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WP2750: DEVELOPMENT OF SOLVENT-FREE NITRATION PROCESSES USING TERT-BUTYL NITRITE

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FOREWORD

The work reported herein was performed at the Naval Surface Warfare Center, Indian Head Explosive Ordnance Disposal Technology Division (NSWC IHEODTD) from March 2017 to March 2018. This work was sponsored by SERDP under project number WP-2750 in response to a statement of need from SERDP for the development of solventless nitration processes.

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EXECUTIVE SUMMARY

Objective: The SERDP SEED FY17 Statement of Need sought a solution to the issue of the amount hazardous waste produced during the synthesis of energetic materials. Syntheses of energetic materials through processes that either eliminate waste streams or greatly reduce them to a minimum were required. Investigated processes were required to not be energy-intensive, meaning the reactions should not require high degrees of temperature control. The objective of the proposed work was to develop nitration methods that can be applied to green synthesis and scale-up of energetic materials in such a manner that waste generation and energy expenditure were kept to a minimum.

Technical Approach: Mild nitration methods utilizing *tert*-butyl nitrite at ambient temperature under open air to access directed C-nitro functionalization on aromatic molecules and alkenes were recently reported in the academic literature. To a lesser extent, syntheses of nitramines and nitrate esters using *tert*-butyl nitrite were also reported in the academic literature. The work reported herein focused on maturing this nitration technology into a process useful for the green chemical scale-up of aromatic/heteroaromatic nitro compounds, nitramines, and nitrate esters. A design of experiments- inspired approach screening various conditions and additives was undertaken to investigate whether processes to conventional nitrate ester, nitroaromatic, and nitramine explosive ingredients was feasible. During the course of this work, it was discovered that very small amounts of nitroglycerin could be synthesized in a reproducible manner, but the major product of the reaction of *tert*-butyl nitrite with glycerol was glycerol trinitrite. It was also discovered that isomeric mixtures of nitrotoluene and dinitrotoluene could be obtained when toluene was combined with *tert*-butyl nitrite in the presence of catalyst. It was found that hexamine could not be nitrolyzed through a truly solventless process in the presence of *tert*-butyl nitrite and a nitrate salt, but adding a co-solvent did afford small amounts of product which, when analyzed by NMR, exhibited peaks attributable to RDX and HMX.

Benefits: It was thought that maturing nitration technology utilizing tert-butyl nitrite could provide multiple benefits in the chemical scale-up and production of energetic materials. If the amount of waste in a process could be reduced through use of mild reactions run neat or with a minimal amount of solvent under pH-neutral conditions, then there would likely be a reduced environmental impact and also significant cost-savings to stakeholders. With no need to neutralize the waste streams, it was postulated that the saved labor associated with neutralization result in additional cost-savings for stakeholders. Beyond the scope of process development, the energetics community had a general interest in developing efficient nitration processes that proceed under mild reaction conditions. Maturing this technology was thought to also be of benefit researchers at the 6.1 level who required more mild nitration conditions to access novel energetic material targets.

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ACRONYMS AND ABBREVIATIONS

ACS	American Chemical Society
Ar	Aromatic Ring/Aryl Group
Cat.	Catalyst
DoD	Department of Defense
DOE	Design of Experiments
DG	Directing Group
DSC	Differential Scanning Calorimetry
DTIC	Defense Technical Information Compendium
EOD	Explosive Ordnance Disposal
ESD	Electrostatic Discharge
FTIR	Fourier Transform Infrared Spectroscopy
FY	Fiscal Year
GC	Gas Chromatography
GC/MS	Gas Chromatography/Mass Spectrometry
HMX	1,3,5,7-Tetranitro-1,3,5,7-tetrazocine
HPLC	High Performance Liquid Chromatography
IR	Infrared Spectroscopy
LC/MS	Liquid Chromatography/Mass Spectrometry
LRF	Laboratory Review Form
MODDE	Modelling and Design Program
MS	Mass Spectrometry
NMR	Nuclear Magnetic Resonance Spectroscopy
NG	Nitroglycerin
NSWC IHEODTD	Naval Surface Warfare Center Indian Head and Explosive Ordnance Disposal Technology Division
ONR	Office of Naval Research
pH	Potential Hydrogen
Ph.D.	Doctor of Philosophy
PSD	Particle Size Distribution
RC1	Mettler Toledo's Reaction Calorimeter brand
RDX	1,3,5-Trinitro-1,3,5-triazine
SEED	SERDP Exploratory Development
SEM	Scanning Electron Microscopy
SERDP	Strategic Environmental Research and Development Program
TEMPO	2,2,6,6-Tetramethylpiperidine 1-oxyl
TLC	Thin Layer Chromatography
TNT	Trinitrotoluene

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RESEARCH OBJECTIVE AND IMPACT

The SERDP SEED FY 2017 Statement of Need sought out new processes in which hazardous waste streams from nitrations would be substantially decreased and energy consumption during the reaction (e.g., cooling) would be lowered in order to reduce environmental impact and simultaneously afford cost savings. This work attempted to address the problem of the need for solvent-free nitration conditions in the manufacture of energetic materials containing aromatic C-nitro functionalities, nitramines, and/or nitrate esters by developing and maturing a mild nitration protocol that had seen recent report in the academic literature.

Energetics manufacturing in and for the Department of Defense is in need of green, cost-effective nitration processes that are able to produce energetic materials within acceptable yields while minimizing waste streams and keeping energy expenditures low. Solvents typically utilized in industrial nitration are often contaminated with by-products of the reaction and are consequently difficult to recycle. Solventless nitration processes or nitration processes which use minimal amounts of solvent could be a suitable solution to minimizing waste streams. This work's objective was to develop nitration methods that can be applied to green scale-up of energetic materials in such a manner that waste would be kept to a minimum. This work sought to develop nitration processes that use *tert*-butyl nitrite (CAS# 540-80-7) in a type of nitration reaction that was reported to proceed at ambient temperature under open air. Reports in the academic literature suggested that this reaction could proceed without solvent or only a minimal amount of solvent in order to minimize waste stream accumulation.

BACKGROUND

Historically, *tert*-butyl nitrite has been prepared commercially in two ways. Early industrial synthesis of *tert*-butyl nitrite, shown in Figure 1a, involved treating *tert*-butyl alcohol with nitrogen dioxide gas, which would afford the aforementioned nitrite product.[1] More recently reported preparations of *tert*-butyl nitrite involve treating *tert*-butyl alcohol with sodium nitrite in concentrated hydrochloric[2] or sulfuric acid,[3] performing Sandmeyer chemistry by generating nitrous acid (HONO) in-situ (Figure 1b) to afford the aforementioned nitrite product. The nitrogen dioxide process has historically required additional facilitation to safely work with the toxic gas,[1] but has been reported to require little in the way of purification and waste treatment. Conversely, the process using Sandmeyer chemistry can be carried out in less costly conventional.[2,3] and continuous flow reactor setups,[4] but the process requires investment into purification and waste treatment.[2c,3c 3f] In a continuous flow setup, tert-Butyl nitrite is typically separated from the acidic liquor at -5° C, then washed with aqueous sodium bicarbonate.[4] The excess nitrous acid is treated with aqueous urea separately.[4,5]

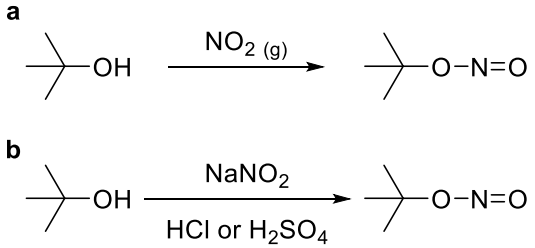


Figure 1. Industrial Synthesis of Tert-butyl Nitrite

tert-Butyl nitrite has been reported in the academic literature as a reagent suitable for nitration,[6-16] nitrosation,[6, 17-20] diazotization,[21-24] and oxidation[25-27] reactions (Figure 2). This reagent has been reportedly used to access aromatic C-nitro functionalities in a regioselective manner[7, 12, 14] and has also been shown to have

reactivity with olefins.[8, 9, 13] Additionally, conditions were reported where secondary nitramines[6, 7, 10] and nitrate esters[9, 13] were accessible through use of *tert*-butyl nitrite. Most literature reports were focused on accessing directed mono-nitration products for targets that are of interest to the pharmaceutical industry and have typically not used *tert*-butyl nitrite in molar ratios above 1.5:1. Interestingly, however, by-products of these reactions have been reported with further nitration occurring.[6, 7, 9, 10, 13] Such results were highly encouraging for the purposes of this work. These reactions were not reported to generate any appreciable exothermic behavior. These reactions have typically been run neat or in solvent at ambient temperature or with heating. Heating was reported to be necessary in the cases of ring-closing reactions with C-nitro group installation [15, 16] and directed nitration reactions, including a Pd-catalyzed protocol.[14] It should be noted, however, that directed nitrations were reported to proceed at ambient temperature without any additional heat needed.[7]

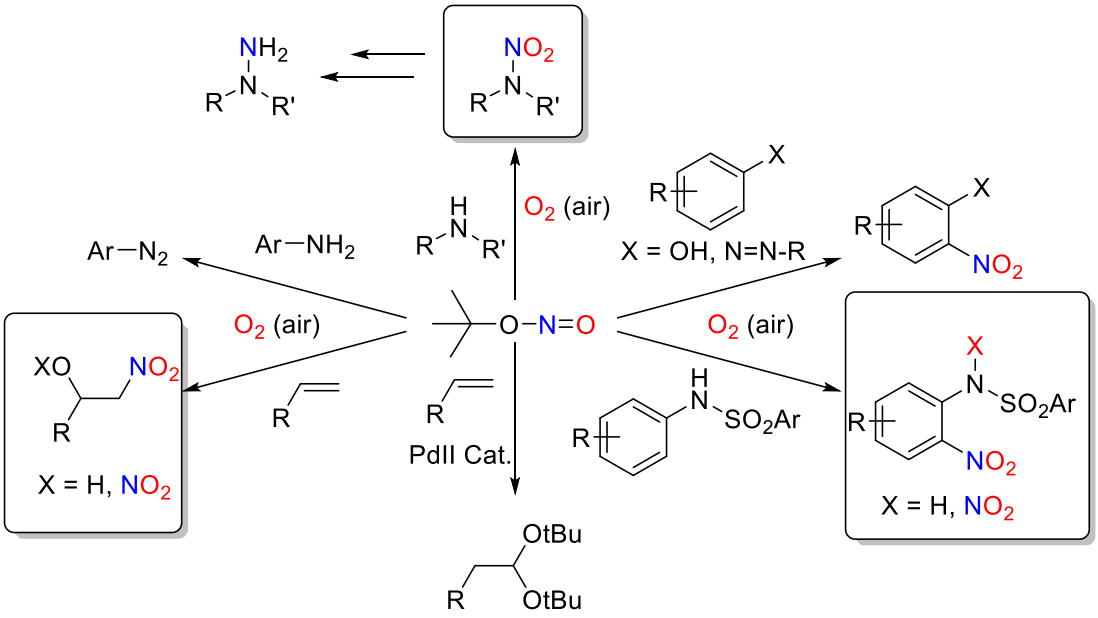
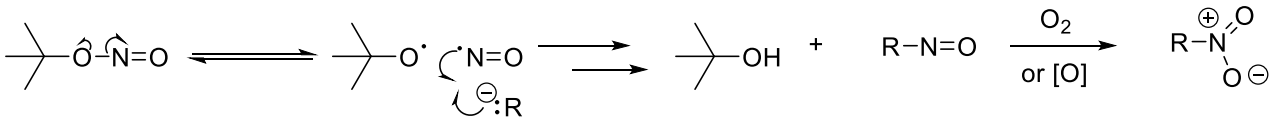


Figure 2. Various Reported Reactions of Tert-butyl Nitrite in the Literature.

As shown in Figure 3, the current understanding of the reaction pathway involves radical disproportionation to provide NO and *tert*-butoxy radical, which then reacts with the substrate. Seminal reports studying the vapor decomposition of *tert*-butyl nitrite[28] reported generation of ·NO, but no NO_2 was detected. Under standard reaction conditions reported in the literature, it would be expected that in the absence of any other substrate, *tert*-butanol and/or *tert*-butoxide radical in solution would capture unreacted NO to regenerate *tert*-butyl nitrite. This expectation is based upon literature data that demonstrates other alkyl nitrites can be generated from an alcohol and *tert*-butyl nitrite in the absence of external oxidant.[2a]



R = alcohol, 2° amine, alkene, arene

Figure 3. The Understanding of Tert-butyl Nitrite's Reactivity in the Literature at the Beginning of this Effort

Directed nitration reactions on aromatic substrates (Figure 4) have been thought to follow a multi-step mechanism.[7, 12, 14] Initial nitroso functionalization has been thought to occur on the directing group, typically an alcohol, amine, amide, or diazine, followed by nitrosyl transfer through interaction with nearby π-electrons from the aromatic ring. Rearomatization and subsequent oxidation produces the directed nitration product.

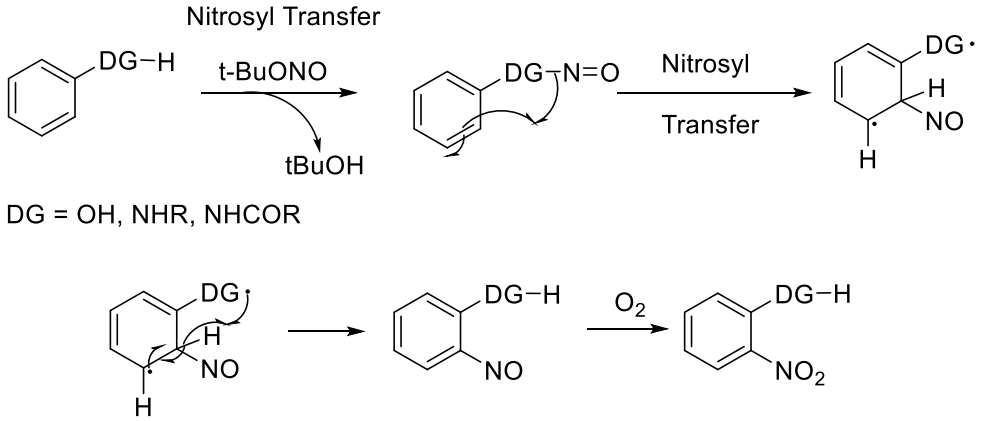


Figure 4. The Understanding of Directed Nitration using Tert-butyl Nitrite at the Beginning of this Effort

The reaction medium has been reported to affect yield, as in the case of varying aprotic organic solvents.[7] Running the reaction in a polar, protic environment, however, appears more complex. It has been reported[13] that when the reaction is run in water, HONO may be generated in-situ, which is known to decompose to NO_2 in the presence of air. Products proposed to arise from radical oxidation and nitration pathways were observed. Another report[15] in the literature studied ^{18}O incorporation in a reaction that involved TEMPO mediated ring formation and nitration with *tert*-butyl nitrite in the presence of water in refluxing ethyl acetate. In this report, ^{18}O labeled water was found majorly to be incorporated into the product's nitro group. In contrast, ^{18}O labeled oxygen was only found to have minor incorporation into the product's nitro group. It stands to reason that reaction between TEMPO and water is likely forming peroxide in this particular reaction, but this also demonstrates the considerations that should be taken into account when screening reaction conditions for nitrations involving *tert*-butyl nitrite.

Based upon the reports in the literature, *tert*-butyl nitrite was believed to be a desirable candidate for solventless nitration strategies to access energetic materials. Maturing nitration technology utilizing *tert*-butyl nitrite was considered to have potential for improved environmental benefits over existing nitration protocols in several ways. Nitration methods using *tert*-butyl nitrite was thought to have the potential for lower fume-off risk due to the anticipated low probability of NO_x generation. During a typical industrial nitration process, NO_x content presents significant environmental concerns, especially regarding the hazard of a fume-off. A fume-off in

a nitration reaction is typically the result of runaway exothermic decomposition of substrate or product material in the nitration media. This is typical of nitrations in mixed acid and white or red fuming nitric acid.

RESEARCH DESCRIPTION, RESULTS AND DISCUSSION

Nitrate Esters

The synthesis of nitrate esters from the corresponding alcohol precursor and *tert*-butyl nitrite was proposed. The report from Hirose, *et al*[13] demonstrating unintended nitrate ester formation arose from the reaction of an intermediate alcohol in the presence of *tert*-butyl nitrite with the absence of another site for nitrosyl transfer to occur; the desired product was a 2-nitro, 1-alcohol from the reaction of an alkene with *tert*-butyl nitrite in the presence of water. Investigations under this effort began by examining the reaction of propylene glycol with *tert*-butyl nitrite under various conditions (Figure 5). The reaction was followed by ^{1}H NMR (90 MHz, Anasazi) neat with 1 equivalent of chloroform added as the internal standard. An initial experiment (Figure 6) using 20 equivalents of *tert*-butyl nitrite (>90% by GC, Sigma-Aldrich) at 25°C was carried out both under oxygen and under open air with a reaction time of 3 hours. Nitrosyl transfer occurred within the 2-hour timeframe. The reaction products were analyzed by ^{1}H NMR, ^{13}C NMR, and HPLC. The samples were subjected to independent analysis by HPLC using a PDA detector. It was determined, after examining the NMR, HPLC, and UV data that only nitrosyl transfer was occurring, and no nitrate ester was being formed. Initially, because the NMR and HPLC data for propylene glycol dinitrite were so close in chemical shift/retention time of the dinitrate ester, PGDN, it was thought that nitrate ester may have been forming. It was confirmed that no nitrate ester was forming when the HPLC sample of the reaction products was spiked with authentic PGDN, and two peaks were observed with close, but different retention times. It was uncertain at this juncture whether concentration of the nitrosyl transfer product in the reaction media mattered for conversion to the desired nitrate ester product. Keeping this data in mind, it was decided appropriate to continue with the Design of Experiment style screen.

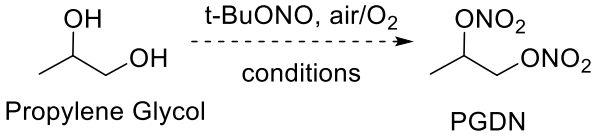


Figure 5. The Attempted Synthesis of PGDN from Propylene Glycol

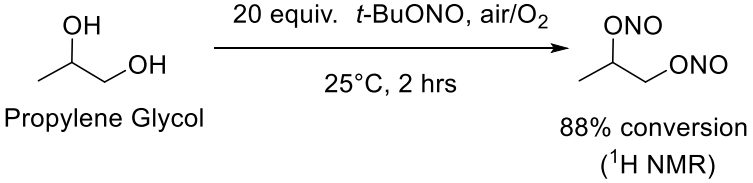
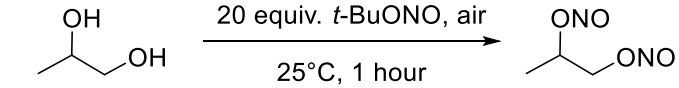


Figure 6. Initial Experiments Exploring the Reaction of Propylene Glycol with Tert-butyl Nitrite

Table I. Design of Experiments Investigation into Conversion of Propylene Glycol in the Presence of Tert-butyl Nitrite

Entry	Equiv. tBuONO	Temp. (°C)	Time (hrs)	%Conv. (NMR)
1	3	0	2	20
2	3	0	20	22
3	3	30	2	22
4	3	30	20	26
5	3	40	2	26
6	3	40	20	31
7	11.5	0	15	65
8	11.5	15	11	66
9	11.5	30	2	54
10	11.5	30	11	56
11	11.5	30	20	58
12	11.5	40	15	63
13	20	0	2	82
14	20	0	20	84
15	20	30	2	88
16	20	30	20	93
17	20	40	2	78
18	20	40	20	72
19	**20**	**15**	**1**	**68**
20	**20**	**15**	**1**	**76**

As shown in Table I, a Design of Experiments style screen was carried out to understand how many equivalents of *tert*-butyl nitrite would be needed, what residence time would be necessary, and at what temperature the reaction would occur and go to completion. Again, these reactions were followed by ^{1}H NMR using chloroform as the internal standard, and reaction products were analyzed by HPLC. Conversions changed depending on how many equivalents of *tert*-buyl were used. Reaction temperature and residence time only gave marginal increases in propylene glycol conversion. No PGDN was detected by HPLC. Using this data, conditions for maximized conversion were tested using Design of Experiments software (entries 19 & 20), where 20 equivalents of *tert*-butyl nitrite would be reacted with propylene glycol at 15°C. These led to lower conversions; final conditions from the screen for optimized nitrosyl transfer were then based upon entries 15 and 16 in Table I, and are displayed in Figure 7.



Propylene Glycol

Figure 7. Optimized Conditions for High Conversion Nitrosyl Transfer in the Reaction of Propylene Glycol with Tert-butyl Nitrite.

Considering no PGDN was observed in any of these experiments, the reports of Hirose, *et al*[13] were re-examined. The reaction conditions used in their report were investigated but with 20 equivalents of *tert*-butyl nitrite, both under oxygen purge and under open air (Table II, Entries 1 & 2), but no PGDN was observed by HPLC. The exact conditions used by Hirose, *et al* were examined (Entry 4), but again, no PGDN was observed. Conditions in Entries 5-7 were explored under the thought that an excess of *tert*-butyl nitrite and *tert*-butanol may have been impeding air oxidation; running with propylene glycol in slight excess did not lead to an observable PGDN formation by HPLC.

Table II. Attempts to Synthesize PGDN

Attempts to Synthesize PGDN instead of Dinitroso-propylene Glycol		
Entry	**Reaction Conditions**	**PGDN Detectable by HPLC?**
1	Add H_2O, 15°C, O_2 purge, 5 hrs	No
2	Add H_2O, 15°C, open air, 5 hrs	No
3	15°C, O_2 purge, 5 hrs	No
4	3 Equiv. *t*- BuONO, add H_2O, 20°C, O_2 purge, 5 hrs	No
5	1.3 equiv. PG, 1 equiv. *t*- BuONO	No
6	1.5 equiv. PG, 1 equiv. *t*- BuONO	No
7	2.0 equiv. PG, 1 equiv. *t*- BuONO	No

At this point, it was thought that exposing either *tert*-butyl nitrite or the nitrosyl transfer product to an oxidant could produce a mixture of reaction products that could facilitate nitrate ester formation. As shown in Figure 8, these reaction products could include NO_2, N_2O_3, an isomer of N_2O_4, or N_2O_5. An oxidant compatibility screen was performed, and the results are summarized in Table III. Hydrogen peroxide in concentration above 20 wt% resulted in observed violent decomposition and orange fume generation (Table III, Entries 1 & 2). At 20 wt%, gas generation was still observed, but slowed at lower temperatures (Entries 3 & 4). Use of *tert*-butyl hydroperoxide as the oxidant did not result in violent decomposition, but heat generation was still observed (Entries 5 & 6). At 25°C, a green color persisted. No reaction was observed with solid urea hydrogen peroxide (Entry 7), oxone (aqueous or solid, Entry 8), or potassium persulfate (aqueous or solid, Entry 9). Miscibility/solubility of the oxidant with *tert*-butyl nitrite was determined to be the major contributing factor to lack of reactivity for these oxidants. TEMPO (Entry 9) did react to give an orange precipitate. Analysis of the orange precipitate by NMR appeared very similar to TEMPO, indicated reaction may have occurred with TEMPO involving the ring C-H. At this point, it was decided that *tert*-butyl hydroperoxide and 20% hydrogen peroxide would be suitable oxidants to examine moving forward.

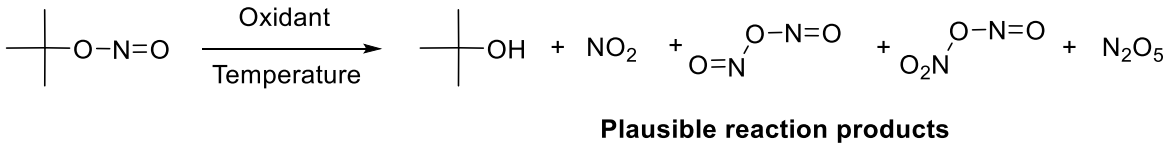


Figure 8. Plausible Oxidation Products of Tert-butyl Nitrite and an Oxidant that could Lead to Nitrate Ester Formation

Table III. Oxidant Compatibility Screen with Tert-butyl Nitrite

Oxidant Compatibility with *tert*- Butyl Nitrite			
Entry	**Oxidant**	**Temp. (°C)**	**Observations**
1	50% H_2O_2	25	Violent decomposition & fume-off
2	50% H_2O_2	8	Violent decomposition & fume-off
3	20% H_2O_2	25	Bubbling/gas generation
4	20% H_2O_2	8	Bubbling/gas generation
5	70% *t*- BuOOH	25	Exotherm, gas generation, green color
6	70% *t*- BuOOH	8	Milder exotherm, clear
7	Urea · H_2O_2	25	No solubility; no reaction
8	Oxone	25	No solubility; no reaction
9	$K_2S_2O_8$	25	No solubility; no reaction
10	TEMPO	25	Orange color, yellow precipitate

Attempts to isolate propylene glycol dinitrate as a pure compound proved difficult due to its known high vapor pressure. It was decided that glycerol would be used as the substrate for studies moving forward (Figure 9). Around this time, a new report by Bag, *et al*[29] was published which also investigated nitrate ester generation from alcohols with application to active pharmaceutical ingredients for heart disease. In that report, it was found that nitrate esters were not directly accessible from alcohols. Instead, only the nitrosyl transfer previously described by Doyle was observed. The authors of this report did find, however, that nitrate esters were directly accessible from peroxy-alcohols (Figure 10), and in cases where nitrate esters were generated from alkenes, as in the case of the report by Hirose, the reaction proceeded through a peroxide intermediate that was converted into a peroxynitrite which would rearrange to the nitrate ester. At the same time, we began considering the possibility of using the oxidant to generate peroxynitrite *in-situ* from the alkyl nitrite, which would hopefully undergo that same type of rearrangement.

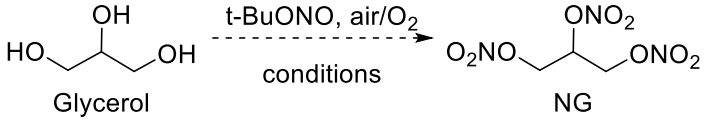


Figure 9. Attempted Reaction of Glycerol with Tert-butyl Nitrite Under Various Conditions Toward Synthesizing Nitroglycerin

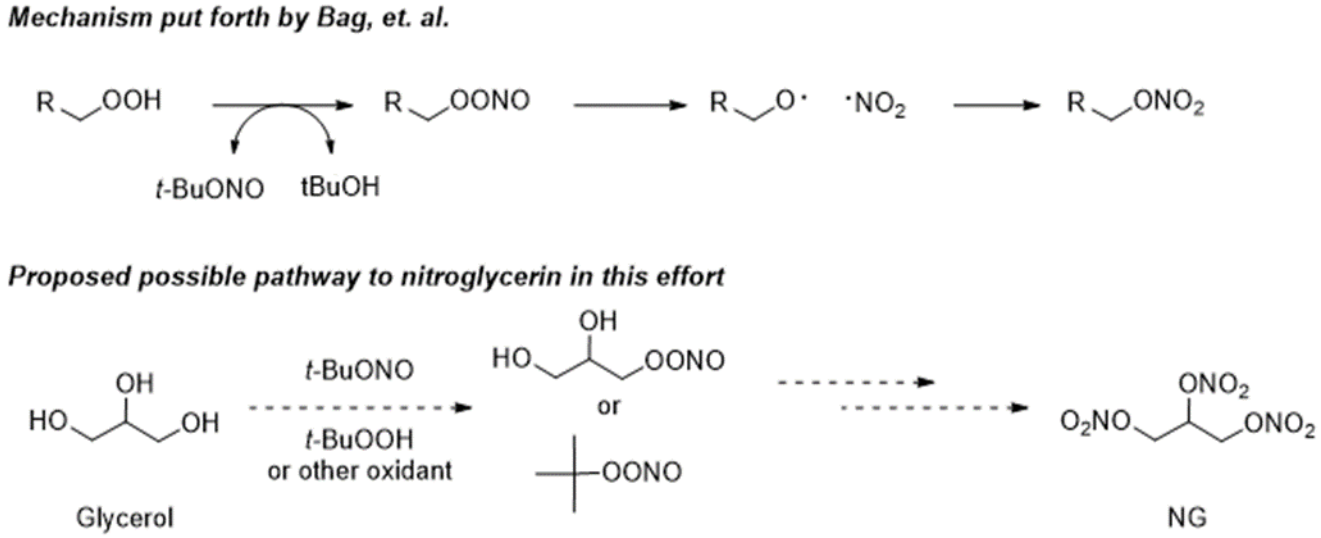


Figure 10. Nitrate Esters Were Reported to be Accessible Through a Peroxynitrite Intermediate.

As shown in Table IV, conditions with this information in mind were examined. As with propylene glycol, when glycerol was subjected to excess t*ert*-butyl nitrite, only nitrosation products were observed, including incomplete reaction. When *tert*-butyl hydroperoxide was used as the oxidant, the yields were much lower, with more water-soluble decomposition products being formed (Entries 2 & 3). The major products, identified by ^{1}H NMR, were still alkyl nitrites. Nitrate ester was observed in trace quantities as well by ^{1}H NMR. When *tert*-butyl nitrite was added to a mixture of glycerol and *tert*-butyl hydroperoxide (Entry 4), a white polymer was observed as the product. When excess *tert*-butyl hydroperoxide was added to a mixture of glycerol and *tert*-butyl nitrite (Entry 5), only unidentifiable decomposed material was recovered. At this point, it was discovered that Sigma-Aldrich offered another "90% grade" of *tert*-butyl nitrite. For thoroughness, this grade of t*ert*-butyl nitrite was also tested. As shown in Entries 6-8, when the "90%" grade *tert*-butyl nitrite was examined, small amounts of nitroglycerin were observed by ^{1}H and ^{13}C NMR and was confirmed by HPLC. These results were found to be reproducible and were independently verified by the Chemical Analysis Branch at NSWC IHEODTD using their calibrated HPLC method for detecting nitroglycerin. In Entries 9 &10, catalysts which showed results in the aromatic nitration component of this effort were also examined. Unfortunately, neither copper (II) catalyst provided the desired reactivity.

Table IV. Reaction Screen of Glycerol with Tert-butyl Nitrite

Reaction of Glycerol with *t*-BuONO		
Entry	**Reaction Conditions**	**Result**
1	20 equiv. *t*- BuONO, 25°C	Nitrosation products
2	3.5 equiv. *t*- BuONO; 3.5 equiv. 70% *t*-BuOOH 5°C	Nitrites (major), Nitrate ester (minor, small)
3	**2**, adding glycerol to *t*- BuONO/*t*- BuOOH mixture	Nitrites (major), Nitrate ester (minor, small)
4	**2,** adding *t*-BuONO to glycerol/*t*-BuOOH mixture	White polymer
5	**2**, add excess *t*-BuOOH	Decomposed material
6	5.00 equiv. *t*-BuONO ("90%") 25°C, air	Nitrites (major), Nitroglycerin (minor, NMR)
7	5.00 equiv. *t*-BuONO ("90%") 25°C, O_2	Nitrites (major), Nitroglycerin (minor, NMR/HPLC)
8	5.00 equiv. *t*-BuONO ("90%") 40°C, O_2	Nitrites (major), Nitroglycerin (minor, NMR/HPLC)
9	3.5 equiv. *t*- BuONO; 5 mol% $Cu(HFAcAc)_2$ 25°C	Nitrites; no nitrate ester
10	3.5 equiv. *t*- BuONO; 5 mol% $Cu(NO_3)_2$ 25°C	No product

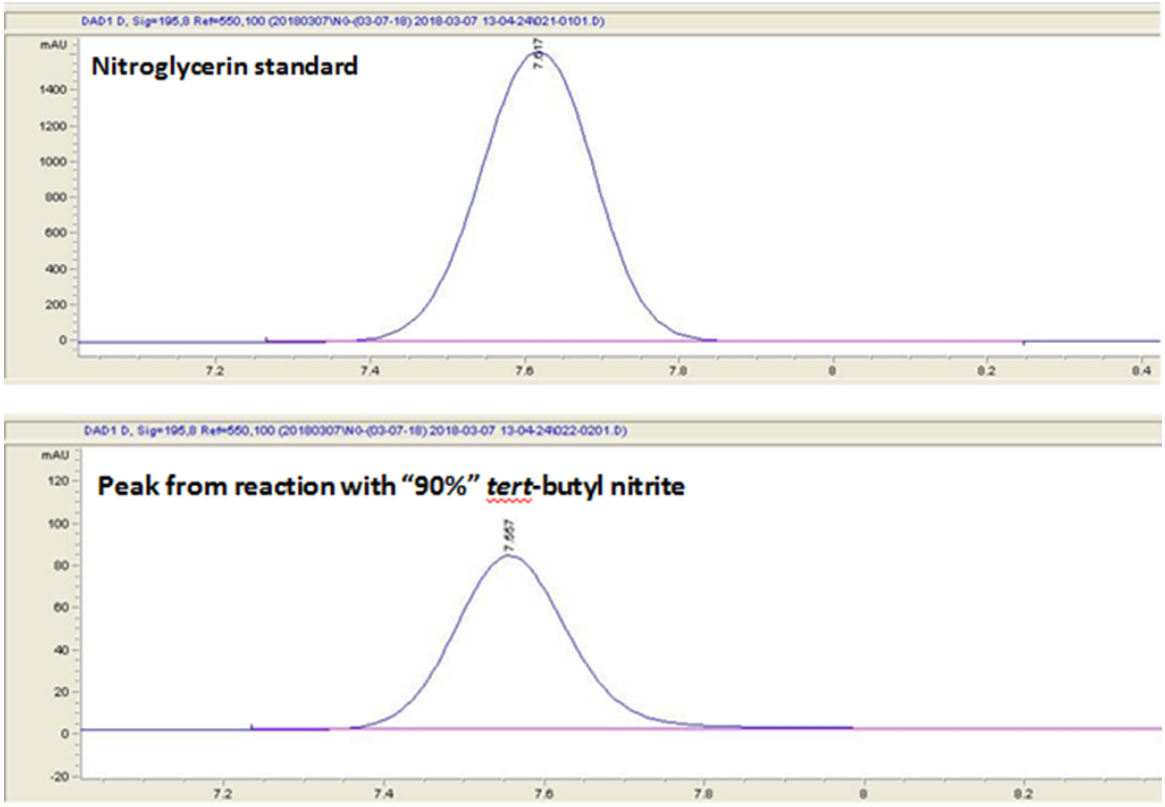


Figure 11. HPLC of Crude Product from Table IV, Entry 7, Indicating Presence of Nitroglycerin

The final experiments performed toward obtaining nitrate esters in useful yield examined the use of 20 wt% hydrogen peroxide with the "higher purity" *tert*-butyl nitrite (Figure 12). In each reaction, gas generation was observed even at low temperature. The reaction products appeared to contain some kind of mixture of alkyl nitrite with possible nitrate ester present by ^{1}H NMR, but ^{13}C NMR analysis did not confirm the presence of PGDN or NG.

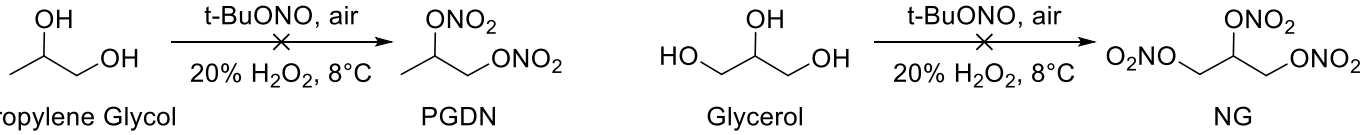


Figure 12. Attempted Reaction of Propylene Glycol and Glycerol with Tert-butyl Nitrite in the presence of 20% Hydrogen Peroxide

The results from Table IV, Entries 6 – 8 provided interesting and unexpected data based upon previous data obtained in this study. It should be noted that the t*ert*-butyl nitrite that provided trace amounts of nitroglycerin was from the same batch number as the ">90% by GC" *tert*-butyl nitrite obtained from Sigma-Aldrich that was used in the previous experiments. Sigma-Aldrich claimed that for ">90% grade," the remainder of the material was *tert*-butanol. The comments on the "90%" grade from Sigma-Aldrich were that the material consisted of only t*ert*-butyl nitrite and could only be certified pure up to 90%. This means the two different grades were likely purified differently. The results in Table IV, Entries 2 & 3, where t*ert*-butyl hydroperoxide was added, also produced small amounts of nitroglycerin by NMR. It is therefore plausible that small amounts of oxidation to obtain a peroxynitrite intermediate may be occurring when very high purity tert-butyl nitrite is used. Another possibility is that small amounts of *tert*-butyl peroxynitrite may be present in the "90%" grade t*ert*-butyl nitrite that reproducibly afforded small amounts of nitroglycerin.

Reaction of tert-butyl nitrite with toluene

While there have been numerous precedents for aromatic nitration using *tert*-butyl nitrite, all of the precedents have involved the use of a directing group present on the ring. Methods involving the use of *tert*-butyl nitrite to access nitration products of toluene, for example, are unprecedented. Nitration of inactivated alkenes, however, were known in the literature, giving the nitration of toluene through this method plausibility. As shown in Figure 13, the goal of this effort was to find reaction conditions that could access various degrees of nitration of toluene using *tert*-butyl nitrite.

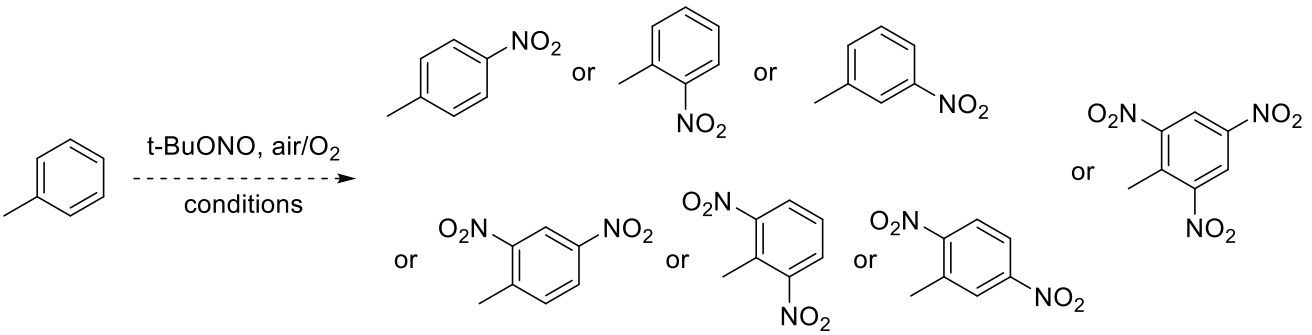


Figure 13. Attempted Reaction of Toluene with Tert-butyl Nitrite

Table V summarizes the experiments performed to find reaction conditions that could afford nitration of toluene in the presence of *tert*-butyl nitrite and oxygen. These reactions were followed by TLC with co-spot with 4-nitrotoluene and any crude reaction products were examined by NMR. As shown in Entries 1-3, exposing toluene to t*ert*-butyl nitrite with heating affords no reaction at all. In the presence of water, it was thought some HONO could form and react with toluene (Entries 4 & 5), and some oxime was observed as a product (Figure 13) of the reaction in Entry 5. Various catalysts were screened to facilitate aromatic C-H nitration. Copper (II) bromide gave no reactivity (Entry 6). Copper (II) chloride gave trace crude product with a complex mixture of various nitration and possibly also nitrosation products, but only when *tert*-butyl nitrite was present in excess (Entries 7 & 9). Catalytic TEMPO afforded trace amounts of unidentified products (Entries 8, 10, 11), but stoichiometric TEMPO afforded no desired products (Entry 12) and instead gave the orange solid observed in Table III, Entry 10. Copper (II) chloride (Entry 13), copper (II) acetylacetonate (Entry 14), copper (II) trifluoroacetylacetonate (Entry 15), and copper (II) hexafluoroacetylacetonate ($Cu(HFAcAc)_2$, Entry 16) were all screened at 30 mol% using 3 equivalents of *tert*-butyl nitrite. Only copper (II) hexafluoroacetylacetonate gave detectable nitration products by TLC and NMR. Both Pd^0 (Entry 17) and Pd^{II} (Entry 18) were examined, but neither afforded any reactivity. Nickel (II) acetylacetonate (Entry 19) afforded trace amounts of mono-nitration product at 30 mol% catalyst loading, but no reactivity was observed at lower catalyst loading (Entry 21). Likewise, nickel (II) chloride afforded no product at 10 mol% catalyst loading (Entry 20). Examining $Ni(AcAc)_2$ with BiPy and BrettPhos ligands (Entries 22 & 23) only afforded reaction on the ligands. Reaction with copper (II) nitrate (Entry 24) gave small amounts of reaction, which resulted in <5% crude material composed of a complex product mixture. Performing reaction with 10 mol% $Cu(HFAcAc)_2$ (Entry 25) gave a mixture of mono- and di-nitration products. Examining the same catalyst loading but with BiPy (Entry 26) and BrettPhos (Entry 27) afforded no detectable reaction products. As shown in Entry 28, doubling the equivalents of *tert*-butyl nitrite used with 10 mol% $Cu(HFAcAc)_2$ did not significantly impact the reaction yields, even at the gram scale. In this particular reaction, one equivalent was added first, and then a second equivalent was added at 60°C. The reaction products from Entry 28 were isolated by flash column chromatography and analyzed by NMR. The two isolated products were identified to be mixtures of mono-nitration isomers and di-nitration isomers. The NMR spectra of the chromatographed isomer mixtures are displayed in Figures 14 and 15.

Table V. Reaction Condition Screening toward the Nitration of Toluene using Tert-butyl Nitrite. *Reaction Products Were Isolated; Mono-nitration Isomeric Mixture in 5% Isolated Yield, Di-nitration Isomeric Mixture in 10% Isolated Yield at Gram Scale

Screen: Reaction of Toluene with *tert*- Butyl Nitrite (all reactions under O_2 purge)				
Entry	**Equiv. tBuONO**	**Temp. (°C)**	**Catalyst/Additive**	**Result**
1	up to 20	20	None	No reaction
2	up to 20	40	None	No reaction
3	up to 20	60	None	No reaction
4	up to 20	25	H_2O (3.00 equiv.)	No reaction
5	10	60	H_2O (5.00 equiv.)	Oxime (<10%)
6	20	25	3 mol% $CuBr_2$	No reaction by TLC or NMR
7	20	25	3 mol% $CuCl_2$	Complex product mixture (<10%, NMR)
8	20	25	3 mol% TEMPO	Mixture of products (<5%, NMR)
9	20	50	3 mol% $CuCl_2$	Complex product mixture (<10%, NMR)
10	10	20	3 mol% TEMPO (air)	Mixture of products (<5%, NMR)
11	10	20	3 mol% TEMPO	Mixture of products (<5%, NMR)
12	10	20	TEMPO (3.00 equiv)	No desired products (NMR)
13	3	60	30 mol% $CuCl_2$	No product by TLC
14	3	60	30 mol% $Cu(AcAc)_2$	No product by TLC
15	3	60	30 mol% $Cu(Trifluoro\text{-}AcAc)_2$	No product by TLC
16	3	60	30 mol% $Cu(Hexafluoro\text{-}AcAc)_2$	Mono-nitration by TLC, NMR (<25% yd), possibly Di-
17	3	60	30 mol% $Pd(dba)_2$	No product by TLC
18	3	60	30 mol% $Pd(OAc)_2$	No product by TLC
19	3	60	30 mol% $Ni(AcAc)_2$	Mono-nitration by TLC, mixture by NMR (10% yd)
20	3	60	10 mol% $NiCl_2$	No product by TLC
21	3	60	10 mol% $Ni(AcAc)_2$	No product by TLC
22	3	60	10 mol% $Ni(AcAc)_2$, 10 mol% BiPy	Reaction on the ligand by NMR
23	3	60	10 mol% $Ni(AcAc)_2$, 10 mol% BrettPhos	Reaction on the ligand by NMR
24	3	60	10 mol% $Cu(NO_3)_2$	Reaction by TLC; complex mixture by NMR, (<5%)
25	3	60	10 mol% $Cu(HFAcAc)_2$	Mono- & Di-nitration by TLC, NMR (<20% yd)
26	3	60	10 mol% $Cu(HFAcAc)_2$, 10 mol% BiPy	No product by TLC
27	3	60	10 mol% $Cu(HFAcAc)_2$, 10 mol% Brettphos	No product by TLC
28	6	60	10 mol% $Cu(HFAcAc)_2$	Mono- & Di-nitration by TLC, NMR (<20% yd)*

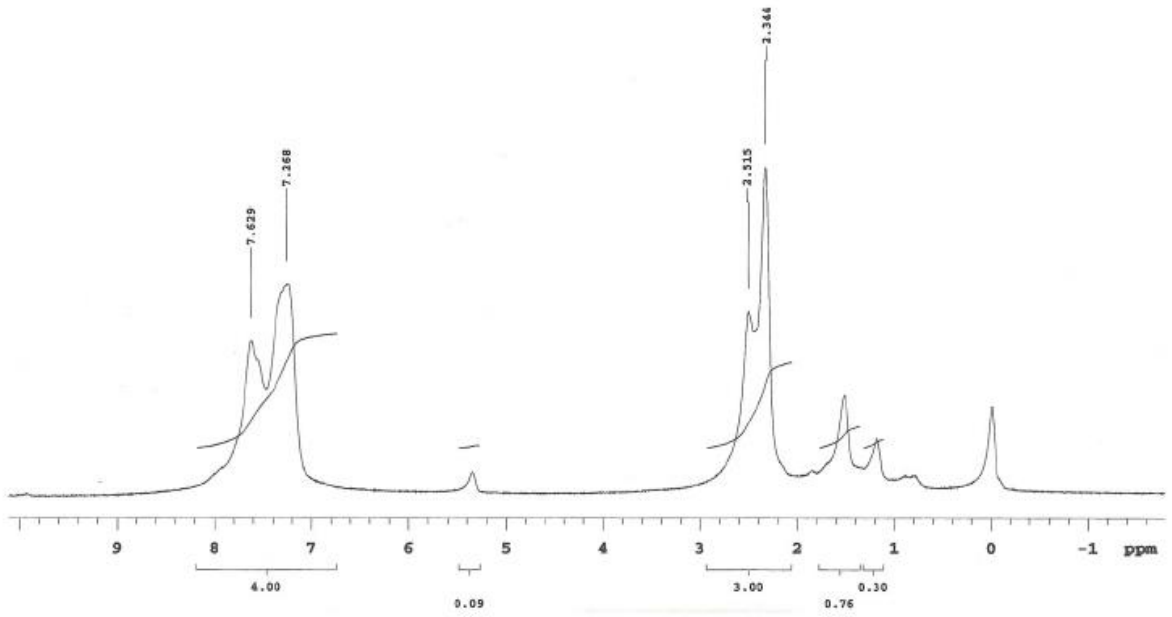


Figure 14. ^{1}H NMR Spectra of Chromatographed Mono-nitration Isomeric Mixture; Contains Complexed Copper which is Causing Peak Broadening in the Spectral Data

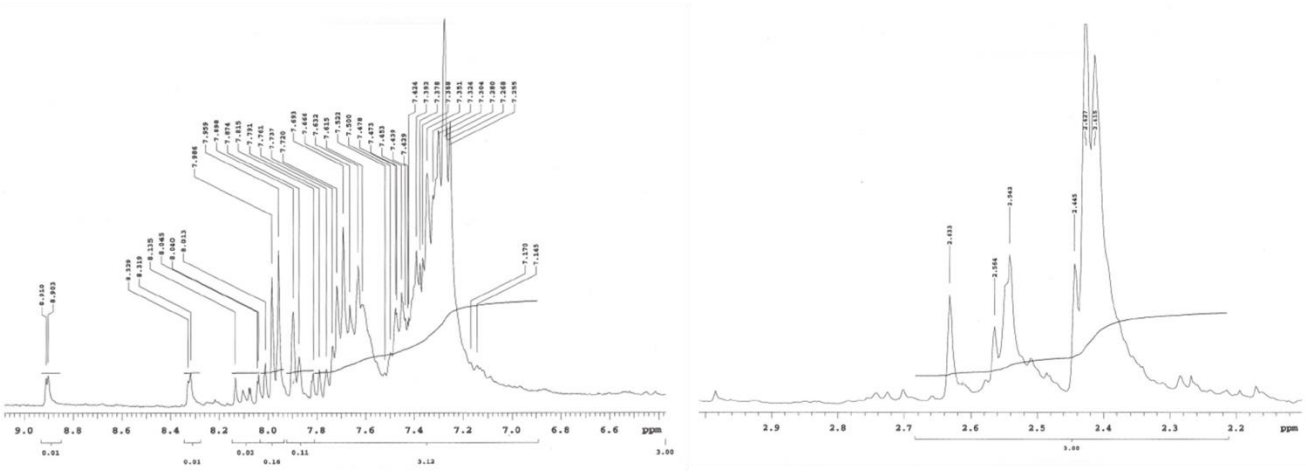


Figure 15. ^{1}H NMR Spectra (magnified) of Chromatographed Di-nitration Isomeric Mixture

Reaction of Hexamine with Tert-butyl Nitrite

The synthesis of RDX (and/or HMX) from hexamine and *tert*-butyl nitrite was proposed to be performed using various additives, such as nitrate salts, in order to mimic the conditions necessary for the nitrolysis of hexamine like those in the N_2O_5 mediated nitrolysis mechanism[30] while maintaining mild, non-acidic conditions (Figure 16). Various reaction conditions were examined toward the nitrolysis of hexamine in the presence of *tert*-butyl nitrite and a nitrate salt (Figure 17). These results are summarized in Table VI. When no additive is used (Entries 1 & 2), there is no reaction, even when heating. When sodium nitrate is added (Entry 3), solubility is too poor to induce reactivity. When water is added to sodium nitrate in the presence of *tert*-butyl nitrite (Entry 4), a small amount of reaction occurs that is attributed to partial ring opening. When acetonitrile (Entry 5), N,N-dimethylformamide (Entry 6), and dimethylsulfoxide (Entry 7) are added to sodium nitrate and *tert*-butyl nitrite, only trace reactivity with hexamine is observed. When tetramethylammonium nitrate was used as the salt additive (Entries 8 & 9), trace amounts of chemical shifts commonly assigned[31] to RDX (sharp singlet around 6.0 ppm) and possibly HMX (sharp singlet around 6.1 ppm) were observed in the crude ^{1}H NMR data when acetonitrile was added as a co-solvent. Copper (II) nitrate with added acetonitrile (Entry 11) gave only small amounts of reaction as well, but significantly more of the chemical shift commonly assigned to RDX was observed in the crude ^{1}H NMR data. Silver nitrate with added acetonitrile (Entry 13) gave similar reactivity and product distribution to the result using copper (II) nitrate.

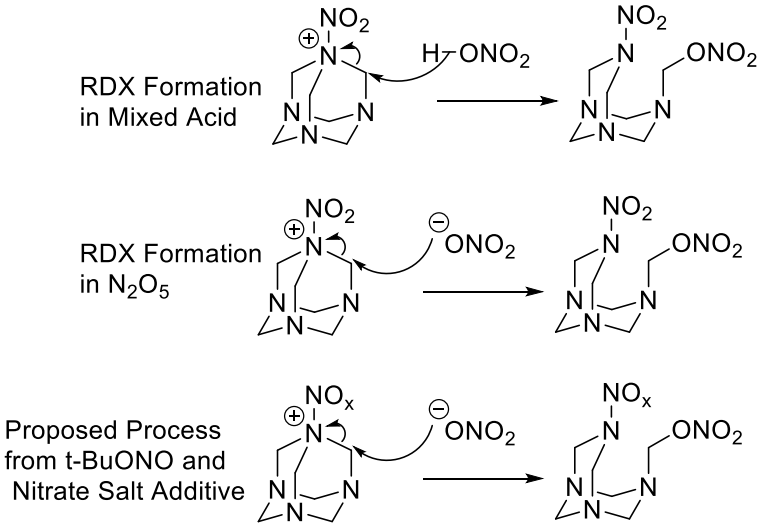


Figure 16. Proposed Mechanism for Nitrolysis: Hexamine in the Presence of Tert-butyl Nitrite and Nitrate Salt

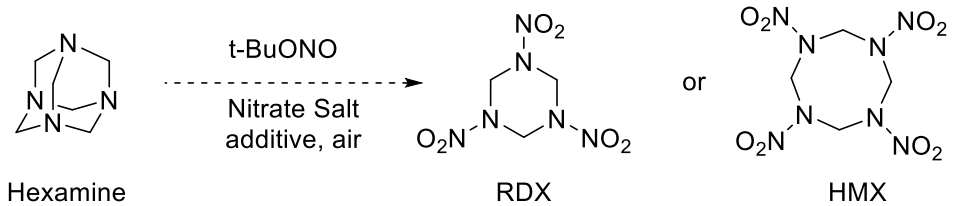


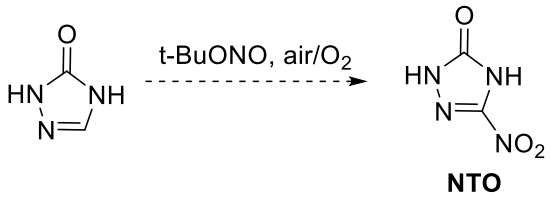
Figure 17. Attempted Nitrolysis of Hexamine using Tert-butyl Nitrite and a Nitrate Salt

Table VI. Reaction Condition Screening Toward the Nitrolysis of Hexamine

Attempted Nitrosative/Nitrative Cleavage of Hexamine				
Entry	**Equiv. tBuONO**	**Temp. (°C)**	**Catalyst/Additive**	**Result**
1	6	20	None	No reaction by NMR
2	6	60	None	No reaction by NMR
3	6	25	Sodium Nitrate	No reaction by NMR
4	6	25	$NaNO_3$+ H_2O	Partial ring opening by NMR (<10% yd)
5	6	25	$NaNO_3$+ MeCN	Trace reaction by NMR
6	6	25	$NaNO_3$+ DMF	No reaction by NMR
7	6	25	$NaNO_3$+ DMSO	Trace reaction by NMR
8	6	25	NMe_4NO_3	No reaction by NMR
9	6	25	NMe_4NO_3 + MeCN	Partial ring opening by NMR (<10% yd); traces of RDX + HMX by NMR
10	6	25	$Cu(NO_3)_2$	No reaction by NMR
11	6	25	$Cu(NO_3)_2$ + MeCN	Partial ring opening by NMR (<10% yd); RDX present by NMR
12	6	25	$AgNO_3$	No reaction by NMR
13	6	25	$AgNO_3$ + MeCN	Partial ring opening by NMR (<10% yd); RDX present by NMR

Reaction of Triazolone with Tert-butyl Nitrite

The synthesis of 3-nitro-triazolone (NTO, Figure 18) was attempted using *tert*-butyl nitrite. As shown in Table VII, when triazolone was exposed to *tert*-butyl nitrite, no reactivity was observed, even when water (Entry 2) or acetonitrile (Entry 3) were added. In the case of no additive (Entry 1), no solubility was observed, and starting material was completely recovered. Solubility was deemed to be too much of an issue for this substrate, and further study for solventless nitration was not pursued.



NTO

Figure 18. Attempted Nitration of Triazolone

Table VII. Reaction Condition Screening Toward the Nitration of Triazolone

Entry	**Equiv. tBuONO**	**Temp. (°C)**	**Additive**	**Result**
1	6	25	None	No reaction by NMR or TLC
2	6	25	H_2O	No reaction by NMR or TLC
3	6	25	MeCN	No reaction by NMR or TLC

MATERIALS AND METHODS

General Considerations

^{1}H NMR and ^{13}C NMR spectra were obtained on either an Anasazi 90 MHz spectrometer or an Agilent 300 MHz spectrometer. The chemical shifts of the compounds as solutions in $CDCl_3$ and DMSO-d_6 are measured against the respective residual solvent peaks and/or TMS. Integration assignments were interpreted to the nearest whole number of protons unless otherwise noted. All reactions were carried out in 25 mL EasyMax Tubes unless noted otherwise. Temperatures for reactions were achieved using an aluminum block controlled by an EasyMax jacket.

General Screening Procedure – Nitrate Esters

A predetermined amount of *tert*-butyl nitrite was added to a 25 mL EasyMax reaction tube equipped with a magnetic stir bar and a thermocouple. The jacket temperature of the aluminum heating block was adjusted to a predetermined setting, and agitation is initiated to a predetermined setting (typically 500 rpm) to ensure good mixing. An optional catalyst of predetermined amount may be added. An optional oxidant (*tert*-butyl hydroperoxide or 20 wt% hydrogen peroxide) may be added very slowly by syringe at this point instead of a catalyst, such that the internal reaction temperature did not exceed 12°C. A predetermined amount of alcohol (propylene glycol or glycerol) was added slowly by syringe to the reaction vessel. If oxidant had not been previously added, at this point oxidant may be optionally added slowly by syringe such that the internal reaction temperature did not exceed 12°C. The reaction was allowed to stir at a predetermined temperature for a predetermined amount of time. The reaction temperature was then returned to 25°C, and the *tert*-butyl nitrite was removed by sparging with either oxygen or air to afford a crude product. The crude product was analyzed by NMR and HPLC.

Experimental for Table IV, Entry 7

tert-Butyl nitrite (2.27 g, 2.62 mL, 0.0220 mol) was added to an oxygen-purged 25 mL EasyMax reaction tube equipped with a magnetic stir bar and a thermocouple. The jacket temperature of the aluminum heating block was adjusted to 25°C, and agitation is initiated, set at 500 rpm to ensure good mixing. Glycerol (0.407g, 0.00442 mol) was added by syringe to the reaction vessel. The reaction was allowed to stir at a 25°C for 6 hours. Unreacted *tert*-butyl nitrite was removed by sparging to afford a crude product; duplicate runs were set up, with one experiment being sparge with oxygen and the other with air. The crude product was analyzed by NMR (DMSO-d_6), and HPLC; nitroglycerin was detected in small amounts.

General Screening Procedure – Nitration of Toluene

A predetermined amount of catalyst and *tert*-butyl nitrite were added to an oxygen-purged 25 mL EasyMax reaction tube equipped with a magnetic stir bar and a thermocouple. The jacket temperature of the aluminum heating block was adjusted to a predetermined setting, and agitation is initiated to a predetermined setting (typically 500 rpm) to ensure good mixing. A predetermined amount of toluene was added by syringe to the reaction vessel. The reaction was allowed to stir at a predetermined temperature for a predetermined amount of time. The reaction temperature was then returned to 25°C, and the *tert*-butyl nitrite and unreacted toluene were removed either under reduced pressure by rotovap or by sparging with air or oxygen. The crude product was analyzed by NMR.

Experimental for Nitration of Toluene – Table V, Entry 28

Copper (II) hexafluoroacetylacetonate (110 mg) and *tert*-butyl nitrite (454 mg, 0.524 mL, 4.40 mmol), 1.00 equivalent) were added to an oxygen-purged 25 mL EasyMax reaction tube equipped with a magnetic stir bar and a thermocouple. The jacket temperature of the aluminum heating block was adjusted to a 25°C, and agitation is initiated to a setting of 500 rpm to ensure good mixing. Toluene (406 mg, 0.466 mL, 4.40 mmol 1.00 equivalent) was added by syringe to the reaction vessel. The reaction was heated to 60°C over a period of 20 minutes and allowed to stir at temperature for one hour. Additional *tert*-butyl nitrite was added in two portions each consisting of 1.00 equivalent (454 mg, 0.524 mL, 4.40 mmol), and the reaction was allowed to stir at 60°C for a total of 6 hours. The reaction temperature was then returned to 25°C, and the *tert*-butyl nitrite and unreacted toluene were removed either under reduced pressure by rotovap. The crude product was analyzed by TLC and NMR, which indicated isomeric mixtures of mono-nitration and possibly di-nitration products were formed. The crude product was chromatographed on 60A° mesh silica gel while eluting with a gradient of 2%-20% ethyl acetate/hexanes, and the eluted products were analyzed by NMR. Isomeric mixtures of mono-nitration products were recovered in mass of 46 mg in the fast-eluting fractions, and isomeric mixtures of the di-nitration products were recovered in mass 66 mg in the slow-eluting fractions.

General Screening Procedure – Nitration of Hexamine

A predetermined amount of hexamine, nitrate salt, and *tert*-butyl nitrite were added to a 25 mL EasyMax reaction tube equipped with a magnetic stir bar and a thermocouple. The jacket temperature of the aluminum heating block was adjusted to a predetermined setting, and agitation is initiated to a predetermined setting (typically 500 rpm) to ensure good mixing. A predetermined amount of co-solvent additive (water, acetonitrile, N,N-dimethylformamide, or dimethylsulfoxide) was added by syringe to the reaction vessel. The reaction was allowed to stir at a predetermined temperature for a predetermined amount of time. The reaction temperature was then returned to 25°C, and the excess *tert*-butyl nitrite was removed either under reduced pressure by rotovap or by sparging with air or oxygen. The crude product was analyzed by NMR.

General Screening Procedure – Nitration of Triazolone

A predetermined amount of triazolone, and *tert*-butyl nitrite were added to a 25 mL EasyMax reaction tube equipped with a magnetic stir bar and a thermocouple. The jacket temperature of the aluminum heating block was adjusted to a predetermined setting, and agitation is initiated to a predetermined setting (typically 500 rpm) to ensure good mixing. A predetermined amount of co-solvent additive (water or acetonitrile) was added by syringe to the reaction vessel. The reaction was allowed to stir at a predetermined temperature for a predetermined amount of time. The reaction temperature was then returned to 25°C, and the excess *tert*-butyl nitrite was removed either under reduced pressure by rotovap or by sparging with air or oxygen. The crude product was analyzed by NMR.

CONCLUSIONS AND IMPLICATIONS FOR FUTURE RESEARCH

Nitrate Esters

During the course of this effort, a significant time investment was made into understanding how nitrate esters can be accessed using *tert*-butyl nitrite. It was discovered that the initial understanding of a simple nitrosyl transfer and air oxidation mechanism to nitrate esters was not correct. Instead, nitrate esters are now known to be accessible from peroxides, as reported by Bag, *et al.*[29] Unfortunately, there are no known ways to safely make propylene glycol dihydroperoxide or glycerol trihydroperoxide, let alone a solventless and environmentally friendly method. Methods that could lead to such products *in-situ* would likely require the use of solvents. The use of a co-oxidant to encourage peroxynitrite formation and rearrangement to nitrate ester only gave traces of nitrate ester by NMR.

Interestingly enough, switching to a "different" purity (this is still not confirmed; no discernable difference by NMR analysis of the two grades) of *tert*-butyl nitrite available from Sigma-Aldrich provided trace amounts of nitroglycerin, and this phenomenon is reproducible. Heating the reaction does not increase the yield of nitroglycerin, nor does post-process treatment of this product mixture with oxygen. The working hypothesis from the data available is that this "different" grade of *tert*-butyl nitrite either is able to oxidize glycerol to the trihydroperoxide during the course of the reaction, or this particular batch of *tert*-butyl nitrite contains small amounts of *tert*-butyl peroxynitrite.

In its current state, this research is not ready to transition to a scale-up effort. Nitroglycerin has only been synthesized in trace quantities, and it is still not fully understood how it is being made in spite of the amount of work performed. If this work were to continue, significant amounts of research would need to be conducted in order to fully understand just how nitroglycerin is being accessed in trace quantities from this "different" purity *tert*-butyl nitrite and exploit that chemistry once the identity of the minor reaction pathway is discovered.

Nitroaromatics

During the course of these studies, it was shown that it is possible to nitrate toluene in the presence of *tert*-butyl nitrite and a catalyst at elevated temperature. It was discovered that copper catalysts with ligands containing strong electron withdrawing groups provided the desired reactivity. Although the yields are not high, isomeric mixtures of mono- and di- nitrotoluene products were accessed, which is unprecedented. The mono- and di-nitration products were found to be separable from each other (still as isomeric mixtures) by flash column chromatography. While no trinitrotoluene (TNT) was detected from the reactions performed thus far, these results are highly encouraging.

We recommend further development work in this research area, as the work so far has yielded promising, unprecedented results. It is not unreasonable to think that different catalysts and/or more forcing temperature and pressure regimes could provide access to TNT in useful yields. Future work would examine a broadened scope of transition metal catalysts, focusing on the use of electron deficient ligands. The temperature regimes explored thus far only investigated up to near the boiling point of *tert*-butyl nitrite, but future work would allow for chemistry in a pressure vessel instead of a conventional glass reaction vessel to encourage higher degrees of nitration.

Nitramines from Hexamine

During the course of our studies on the reaction of hexamine with *tert*-butyl nitrite and a nitrate salt, it quickly became clear that truly solventless nitration would not be achievable on hexamine to produce RDX or HMX. The reason for this is the solubility of hexamine in *tert*-butyl nitrite is quite poor, even near reflux temperatures. The solubility of nitrate salts, even tetramethylammonium nitrate, are also poor in *tert*-butyl nitrite. A co-solvent was found to be necessary for reaction to proceed, but when keeping solvent levels low enough to the point where they could be considered additives (which may still be a stretch) was insufficient to afford desired reaction products in useful quantities. The actual use of a solvent likely would increase the reaction yield, but this would be outside the scope of the SERDP SEED program. Further work on this component is not recommended.

REFERENCES

1. a) Treacy, J. C. US Patent, US 2739166 December 19, 1950. b) Spaeth, C. P. US Patent, US 2831882 September 16, 1955.
2. a) Glover, S. A.; Goosen, A.; McCleland, C. W.; Vogel, F. R. *S. Afr. J. Chem.*, **1981**, *34*, 96-100. b) Williams, D. L. *Nitrosation*, Cambridge University Press: Cambridge, pp. 150-172, 1988 and references cited therein. c) Fruchey, O. S. US Patent, US 4980496 December 25, 1990. d) Wei, X.-H.; Zhou, K.-Y.; Jiang, C.-X.; Yang, L.-R. *Zhejiang Huagong* **2013**, *44*, 7-9.
3. a) Das, J.; Patil, S. N.; Awasthi, R.; Narasimhulu, C. P.; Trehan, S. *Synthesis*, **2005**, 1801. b) Syn*lett.* **2010**, 904-808. c) Meng, G.; Yang, T.; Liu, Y. *Org. Prep. Proc. Int.* **2011**, *43*, 354-359. d) Jiang, B.; Huang, C.; He, J. *Faming Zhaunli Shenqing*, CN 103012310 April 3, 2013. e) Liu, J.; Zheng, H.-X.; Yao, C.-Z.; Sun, B.-F.; Kang, Y.-B. *J. Am. Chem. Soc.* **2016**, *138*, 3294-3297. f) Liu, Z.; Liu, L.; Hao, G.; Zhang, M.; Li, J. *Faming Zhaunli Shenqing*, CN 105237403 A January 13, 2016.
4. Monbaliu, J.-C. M.; Jorda, J.; Bérengére, C.; Stevens, C. V.; Morvan, B. *Chemistry Today*, **2011**, *29*, 50-52.
5. Lasalle, A.; Roizard, C.; Midoux, N.; Bourret, P.; Dyens, P. J. *Ind. Eng. Chem. Res.* **1992**, *31*, 777-780.
6. Lazny, R.; Aneta, N.; Nodzewska, M.; Sienkiewicz, M.; Wolosewicz, K. *J. Comb. Chem.* **2005**, *7*, 109.
7. Koley, D.; Colon, O. C.; Savinov, S. N. *Org. Lett.* **2009**, *11*, 4172.
8. Prateeptongkum, S.; Jovel, I.; Jackstell, R.; Vogl, N.; Weckbecker, C.; Beller, M. *Chem. Commun.* **2009**, *15*, 1990.
9. Taniguchi, T.; Yajima, A.; Ishibashi, H. *Adv. Synth. Catal.* **2011**, *353*, 2643-2647.
10. Taniguchi, T.; Sugiura, Y.; Hatta, T.; Yajima, A.; Ishibashi, H. *Chem. Commun.* **2013**, *49*, 2198-2200.
11. Maity, S.; Naveen, T.; Sharma, U.; Maiti, D. *Org. Lett.* **2013**, *15*, 3384-3387.
12. Kilpatrick, B.; Arns, S. *Chem. Commun.***2013**, *49*, 514-516.
13. Hirose, D.; Taniguchi, T. *Beilstein J. Org. Chem.* **2013**, *9*, 1713-1717.
14. Majhi, B.; Kundu, D.; Ahammed, S.; Ranu, B. C. *Chem. Eur. J.* **2014**, *20*, 9862-9866.
15. Yang, X.-H.; Ouyang, X.-H.; Wei, W.-T.; Song, R.-J.; Li, J.-H. *Adv. Synth. Catal.* **2015**, *357*, 1161-1166.
16. Deng, G.-B.; Zhang, J.-L.; Liu, Y.-Y.; Liu, B.; Yang, X.-H.; Li, J.-H. *Chem. Commun.* **2015**, *51*, 1886-1888.
17. Doyle, M. P.; Terpstra, J. W.; Pickering, R. A.; LePoire, D. M. *J. Org. Chem.* **1983**, *48*, 3379.
18. Wismach, C.; Mont, W.-W.; Jones, P. G.; Ernst, L.; Papke, U.; Mugesh, G.; Kaim, W.; Wanner, M.; Becker, K. D. *Angew. Chem.* **2004**, *43*, 3970.
19. SanMartin, R.; Olivera, R.; Martinez de Marigorta, E.; Dominguez, E. *Tetrahedron* **1995**, *51*, 5361.
20. Hirabayashi, T.; Sakaguchi, S.; Ishii, Y. *Angew. Chem.* **2004**, *43*, 1120.
21. Devivar, R. V.; Drach, J. C.; Townsend, L. B. *Bioorg. Med. Chem. Lett.* **1992**, *2*, 1105-1110.
22. Akama, T.; Baker, S. J.; Zhang, Y.-K. *Bioorg. Med. Chem. Lett.* **2009**, *19*, 2129.
23. Barral, K.; Moorhouse, A. D.; Moses, J. E. *Org. Lett.* **2007**, *9*, 1809.
24. Palumbo Piccionello, A.; Pace, A.; Pierro, P.; Pibiri, I.; Buscemi, S.; Vivona, N. *Tetrahedron* **2008**, *65*, 119.
25. Xie, Y.; Mo, W.; Xu, D. *J. Org. Chem.* **2007**, *72*, 4288.
26. Chen, C.; Zhang, H.; Zhang, L.; Li, L.; Yan, Y. *Chin. J. Org. Chem.* **2008**, *28*, 1978.
27. Izumi, T.; Soutome, M.; Miura, T. J. *Heterocycl. Chem.***1992**, *29*, 1625.
28. a)Kuhn, L. P.; DeAngelis, L. *Am. Chem. Soc.* **1954**, *76*, 328. b) Kuhn, L. P.; Wright, R.; DeAngelis, L. *J. Am. Chem. Soc.* **1956**, *78*, 2719-22.
29. Bag, R.; Sar, D.; Punniyamurthy, T. *ACS Omega*, **2017**, *2*, 6278-6290.

REFERENCES (Continue)

30. Fischer, J. W.; York, S. P.; Atkins, R. L. *Synthetic Studies of Dinitrogen Pentoxide (N_2O_5)* **1987**, NWC TP 6739.
31. Szala, M.; Szymanczyk, L. *Cen. Eur. J. Ener. Mat.* **2014**, *11*, 129-142.

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