conditions of Scheme 11 and resulted in two products and showed benzofurazan to be present.

1:1 5-nitro-2-furaldehyde and Vinylene Carbonate (Scheme 9). 100 mg of 5-nitro-2-furaldehyde and 61 mg of vinylene carbonate were dissolved and refluxed in 10 mL of mesitylene for 1 hour (CA-2-19-1). TLC #21 was run under the same conditions in Scheme 11 and showed that a product was made. However both reactants were still present in this reaction mixture.

1:1 5-nitro-2-furaldehyde and 4,5-diphenyl-1,3-dioxol-2-one (Scheme 10). 100 mg of 5-nitro-2-furaldehyde and 169 mg of 4,5-diphenyl-1,3-dioxol-2-one was dissolved in 2 mL of *o*-dichlorobenzene. The reaction mixture was heated by microwave for 5 minutes at 100°C with magnetic stirring (CA-2-20-1). TLC #22 was run in 75% hexane and 25% ethyl acetate with diluted reagents. The TLC analysis showed a product and both reactants present. CA-2-20-1 was heated again by microwave for 3 minutes at 160°C, producing a darker solution (CA-2-20-2). TLC #23 was run with the above stated conditions. The analysis showed the same results as TLC #22.

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