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Process Optimization, Product Profile Mapping and Intensification of 1, 1-Diamino-2,2-Dinitroethylene

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Abstract

Industrialization of a chemical process needs an understanding of process chemistry; optimal process envelope and the best choice of operation. 1,1-Diamino-2,2-dinitroethylene (FOX-7) is a new generation, and highly insensitive compound finds application in high energy formulations as well as preparation of novel high energy compounds. The present study highlights efforts made for establishing a continuous process for FOX-7. The intermediates of nitration of 2-methylpyrimidine-4, 6-dione were isolated and characterized by spectroscopic tools. Reaction kinetics was also derived for the formation of intermediates. Product profiles of reaction were evaluated on deriving expressions for various reactors. The simultaneous effect of heat and reaction was evaluated in a tubular reactor to obtain the runaway reaction condition. Effective reactor scheme was evaluated, designed and experimented. Process intensification was carried out in continuous set up comprising various contact patterns. The present study delivered a safe and productive method for FOX-7 processing.

Keywords: FOX-7, Reaction kinetics, Reactor design, Stability analysis, Process intensification

1. Introduction

1,1-Diamino-2,2-dinitroethene (FOX-7) has emerged as an interesting high explosive compound since its discovery because of its diversified applications. It has a superb explosive characteristics like high detonation performance, thermal stability, less sensitivity to impact and friction, etc.[1] Hence, it is reported as a potential candidate for high energy formulations over conventional secondary explosives such as 1,3,5-trinitro-1,3,5-triazinane (RDX) and 1,3,5,7-tetranitro-1,3,5,7-tetrazoctane (HMX) in view of comparable performance with enhanced safety.[2] Performance characteristics of FOX are provided in table S1 in supporting information. Ostmark et al.[3] reported the compatibility of FOX-7 with a range of binders (including GAP and HMDI) and the energetic plasticizers (butyl-NENA and K-10) which indicated its applicability in various high energy formulations. Stability of FOX-7 with TNT encouraged its usage in polymer bonded explosives (PBX).[4] FOX-7 and HMX containing PBX formulations showed better mechanical properties as well as comparable performance characteristics in comparison with RDX based PBX.[5] Moreover, FOX-7 containing shaped charges showed better characteristics of the cumulative jet as well as its penetration ability better than Hexotol (60% RDX and 40% TNT) charges.[6] Application of FOX-7 in aluminized composite propellant was found to be promising as FOX-7 decreased detonation properties of propellant without compromising performance characteristics.[7]

In addition, the “push-pull” effect in FOX-7 structure due to the presence of electron-donating amino groups and electron-withdrawing nitro groups on adjacent carbons has attracted great attention amongst academic and industrial chemists. Several derivatives of FOX-7 have been reported over the last five years which were obtained by condensation, halogenation, nitration, acid-base reactions, and coordination reactions.[8] FOX-7 is found as a superb precursor to acyclic or cyclic compounds; hence it has become important to synthetic chemistry community in the development and applications of its new derivatives. Study of the metals with FOX-7 highlights its features as a potential ligand or an anionic species.[9] Halogen, hydrazine and polynitro derivatives of FOX-7 are of great interest in energetic materials community as the products are found to be rich in energy content.[10] Some of the halogenated and polynitro derivatives of FOX-7 are yielded as oxygen-rich species and found application in propellant formulations.[11]

Thus, FOX-7 is a highly important compound for academic, industrial chemists and energetic community. Its diversified application in various fields demands process intensification study to meet the requirement in a huge way.

2. Synthesis routes of FOX-7

FOX-7 has a relatively simple molecular structure, while the chemical precursor to synthesize FOX-7 has been known for many years but obtaining the two amino groups on an ethene is difficult with straightforward synthetic techniques. A more complex nitrogen-containing heterocyclic ring is first nitrated, and then the ring is broken, forming both of the amines and the double bond to ethane. The different routes of FOX-7 synthesis are discussed below.

2.1 Route 1: Latypov et al. reported synthesis of FOX-7 from the nitration of 2-methylimidazole at a controlled temperature (15-20°C).[1a] 2-Dinitromethylene-5,5-dinitro-imidazolidin-4-one is one of the key intermediates (Figure 1) of the reaction which loses nitrogen oxides to obtain 2-dinitromethylene-imidazolidne-4,5-dione, which further dissolved in aqueous ammonia to yield bright yellow solid (FOX-7) with an overall yield of about 13%. Applicability of this route is limited due to temperature sensitive nature of reaction, formation of nitroformate and parabamic acid as byproducts, product contamination due to oxamide and low yield.

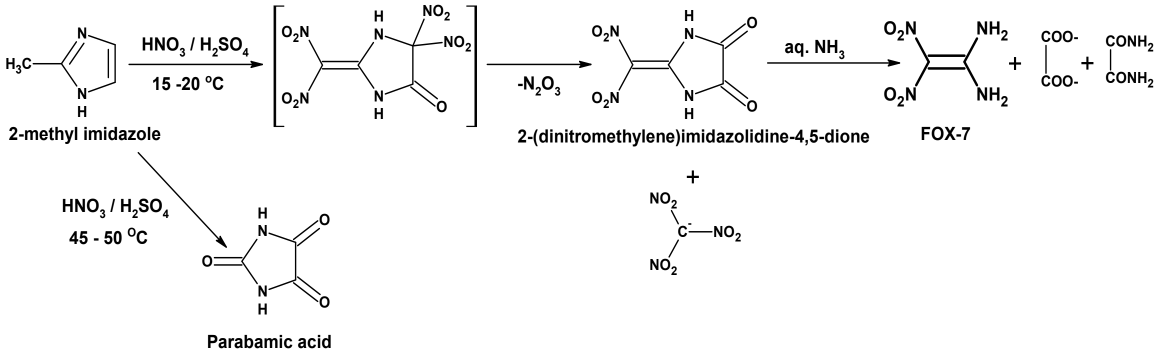


Figure 1. Reaction scheme for route 1: Nitration of 2-methylimidazole

2.2 Route 2: In this route (Figure 2), nitration of 2-methoxy-2-methyl-4,5-imidazolidinedione and /or 2-methyl-4,5-imidazolidinedione gives 2-dinitromethylene-imidazolidine-4,5-dione.[12] Henceforth ammonolysis path follows same as route 1 to yield FOX-7. However, process becomes unfeasible due cumbersome and inconvenient way of synthesizing starting materials, usage of dry HCl gas and product contamination.

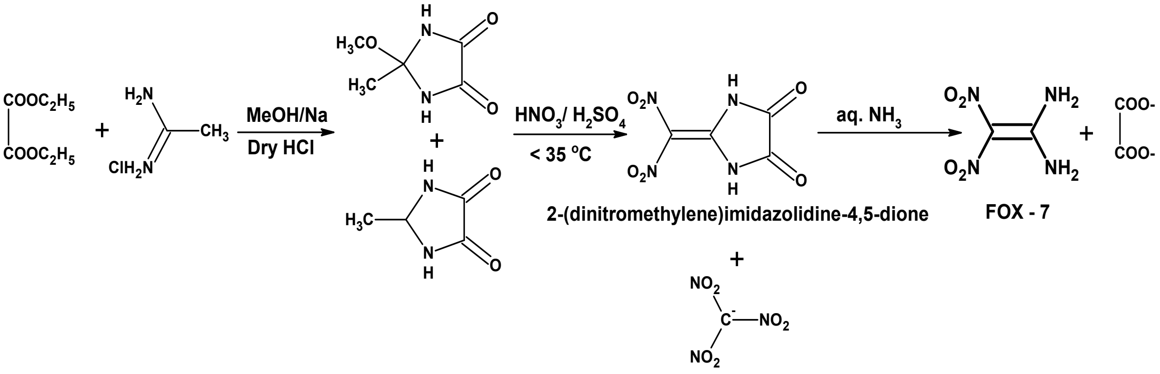


Figure 2. Reaction scheme for Route 2: Nitration of 2-methoxy-2-methyl-4,5-imidazolidinedione and /or 2-methyl-4,5-imidazolidinedione

2.3 Route 3: Astrat'ev et al.[13] reported synthesis of FOX-7 from nitration of 2-methyl-pyrimidine-4,6-dione in mixed acids at about 5 °C and followed by hydrolysis of 2-dinitromethylene-5,5-dinitro-dihydro-pyrimidine-4,6-dione (Figure 3). 2-Methyl-pyrimidine-4,6-dione is easily prepared from acetamidine hydrochloride and diethyl malonate in contrast to starting materials of above route. The overall yield of FOX-7 from of 2-methyl-pyrimidine-4, 6-dione is 80%.

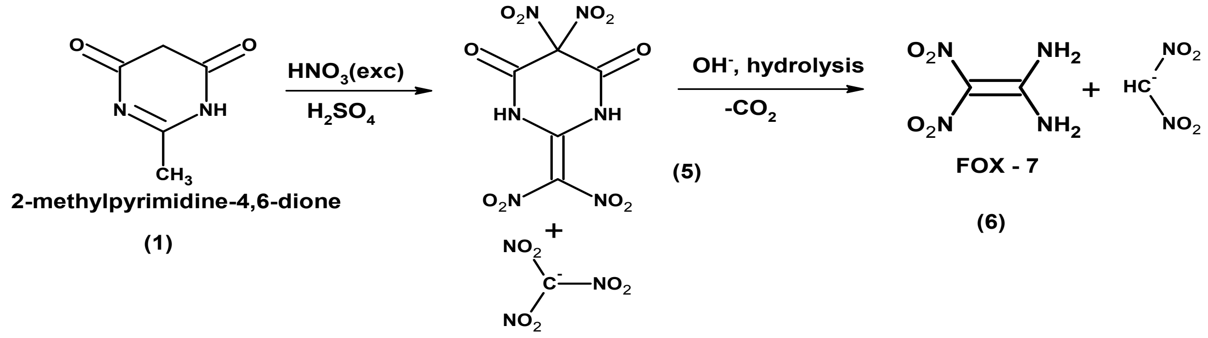


Figure 3. Reaction scheme for Route 3: Nitration of 2-methyl-pyrimidine-4,6-dione

In view of improvisation of FOX-7 synthesis, attempts were made by researchers on considering various precursors mainly 6-methyl-1,3,5-triazine-2,4-dione and 2,4-dimethoxy-6-methyl-1,3,5-triazine.[14] However, encouraging results were not obtained. Thus, the nitration of 2-methyl-pyrimidine-4,6-dione is found to be suitable and productive route for the production of FOX-7 on a larger scale, hence adopted for intensification studies.

3. Process chemistry of 2-methyl-pyrimidine-4,6-dione nitration

Process chemistry has a profound role in the scale-up. To successfully scale-up of any chemical process, it is necessary to understand the reaction mechanisms. Influence of each reaction parameters on the overall process should be clearly understood before going for the scale-up as it is useful in designing the equipment, and operating methods. Synthesis of FOX-7 involves the successive nitration on the pyrimidine ring followed by hydrolysis. Figure 3 indicates that FOX-7 synthesis is achievable only after formation of **5**. Nitration of 2-methyl 4,6-dihydroxy pyrimidine is believed to be a sequential attack of nitronium ions at an active methylene site and the methyl side chain. [14b, 15] The expected reaction scheme is shown in Figure 4.

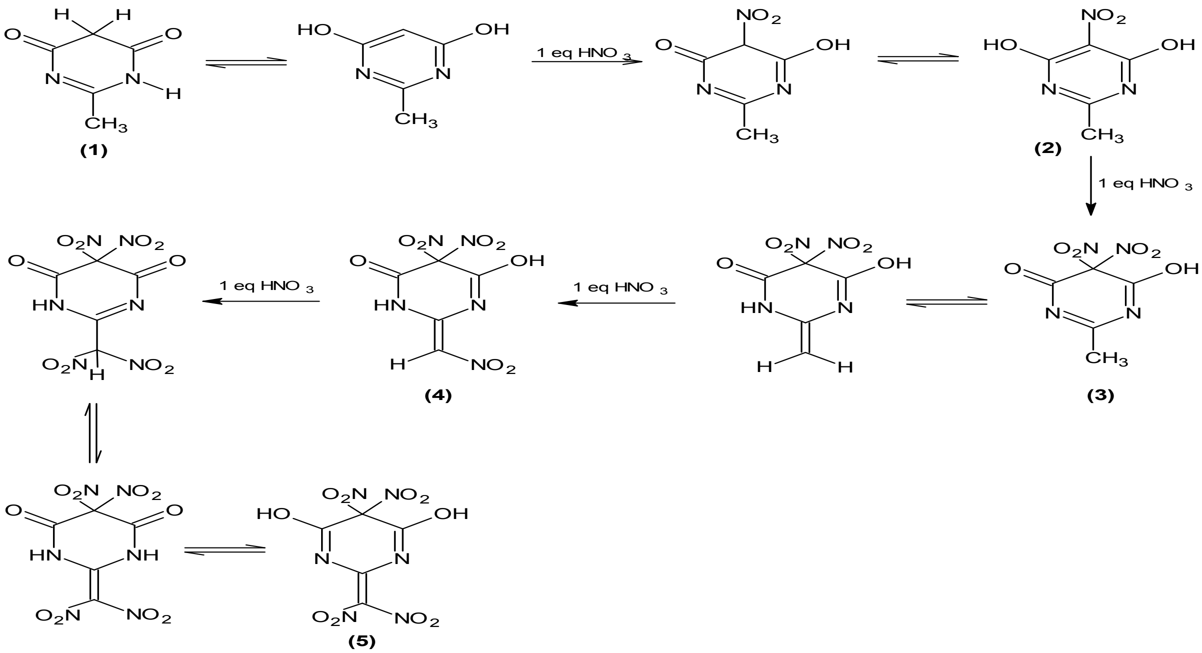


Figure 4. Reaction mechanism for the formation of mono, di, tri and tetra nitro derivatives of 2-methyl 4, 6-dihydroxy pyrimidine

The nitronium ion preferentially would attack the 5th position of 2-methyl-pyrimidine-4,6-dione since it possesses an active methylene group. This is supposed to be the fast reaction and yields the mono nitro derivative of 2-methyl 4, 6-dihydroxy pyrimidine (**2**). However, further nitronium ion attack would be unfavorable at 5th position of 4,6 dihydroxy 2-methyl-5-nitro pyrimidine due to the destruction of the aromatic system (in **3)**, hence, this process is expected to be slow. These mechanisms for the formation of **2** and **3** reveal the scope of series reactions with different reaction pace. Figure 4 also shows the mechanism involved in the formation of 6-hydroxy-2-methyl-5,5-dinitropyrimidine-4(5*H*)-one **(3)**. Further, the introduction of nitro group on the methyl group of **3** would yield trinitro-derivative of **1**. This reaction may be relatively faster than the formation of **3**. Figure 4 illustrates the expected mechanism for formation of (2*Z*)-6-hydroxy-5,5-dinitro-2-(nitromethylidene)-2,5-dihydropyrimidin-4(3*H*)-one. Figure 4 also indicates the mechanism for the formation of 2-(dinitromethylidene)-5,5-dinitro-2,5-dihydropyrimidine-4,6-diol on a further attack of the nitro group on **4**. Thus the mechanism supports that nitration of 2-methyl 4, 6-dihydroxy pyrimidine is sequential steps where the formation of intermediates plays a vital role in deciding the reaction profile for the desired product. Moreover, it demands special treatment for a selection of contact patterns in view of maintaining higher product profile as well as reaction pace. In the present study, intermediates **2**, **3**, **4** and **5** were isolated from a reaction and studied to determine their nature as well rate of formation. The derived information was utilized for designing of contact pattern and established a continuous process for FOX-7 production.

4. Experimental and characterization details

2-Methyl 4,6-dihydroxy pyrimidine (50 g) was dissolved in concentrated (98% wt.) sulfuric acid (225 ml) in a cylindrical jacketed glass reactor. This feedstock was used for the synthesis of **2**, **4** and **5** compounds while **3** was prepared from **2**. The obtained products were characterized by spectroscopic, chromatographic techniques, and thermal analysis. The IR spectra were recorded on PerkinElmer FTIR-1600 spectrophotometer in KBr matrix and ^{1}H NMR spectra scanned on a 300 MHz Varian instrument in deuterated dimethyl sulfoxide at 30 °C with TMS as an internal standard. The DSC studies were undertaken on a PerkinElmer DSC-7 instrument at the heating rate of 10 °C/min.

Chromatographic analyses were carried out on Waters Alliance HPLC system equipped with an autosampler and UV-Visible absorbance detector. Isocratic elution was performed using 3.9 x 150mm Novapak C18 (4µm) column with a mixture of methanol and water (40:60) as eluent. Figure S1 in supporting information shows combined spectra of HPLC analysis of **2**, **3**, **4**, **5,** and **6**.

4.1 Synthesis of 2

One equivalent of fuming nitric acid (98% wt.) was added to 20 ml feedstock solution (4 gm of **1**). The reaction was allowed to proceed at isothermal conditions under constant agitation. The reaction mass was quenched in ice water (90 ml) at a different time interval to obtain the extent of reaction. The product was filtered, water washed, dried, and weighed.

4.2 Synthesis of 3

One equivalent of fuming nitric acid (98% wt.) was added to 20 ml feedstock solution (4 gm of **2**). The above-said procedure was followed for isolation and characterization of **3**. The pure **3** was obtained after performing the reaction in a tubular reactor.

4.3 Synthesis of 4 and 5

3 was nitrated with both one and two equivalence of fuming nitric acid (98% wt.). The reaction mass was isolated in methanol as well as chloroform to obtain **4** and **5**. Further, the formation of **4** and **5** was also carried out on the addition of three and four equivalents of fuming nitric acid (98% wt.) to **1** respectively.

The above experiments were also carried out at a different temperature ranges from 15 to 35^{o}C at the increment of 10^{o}C for kinetics determination.

5. Result and Discussion

Preparation of FOX-7 involves the series of nitration reactions followed by hydrolysis. Formation of the intermediate is vital for these types of reactions where the mixing of fluid of different compositions is involved. The maximum possible amount of intermediates is obtained if fluids of different concentrations and at different stages are not allowed to mix.[16] For series reactions, more intention has always given to maximize intermediates for achieving a higher yield of the final product. The absolute information on rates of formation and disappearance of intermediates facilitate to opt for the best reaction system. On the same line, the present work performed to obtain data on the reactive behavior of intermediates of **1** and is as follows;

5.1 Nitration of 1 to 2

On addition of one equivalent of fuming nitric acid (98% wt.) in the presence of sulfuric acid to **1** gives **2** which was characterized by spectroscopic tools. Figure S2 and S3 show ^{1}H NMR and ^{13}C NMR spectra respectively which confirm the identity of **1**. Structure of **2** was confirmed from the peaks in IR spectra for NH_2 (3408 & 3330 cm^{-1}) and NO_2 (1520 & 1472 cm^{-1}) groups and peaks in ^{13}C NMR at δ 158 (C-NO_2) and δ 128 (C-NH_2). DSC of **2** showed decomposition peak at 296°C with a heat release of 1188.4 J/g which was different than **1** and **6**. Impact insensitivity analysis showed that **2** is highly insensitive and could not explode on the impact of 2 kg mass up to 170 cm and 36 kg of friction.

Further, a study on the rate of formation of **2** at 15, 25 and 35°C revealed that the formation of **2** decreases with increasing temperature in the batch reactor. Table 1 shows that reaction extent at various temperatures. The conversion towards **3** and further to **6** was observed at a higher temperature even addition of one equivalent of fuming nitric acid (98% wt.). This indicates that the rate of intermediates formation are comparable and cannot be controllable unless proper contact of reaction entities. The time required for complete conversion at low temperature was more than 1.5 hours. The higher conversion of **2** from rate equation was expected by increasing the concentration of nitric acid in the reactor. This could not achieve as reaction proceeds further to the formation of **3**, **4** and **5** in a batch reactor.

Table1: Product distribution based on temperature and nitric acid quantity

Reaction temp. (K)	Nitric acid equivalence	Reaction path	Product constituents	% Yield
288	1	1 - 2	2	55
298	1	1 - 2	2	67

308	1	1- 2	2 and 3	50
298	2.5	1 - 2	2, 3 and 6	19
288	1	2 - 3	2 and 3	55
298	1	2 – 3	2 and 3	50
298	1	2 – 3*	3	15
298	3	1 – 4	4, 5 and 6	-
298	4	1 - 5	4, 5 and 6	-

* Reaction in a tubular reactor

\- Yield of 4 and 5 could not realize separately due to their pyrophoric nature and analogous spectroscopic characteristics.

Reaction kinetics was evaluated for nitration of **1** on the addition of equivalence of fuming nitric acid at 288, 298 and 308 K. The decay in the concentration of **1** was monitored on isolation of reaction mass fixed interval of time (stopped flow analogy).[17] The results are depicted in Figure 5.

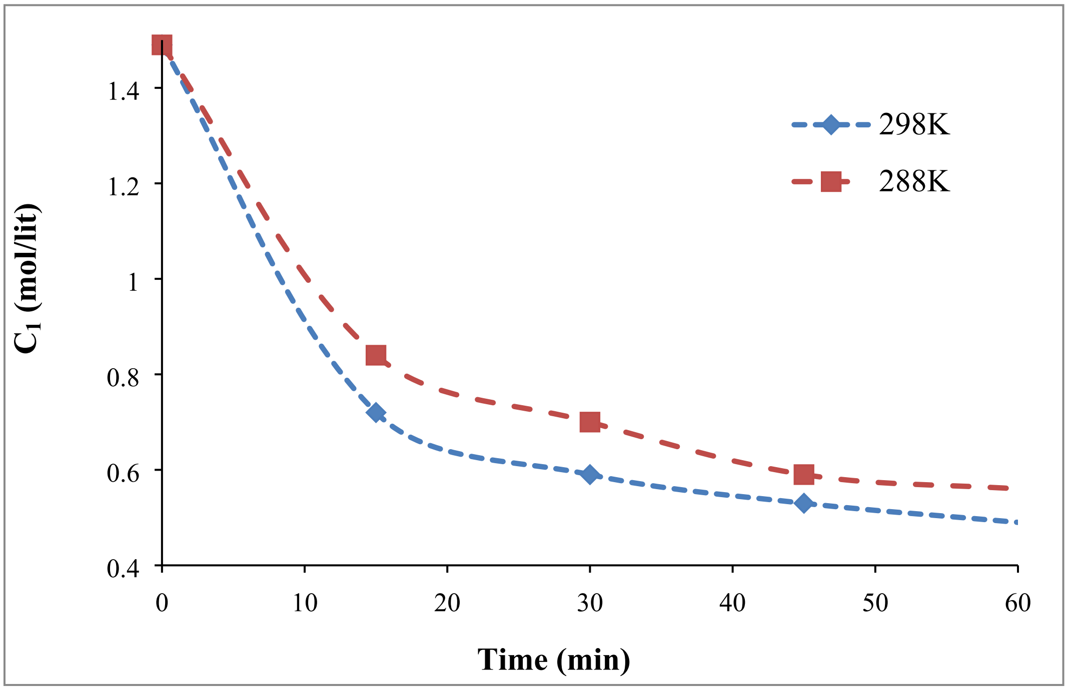


Figure 5. C-t profile of 1 during the formation of 2

This shows that the complete conversion of **1** for **2** is not obtained even at 60 minutes, indicating the slow nature of reaction with less energy-intensive characterization. Overall, reaction kinetics was found to be second-order denoting first order with respect to **1** and nitric acid. Arrhenius parameters were governed for the formation of **2** and confirmed that the slow pace of reaction with less activation energy. Kinetics parameters are tabulated in Table 2.

Table 2: Kinetics for nitration of 1 (Rate constants units: mol/lit and min.)

Reaction step	**Rate expression**	k_{288}	k_{298}	k_{308}	**Ea, kcal/mol**
1-2	$-r_1=k_1C_1C_{HNO3}$	0.0210	0.0450	0.091	12.74
2-3	$-r_2=k_2C_2C_{HNO3}$	0.0051	0.0136	0.034	16.83
3-5	$-r_3=k_3C_3$	0.0085	0.0130	0.021	7.90

5.2 Nitration of 2 to 3

In series reaction, intermediates form sequentially in the presence of excess reagents and intermediates. This situation is valid when the rates of each step are comparable. The similar observations were noticed when **2** was nitrated under various temperatures and prolonged period on the addition of one equivalent of fuming nitric acid in a batch reactor. In all cases, it was found that reaction proceeded further and yielded in **4** and **5**. This restricts isolation of **3** to obtain it in pure form. This was overruled by modifying the contact pattern and preparation method. The product obtained from a tubular reactor was analyzed and found to contain small traces of **2** in a higher content of **3**. Further, it was purified by leaching them for several instances in methanol. Purified **3** was characterized by spectroscopic tools. Figure S1 shows a single peak of **3**, which was found different than **2** and **6**. IR and ^{13}C NMR spectra of **3** showed spectra analogous to that of **2**. This was due to attachment same functional group (nitro) on the same carbon atom (5th position of carbon in the ring). However, ^{1}H NMR spectrum and decomposition of **3** was different than **2**. Figure S4 shows that the absence of hydrogen peak at 13.31 ppm in comparison with the ^{1}H NMR spectrum of **2** as shown in Figure S2. This confirms the formation of **3** due to the replacement of hydrogen from the 5th position of **2** by the nitro group.

Figure S5 shows that decomposition of **3** at 252°C with a heat release of 134 J/g in DSC analysis which was different than the **2** and **6**. This confirmed the formation of **3** from **2** under controlled nitration conditions. The impact sensitivity (h_{50}) and figure of the insensitivity of **3** were found about 60 cm and 71 respectively; however, it was not shown stimulus at 36 kg friction. Reaction kinetics for the formation of **3** was derived and tabulated in Table 2. The formation of **3** plays an important role in deciding the yield and purity of FOX-7 as it is a slower step than other steps. Hence it is necessary to improve its processing to increase the productivity of the process.

5.3 Formation of 4 and 5:

The formations of **4** and **5** were expected on the addition of one and two equivalence of fuming nitric acid to **3** respectively. However, both the samples have shown almost similar HPLC spectra (figure S1). This indicated that the formation of **4** and **5** take place simultaneously. With this, reaction kinetics were derived considering single step and outcome provided in table 2. The rate of formation of **5** was found to be slow in comparison with other steps. However, their formation possesses lower activation energy. This indicates that formation of **5** is feasible even at low energy barrier. **Caution:** Compounds **4** and **5** are pyrophoric. Compounds are catching fire in the absence of acid and at about 50°C. Hence, these compounds shall be handled with special precautions.

5.4 Effect of contact patterns on the product profile

Industrialization of a chemical process needs an understanding of process chemistry; optimal process envelope and the best choice of operation. Selection of mode of operation for scale-up of processes is a combination of science and art. Chemical Process can be conducted in batch, semi-batch, or continuous mode of operation. Understanding of reaction and its mechanism is mandatory in this regard. It gives an idea about the suitability of mode of operation and reactor (contact pattern). The above study pertaining to isolation and characterization of intermediates of FOX-7 synthesis from the nitration of

2-methyl 4, 6-dihydroxy pyrimidine (figure 3) confirms the multiple series reactions nature of the process. In series reaction, it is known that the formation of intermediates plays a vital role in deciding the reaction profile for the desired product due to the involvement of mixing of fluids of different concentrations.[18] Maximum possible amounts of intermediates are required to achieve a higher yield of the final product. Here, reaction kinetics of this process as tabulated in table 2 shows that the least activation energy belongs to the formation of **4** and **5**. This indicates that formation of **4** and **5** will be favored as soon as **3** is available in a reactor. Hence, the concentration of **3** will be almost negligible during the reaction in comparison with concentrations of **2**, **4** and **5**. This condition is likely to affect on yield as well as purity of **6**. Hence, any instance the concentrations of intermediates have to be increased to obtain the higher yield and purity of **6**. Selection of the best contact pattern (reactors) is essential here to achieve higher concentrations of intermediates. Batch mode is usually preferred for small scale production because it is a relatively simple device and needs small auxiliary equipment or instrumentation. Hence, initial concentrations of intermediates were evaluated in a batch reactor. Table 2 shows the three independent reactions and their kinetics. Thus, it is essential to govern a single rate expression in terms of concentration of **1**. The rate expressions and their rate constants are as follows;

$$r_1 = -\, k_1 * C_1 * C_{HNO_3} \tag{1}$$

$$r_2 = k_1 * C_1 * C_{HNO_3} - k_2 * C_2 * C_{HNO_3} \tag{2}$$

$$r_3 = k_1 * C_1 * C_{HNO_3} + \ k_2 * C_2 * C_{HNO_3} - k_3 * C_3 \tag{3}$$

$$r_5 = \ k_3 * C_3 \tag{4}$$

Equation one can be solved for the equimolar concentration of **1** and nitric acid and solution is as follows;

$$C_1 = \frac{C_0}{(C_0 k_1 t + 1)} \tag{5}$$

Where, C_0 is initial concentration of **1** and t is reaction time.

On substituting eq. 5 in eq. 2 for solving C_2 for equimolar concentration, it becomes,

$$\frac{dC_2}{dt} + k_2 * (C_2)^2 = k_1 * \left(\frac{C_0}{(C_0 k_1 t + 1)}\right)^2 \tag{6}$$

Where, eq. 6 is found to be in the form of Riccati differential equation[19] which can be solved by quadrature to obtain the solution.

$$C_2 = \frac{(kC_0^2k_2)\left((1+(C_0k_2t))^{(A+1)}-1\right)}{(C_0^2k_2)(C_0k_2t+1)+\left((k_1k^2)(1+(C_0k_2t))^{(A+2)}\right)} \tag{7}$$

Where, $k = \frac{(-k_2C_0)-\sqrt{\left((C_0^2k_2^2)+4C_0^2k_1k_2\right)}}{2k_1}$ and $A = \frac{2kk_1}{C_0k_2}$

Substituting equation 5 and 7 for C_1 and C_2 respectively in equation 3, equation can be deduced in the form of C_o and C_3 analogous to equation 6. However, this differential equation for C_3 becomes very complex due to the involvement of two independent terms of C_o. The derived form of C_3 is as follows;

$$C_3 = \left(e^{-k_3t}\right)$$

$$\Bigg(C + \Bigg(\left\{C_0e^{\left(\frac{-k_3}{C_0k_1}\right)}\right\}\Bigg(\frac{-e^{\frac{-k_3(1+C_0k_1t)}{C_0k_1}}}{1+C_0k_1t} + \left(\frac{k_3}{C_0k}(log(1+C_0k_2t))\right) + \left(\frac{k_3}{C_0k_1}(1+C_0k_1t)\right) + [0.25]\left(\frac{k_3}{C_0k_1}(1+C_0k_1t)\right)\Bigg(\frac{k_3}{C_0k}($$

(8)

Where, $C = C_0e^{\left(\frac{-k_3}{C_{0k_1}}\right)}\left(\left(e^{\frac{-k_3}{C_{0k_1}}}\right)-\left(\frac{k_3}{C_{0k_1}}\right)-\left(\frac{k_3^2}{4C_0^2k_1^2}\right)\right)$

Finally, the concentration of C_5 was obtained from the above equations. These concentration profiles were evaluated in a batch reactor at 20°C and outcome is plotted in figure 6.

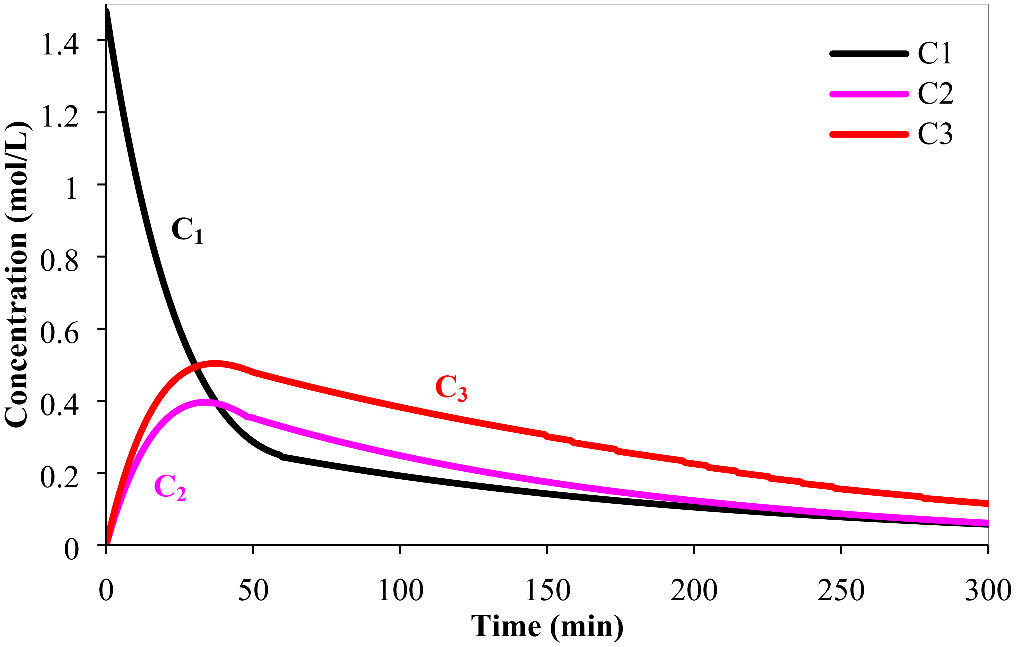


Figure 6. Concentration profile in the batch reactor

Figure 6 shows the outcome of batch reactor analysis. This indicates that the formation of mono (**2**) and dinitro (**3**) derivatives are comparable at initial stages and significant decay in mononitro (**2**) derivative at the later course of reaction.

On the other hand, C-t analysis was carried out in PFR, and CSTR and outcome are shown in figure 7 which was derived on governing equations of concentration in CSTR as follows.

$$C_1 = \frac{(k_1\tau)^{-1} + \sqrt{(k_1\tau)^{-2} + 4(k_1\tau)^{-1}C_0}}{2} \tag{9}$$

$$C_2 = \frac{(k_2\tau)^{-1} + \sqrt{(k_2\tau)^{-2} + 4k_1{k_2}^{-1}{C_1}^2}}{2} \tag{10}$$

$$C_3 = \frac{(k_1{C_1}^2 + k_2{C_2}^2)\tau}{k_3\tau + 1} \tag{11}$$

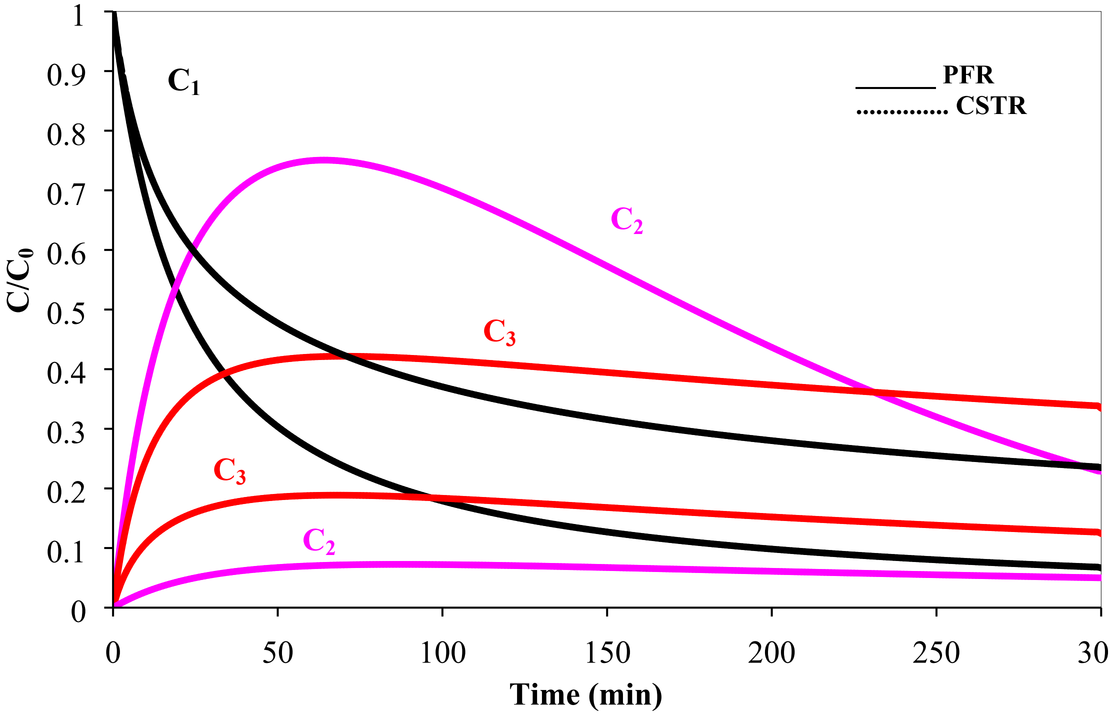


Figure 7. Concentration profile in plug flow and continuous stirred tank reactors

Slow decay of concentration of **1** was observed in CSTR in comparison with PFR. The concentration of **3** was found to be higher in PFR than CSTR. This analysis showed that the single contact pattern is insufficient to meet the desired concentrations of intermediates in a reactor.

5.5 Reactor configuration and stability analysis

The above studies of reaction kinetics and product distribution suggest that the batch and mixed flow reactors are diverting the reaction course as well as yielding lower concentrations of intermediates which hamper final productivity. Hence, the application of plug flow reactors is vital to maintain the higher concentrations of intermediates. Moreover, the plug flow reactor facilitates in altering reaction pace of slow step on enhancing reaction temperature, here especially for the formation of **3**. Overall, the formation of **2** and **3** is essential in the tubular reactor due to reaction kinetics and achieving higher yield of the reaction. In contrast, the plug flow reactor offers a variation in reaction rate along its length. This also affects on isothermal conditions of the reaction. It has been found that the tubular reactor may exhibit multiple temperatures and concentration profiles along its axis when an exothermic chemical reaction is performed.[20] Hence, it is essential to obtain the temperature profile of the tubular reactor along its length. This also helps in showing the runaway condition of reaction. Here, countercurrent flow of coolant is considered to maintain the outlet temperature reaction mass within a favorable range for maximization of nitronium ions formation. Heat and mass balance equations for the plug flow reactor were clubbed to evaluate the simultaneous effect on temperature and concentration during reaction for formation of **2** along the length of reactor.

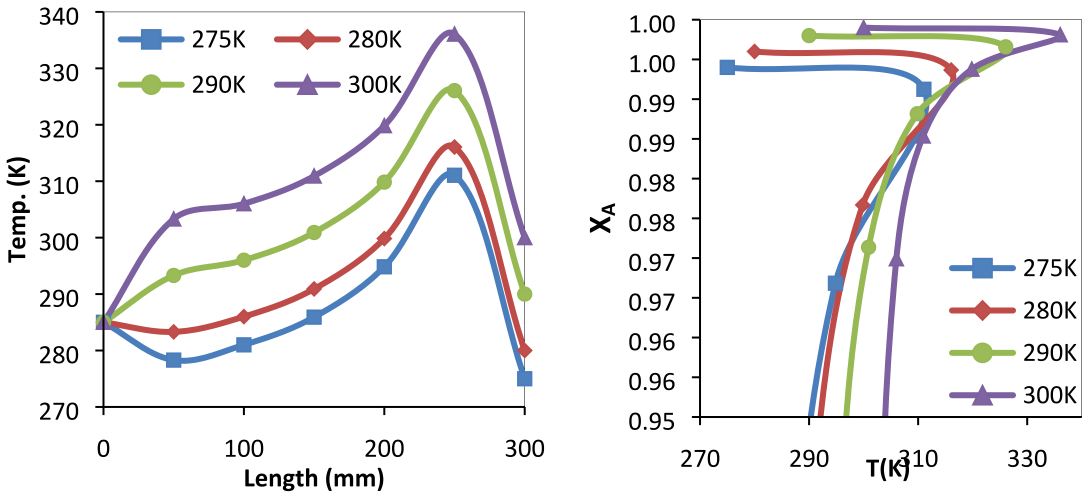
Thermal energy balance for reactive fluid within the inner tube:

$$\rho_R C_{pR} \frac{dT_R}{dt} = \frac{2U_{in}}{R_{in}}(T_{cool} - T_R) + (-\Delta H_R) r_A \qquad (12)$$

Thermal energy balance for cooling fluid:

$$\rho_{cool} C_{pcool} \frac{dT_{cool}}{dt} = \frac{2U_{in}}{R_{in}} \frac{k^2}{1-k^2}(T_R - T_{cool}) \qquad (13)$$

Where, U is overall heat transfer coefficient which derived by standard analogies, R radius of the tube, T is temperature, cool is coolant, ρ is density, k is radius ratio and H_R is the heat of reaction. The profiles of heat generation and removal along the length of reactor were generated for various temperatures ranges of feed as well as a coolant fluid.



(a) (b)

Figure 8. (a) Temperature variation profile along the length and (b) actual conversion profile

The effect of coolant temperature on reaction temperature was evaluated. The selected coolant temperatures were 275, 280, 290 and 300K. It was desired to control the reaction temperature at 285K. The observed profiles are shown in figure 8(a). This clearly showed that reaction temperature varies along the length of the reactor. The maximum reaction temperature was found to be near the exit end of the reactor. The outlet temperature of the reactor was found to be close to the coolant temperature. It was inferred that coolant temperature beyond the feed temperature is not able to withdraw the heat of reaction and leads to runway condition. Alternatively, the conversion profile against the coolant temperature was evaluated and shown in figure 8(b). This shows that the sudden rise in conversion level near the exit end of reactor where a rise in temperature was noticed. The conversion level after that remains constant as the maximum conversion is achieved in that region. The sharp rise in conversion level was obtained using coolant temperature than feed temperature. This indicates the runway condition of reaction for these coolant temperatures. The analysis helped in identifying the temperature control ability of selected hardware and runway condition of reaction. The analysis also revealed the appropriate range of coolant temperature to control the runway condition of reaction.

5.6 Process intensification in continuous set-up

With this, two different sizes PFRs followed by a CSTR is formulated for processing of FOX-7 in continuous mode. The reactor scheme is shown in figure 9.

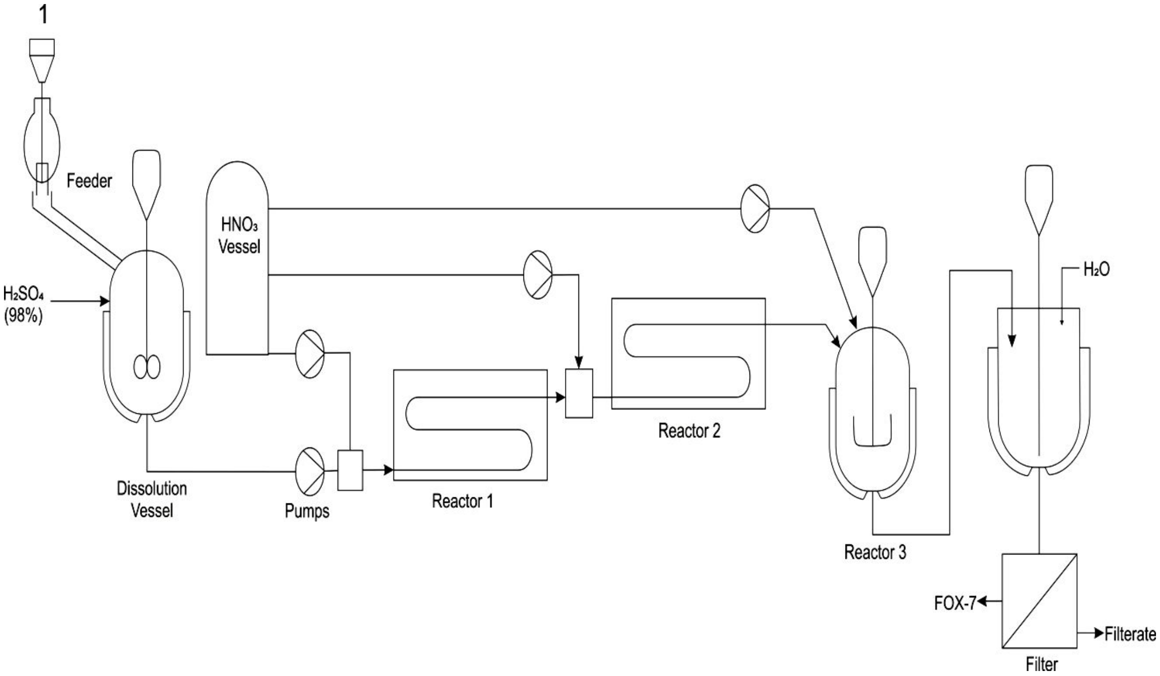


Figure 9. Reactor scheme for FOX-7 processing in the continuous mode

Here, plant capacity is considered to be 60g/hr of 2-methyl-pyrimidine-4,6-dione. A solution of 2-methyl 4, 6-dihydroxy pyrimidine (**1**) and concentrated sulfuric acid was prepared as a stock solution. A solution was prepared at elevated temperature to minimize the processing time. The mixture of **1** was to be added to 1st PFR along with only an equivalent of fuming nitric acid. Coolant was introduced in a jacket of PFR in countercurrent flow manner. The residence time was varied from 20 to 45 minutes. An outlet of **2** was mixed with another equivalent of fuming nitric acid in pre-mixer before entering to 2nd PFR. Reaction pace was increased by circulating water of ambient condition in the jacket of reactor. Another part of fuming nitric acid and outlet of 2nd PFR were continuously fed to CSTR. The reaction was controlled at the isothermal condition in CSTR by circulating coolant in its jacket. A slurry of CSTR was quenched in ice-cold water continuously. Solids were washed, filtered and dried to obtain FOX-7 at about 75% yield. The reaction was completed within 120 minutes; thus an improvement in productivity was achieved. This technology requires low inventory and a higher degree of safety. These characteristics convey high prospective for scaling of this technology because of meeting the production requirement of FOX-7 for its direct application in HE formulation as well as for the preparation of other novel HEMs.

6. Conclusions

There is dire need to establish an effective and safe processing technology for FOX-7 to cope with the future requirement. 2-Methyl 4, 6-dihydroxy pyrimidine **(1)** based route for FOX-7 synthesis is found to be the adaptive as well as productive. Isolation of mono, di, tri and tetra nitro derivatives of 2-methyl-4, 6-dihydroxy pyrimidine is challenging and needs special treatment. Isolation of 6-hydroxy-2-methyl-5,5-dinitropyrimidine-4(5*H*)-one **(3)** in a large extent is possible in only tubular reactor. Tri and tetra nitro derivatives of **1** are found to be pyrophoric in dry condition. In a batch reactor, formation of 4, 6-dihydroxy-2-methyl-5-nitro pyrimidine (**2**) increases till 298K and decreases thereafter. Reaction kinetics supports the formation of tri and tetra nitro derivatives of **1** at low temperature in batch reactor even on a limited supply of fuming nitric acid. Product profile in various reactors showed that the batch reactor, as well as single mixed flow reactor, is not appropriate to maintain the intermediate concentration at a high level. Application of plug flow reactors for formation of **2** and **3** is vital to obtain a higher reaction rate as well as yield. Tubular reactor stability analysis indicated the runaway condition of reaction in case of circulating jacket fluid of more than 300K. Based on these results, the continuous plant comprising two tubular reactors followed by a mixed flow reactor is found to be appropriate for processing of FOX-7 in a safe, efficient, and productive manner. Overall, this study finds efficacy for scaling of FOX-7 process at higher production capacity level to deal with the requirement of its application in high energy formations as well as in the preparation of its novel derivatives.

7. Acknowledgment

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8. Supporting Information

Comparison of performance characteristics of FOX-7 with conventional explosives and copies of HPLC spectra of 2, 3, 4, 5 and 6, ^{1}H NMR spectra of 2 and 3, ^{13}C NMR spectra of 2 and DSC profile 3.

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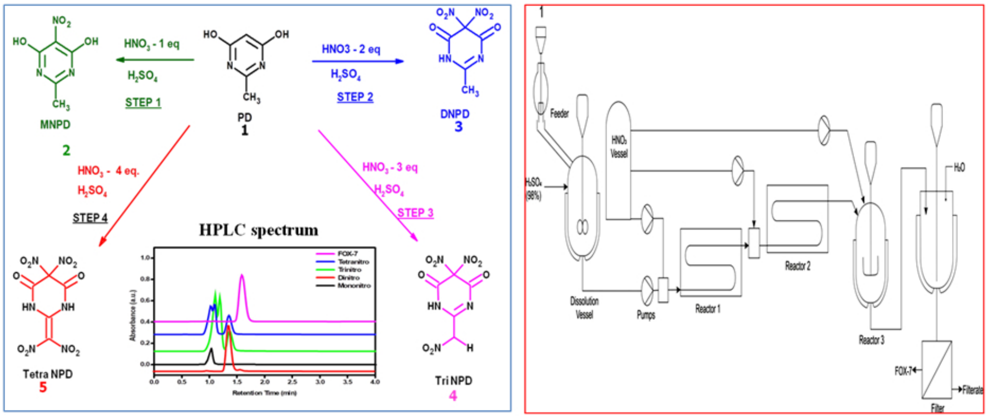

Process Chemistry of FOX-7 synthesis

Intensification scheme

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