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Theoretical Investigation of the Formation Mechanism of NH₃ and HCN during Pyrrole Pyrolysis: The Effect of H₂O

Ji Liu ¹, Qiang Lu ¹,*, Xiao-yan Jiang ¹, Bin Hu ¹, Xiao-lei Zhang ²,*, Chang-qing Dong ¹ and Yong-ping Yang ¹

¹ National Engineering Laboratory for Biomass Power Generation Equipment, North China Electric Power University, Beijing 102206, China; liujipower@126.com (J.L.); jiangxy90@126.com (X.-y.J.);
binhu92@126.com (B.H.); cqdong1@163.com (C.-q.D.); yyp@ncepu.edu.cn (Y.-p.Y.)
² School of Mechanical and Aerospace Engineering, Queen’s University of Belfast, Belfast BT9 5AH, UK
* Correspondence: qianglu@mail.ustc.edu.cn (Q.L.); xiaolei.zhang@qub.ac.uk (X.-l.Z.);
Tel.: +86-010-6177-2030 (Q.L.); +44-(0)28-9097-4490 (X.-l.Z.)

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Abstract: Coal is a major contributor to the global emission of nitrogen oxides (NOₓ). The NOₓ formation during coal utilization typically derives from the thermal decomposition of N-containing compounds (e.g., pyrrolic groups). NH₃ and HCN are common precursors of NOₓ from the decomposition of N-containing compounds. The existence of H₂O has significant influences on the pyrrole decomposition and NOₓ formation. In this study, the effects of H₂O on pyrrole pyrolysis to form NOₓ precursors HCN and NH₃ are investigated using the density functional theory (DFT) method. The calculation results indicate that the presence of H₂O can lead to the formation of both NH₃ and HCN during pyrrole pyrolysis, while only HCN is formed in the absence of H₂O. The initial interaction between pyrrole and H₂O determines the N products. NH₃ will be formed when H₂O attacks the C₂ position of pyrrole with its hydroxyl group. On the contrary, HCN will be generated instead of NH₃ when H₂O attacks the C₃ position of pyrrole with its hydroxyl group. In addition, the DFT calculations clearly indicate that the formation of NH₃ will be promoted by H₂O, whereas the formation of HCN is inhibited.

Keywords: pyrrole pyrolysis; H₂O; NOₓ precursor; NH₃; HCN; DFT

1. Introduction

Coal is the major energy source in the modern industrial production process. Coal-mining, coal-burning factories, and other coal-related usage are the dominant sources of NOₓ emission [1,2]. The harmful atmospheric pollutants of NOₓ (i.e., NO, NO₂, N₂O, etc.) can form acid rain and photochemical smog and endanger human health [3–5]. Moreover, the contribution of NO to the greenhouse effect is 260 times higher than that of CO₂ [6].

Nitrogen compounds in coal are primarily pyrrole and pyridine, which have already been widely used in different coal structural models, such as the Given, Wiser, and Shinn models [7–9]. The well-known Given model, mainly containing carbon, hydrogen, oxygen, and small amounts of sulfur and nitrogen, was intended to show the types of hydrogen structures in the bituminous coal, and has been widely adopted as a structural representation. The Wiser model, along with “structural alternative” carbon skeletal representations, had an increasing scale, representing the rank transition from 76% C to 90% C (wt % basis) [9]. The Shinn model was created at a larger scale (10,000 amu), in which three relatively small unconnected molecular entities were held within a larger molecule [8].
It is notable that around 60% of total coal nitrogen is the pyrrolic nitrogen [10], and this concentration varies slightly with different coal ranks [10,11]. Hence, the thermal decomposition of pyrrolic groups plays a vital role in NO$_x$ formation. As a result, pyrrole was commonly employed as the N-containing model compound in coal, and has been extensively studied in recent decades.

Many efforts have been made to characterize the pyrolysis of pyrrole using experimental and theoretical approaches [12–17]. Martoprawiro et al. [12] proposed a mechanism for the formation of HCN from pyrrole, which stated that the reaction was initiated by a hydrogen migration to form a cyclic carbene intermediate. Subsequent ring opening and decomposition steps gave rise to HCN and propyne. Moreover, Zhai et al. [18] investigated the mechanisms of pyrrole pyrolysis, outlining the routes for formation of cis-crotonitrile, allyl cyanide, and HCN. Besides HCN, NH$_3$ is another important precursor of NO$_x$ from coal utilization at high temperatures [19–21]. Li et al. [20] conducted pyrolysis experiments on coal and concluded that the formation of both HCN and NH$_3$ was initiated by the N-containing heteroaromatic ring being attacked by radicals. Similarly, Elmer et al. [21] employed a quartz fluidized-bed reactor coupled to a quartz tubular flow reactor for rapid pyrolysis of coal, and suggested that NH$_3$ might be formed from the interactions of N-containing species with donatable H on the soot surface. However, to date, few theoretical studies have focused on the formation of NH$_3$ during pyrrole pyrolysis.

During the coal pyrolysis process, H$_2$O will play an essential role in the decomposition reactions and formation of various products. Hu et al. [22] investigated the pyrolysis behavior and reaction mechanisms of coal samples containing different moisture contents. They found that the moisture content had a significant influence on the tar yield and light tar content, and H$_2$O could upgrade the low-rank coal during pyrolysis [23]. Moreover, Park and co-workers [24] found that studies of coal-N release in the presence of H$_2$O were more authentic than those of the only pyrrole, as H$_2$O inevitably existed in the coal utilization process. However, there are limited studies focusing on the effect of H$_2$O on pyrrole pyrolysis at present. Therefore, in this study, the density functional theory (DFT) method was applied to investigate the detailed pyrolysis mechanism of pyrrole to HCN and NH$_3$ in the presence of H$_2$O, which may help with the development of coal pyrolysis/combustion technologies for NO$_x$ control.

2. Results

Early studies [12,17,25] have already investigated the possible pyrolysis pathways of pure pyrrole using quantum chemistry methods. The obtained activation energies (346 and 316.31 kJ/mol, as shown in Figure 1) are comparable with the activation energy measured from the experimental energy of the overall disappearance of pyrrole between 1300 and 1500 K at 12 atm pressure (310.1 ± 12.5 kJ/mol) [19]. The activation energy difference between the two pathways in Figure 1 is mainly due to the initial H migration to different carbons. In the proposed pathways, the crucial step is the isomerization of pyrrole to the cyclic carbene. Then, the primary N-type product of HCN is formed through a ring opening reaction, as shown in Figure 1. No NH$_3$ will be formed in this pyrolysis process.

When H$_2$O participates in the pyrrole pyrolysis process, it will interact with pyrrole, thus significantly altering the pyrolysis mechanism and pathways. As shown in Figure 2, the possible interactions between pyrrole and H$_2$O may occur in four ways, i.e., adj-OH-C$_2$-H, adj-OH-N-H, ind-OH-C$_1$-H, and ind-OH-C$_3$-H (the adjacent position is abbreviated as adj-, the indirect position is abbreviated as ind-), in which H$_2$O attacks different positions of pyrrole. In the adj-OH-C$_2$-H interaction, H$_2$O reacts with pyrrole by simultaneously donating its hydroxyl group to the C$_1$ position and hydrogen to the C$_2$ position. The energy barrier of this reaction is 226.4 kJ/mol. In an alternate possible interaction, adj-OH-N-H, H$_2$O also donates its hydroxyl group to the C$_1$ position of pyrrole. Differently, H$_2$O provides its hydrogen to the N position, which will result in the opening of the ring. This reaction needs to overcome a higher energy barrier of 297.6 kJ/mol compared to the first reaction (interaction adj-OH-C$_2$-H). In the possible ind-OH-C$_1$-H interaction, H$_2$O also interacts with pyrrole at the C$_1$ and C$_2$ position. Different from the first reaction, the hydroxyl group attacks the C$_2$ position,
whereas hydrogen attacks the C$_1$ position in this reaction. The energy barrier is 235.0 kJ/mol, which is close to that of the first reaction. In the possible ind-OH-C$_3$-H interaction, H$_2$O reacts with pyrrole at the C$_2$ and C$_3$ position with an energy barrier of 293.1 kJ/mol. In summary, based on Figure 2, the initial interaction modes of adj-OH-C$_2$-H and ind-OH-C$_1$-H are more feasible than the other two interaction modes because of the relatively low energy barriers (226.4 and 235.0 kJ/mol). The possible subsequent pyrolysis pathways based on the four initial interaction ways are presented below to investigate the formation of NH$_3$ or HCN.

**Figure 1.** The proposed pyrolysis mechanism of pure pyrrole in previous studies. The exact digits follow the original paper. The numerical values are energies in kJ/mol.

**Figure 2.** Initial interaction and pyrolysis mechanism of pyrrole in the presence of H$_2$O.
2.1. The Effect of H$_2$O on Pyrrole Pyrolysis Based on the adj-OH-C$_2$-H Interaction

Based on the adj-OH-C$_2$-H interaction, five possible pathways might occur and can be classified into two categories according to their products (NH$_3$ or HCN). NH$_3$ is the product in three pathways (a-1, a-2, and a-3), as shown in Figure 3, while HCN is the product in the other two pathways (a-4, a-5), as shown in Figure 4.

![Figure 3. Pyrolytic reaction pathways based on the adj-OH-C$_2$-H interaction to generate NH$_3$.](image1)

![Figure 4. Pyrolytic reaction pathways based on adj-OH-C$_2$-H interaction to generate HCN.](image2)

In Figure 3, the concerted interaction adj-OH-C$_2$-H generates a-1-1m, which may undergo three possible subsequent pathways to form NH$_3$. In pathway a-1, intermediate a-1-2t is converted to intermediate a-1-2m, via concerted ring-opening transition state a-1-2t, with an energy barrier of 148.5 kJ/mol. Then intermediate a-1-2m undergoes a hydrogen transfer reaction via three-membered transition state a-1-3t to form products NH$_3$ and a-1-3m, with an energy barrier of 364.3 kJ/mol. In pathway a-2, a-1-2m undergoes another hydrogen transfer reaction via four-membered transition state a-1-3t, transferring H from C$_3$ position to N position, breaking the C–N bond to form products a-2-1m and NH$_3$ with an energy barrier of 458.5 kJ/mol. In pathway a-3, a-1-1m is transformed into
intermediate a-3-1m, with an energy barrier of 257.3 kJ/mol. Afterwards, intermediate a-3-1m removes
the carbon monoxide through transition state a-3-2t to form the intermediate a-3-2m, with an energy
barrier of 62.4 kJ/mol. Finally, a-3-2m decomposes into a-3-3m and NH$_3$ by homolysis of the C–N
bond, with an energy barrier of 76.4 kJ/mol. Based on the above calculation results, pathway a-3 is
the most favorable one due to having the lowest overall energy barrier (362.3 kJ/mol). It is notable
that previous studies have indicated that only HCN would be formed from pyrolysis of pyrrole or
pyroxene-type products in the absence of H$_2$O [12,17,18], whereas the participation of H$_2$O in pyrrole
pyrolysis can provide hydrogen sources leading to the formation of NH$_3$, which is consistent with
previous experimental results [24].

Based on the adj-OH-C$_2$-H interaction, HCN is the only N product formed through the possible
pathways a-4 and a-5. As shown in Figure 4, intermediate a-1-1m undergoes a dehydration reaction
between the H proton at N position and the hydroxyl group through transition state a-4-1t. This reaction
results in the formation of intermediate a-4-1m, overcoming an energy barrier of 193.1 kJ/mol.
For a-4-1m, it has two possible cracking pathways (a-4, a-5). In pathway a-4, intermediate a-4-1m
undergoes hydrogen transfer reaction through transition state a-4-2t to form intermediate a-4-2m, with
an energy barrier of 474.0 kJ/mol. Then intermediate a-4-2m decomposes into HCN and the a-4-3m
through transition state a-4-3t with an energy barrier of 107.4 kJ/mol. The rate-determining step (the
reaction bearing the highest energy barrier among all the reactions in an individual pathway) is the
reaction of a-4-2m formation, and the overall energy barrier of pathway a-4 is 536.0 kJ/mol. In pathway
a-5, intermediate a-4-1m is converted into intermediate a-5-1m via a ring-opening transition state a-5-1t,
overcoming an energy barrier of 272.9 kJ/mol. Then, intermediate a-5-1m undergoes further C-N shift
reaction through transition state a-5-2t to form intermediate a-5-2m with an energy barrier of 150.8
kJ/mol. Finally, intermediate a-5-2m decomposes into HCN and a-5-3m through transition state a-5-3t
with an energy barrier of 423.6 kJ/mol. The rate-determining step is the reaction to generate HCN (the
reaction with the highest energy), and the overall energy barrier of pathway a-5 is 458.0 kJ/mol. It is
clear that pathway a-5 is more feasible than pathway a-4 by comparing their whole energy barriers.

According to the above calculation results, H$_2$O has a significant effect on the pyrolysis of pyrrole. It
results in the formation of NH$_3$ as a new product, which will not be formed in the
absence of H$_2$O [12,18,23]. Moreover, H$_2$O can also affect the HCN formation. The energy barrier
for the generation of HCN in the presence of H$_2$O is higher than in the absence of H$_2$O [12,17]
(details in Figure 1), which indicates that H$_2$O can inhibit the formation of HCN during the pyrrole
pyrolysis process.

2.2. The Effect of H$_2$O on Pyrrole Pyrolysis Based on the adj-OH-N-H Interaction

Following the initial adj-OH-N-H interaction, three possible routes might occur, i.e., b-1, b-2,
and b-3, as shown in Figure 5. All three pathways result in the formation of NH$_3$ rather than HCN.

Figure 5. Pyrolytic reaction pathways based on the adj-OH-N-H interaction.
As stated above, the model compound pyrrole and H$_2$O pass through transition state b-1-1t with an energy barrier of 297.6 kJ/mol to generate intermediate b-1-1m. Then intermediate b-1-2m is formed with an energy barrier of 39.3 kJ/mol. In this reaction, the hydroxyl H migrates to N position via the four-membered transition state b-1-2t. Following intermediate b-1-2m, there are two possible pathways to produce NH$_3$. One is to generate b-1-3m and NH$_3$ via transition state b-1-3t, with an energy barrier of 158.4 kJ/mol (pathway b-1). The other is to form b-2-1m and NH$_3$ through transition state b-2-1t, with an energy barrier of 166.8 kJ/mol (pathway b-2). In pathway b-3, intermediate b-1-1m decomposes into NH$_2$ radical and b-3-1m through homolysis of C-N bond, with an energy barrier of 219.7 kJ/mol. NH$_2$ radical can easily form NH$_3$ by capturing the H radical in the pyrolysis process. Among the three pathways, pathway b-1 is the most feasible one, with the overall energy barrier of 361.4 kJ/mol (369.8 and 450.5 kJ/mol for pathways b-2 and b-3, respectively). From Figures 3 and 5, it can be seen that NH$_3$ can be produced in different pathways in the presence of H$_2$O.

2.3. The Effect of H$_2$O on Pyrrole Pyrolysis Based on the ind-OH-C$_1$-H Interaction

Following the initial ind-OH-C$_1$-H interaction, four possible pyrolytic pathways, i.e., c-1, c-2, c-3 and, c-4 might take place, as shown in Figure 6. In Figure 6a, pyrrole and H$_2$O interact to generate intermediate c-1-1m, through transition state c-1-1t, with an energy barrier of 235.0 kJ/mol. Then intermediate c-1-1m undergoes a hydrogen transfer reaction via transition state c-1-2t in which the H at the N position migrates to the C$_3$ position. This reaction results in the formation of c-1-2m with an energy barrier of 316.8 kJ/mol. Apparently, intermediate c-1-2m will decompose through two possible pathways (pathways c-1 and c-2). In pathway c-1, intermediate c-1-2m forms c-1-3m by migrating hydroxyl H, with an energy barrier of 328.4 kJ/mol. However, possible subsequent pathways of c-1-3m into HCN or NH$_3$ cannot be found. In pathway c-2, intermediate c-1-2m is converted into intermediate c-2-1m and c-2-2m via four-membered ring transition state c-2-1t, with an energy barrier of 538.6 kJ/mol. Then intermediate c-2-2m undergoes further reaction via transition state c-2-2t, with an energy barrier of 264.8 kJ/mol, finally decomposing into products HCN, c-2-1m, and c-2-3m.

![Figure 6. Pyrolytic reaction pathways based on the ind-OH-C$_1$-H interaction.](image)
As shown in Figure 6b, there are two possible subsequent cracking pathways (pathways c-3 and c-4) following intermediate c-1-1m. In pathway c-3, intermediate c-1-1m is converted into intermediate c-3-1m, via transition state c-3-1t, with an energy barrier of 252.3 kJ/mol. Then intermediate c-3-1m undergoes ring-opening reaction via transition state c-3-2t to form intermediate c-3-2m, with an energy barrier of 348.3 kJ/mol. Intermediate c-3-2m finally decomposes into c-3-3m (CN radical) and c-3-4m, with an energy barrier of 486.7 kJ/mol. Then the CN radical will form HCN easily by capturing the H radical. In pathway c-4, intermediate c-1-1m undergoes dehydrogenation via transition state c-4-1t in which H fission from the C1 position and N position forms H2 and c-4-1m, with an energy barrier of 307.1 kJ/mol. Then intermediate c-4-1m generates intermediate c-4-2m via a five-membered ring-opening transition state c-4-2t, with an energy barrier of 179.7 kJ/mol. Intermediate c-4-2m finally decomposes into c-4-3m and HCN, with an energy barrier of 177.0 kJ/mol. The activation energy of the rate-determining step in pathway c-4 is 455.4 kJ/mol, which is the lowest among the four pathways. It should be pointed out that the activation energy (455.4 kJ/mol) is higher than that of the pyrolysis of hemicellulose, cellulose, or lignin [26]. The main reason can be attributed to the different initial reaction model compounds. The pyrrole structure is highly stable with a five-membered ring, while compounds like hemicellulose and cellulose contain active elements such as oxygen and hydroxyl groups that have promoting effects on the pyrolysis reactions [27]. In summary, the ind-OH-C1-H interaction inhibits the formation of HCN, but does not lead to the formation of NH3.

2.4. The Effect of H2O on Pyrrole Pyrolysis Based on the ind-OH-C3-H Interaction

As shown in Figure 7, following the ind-OH-C3-H interaction, there is only one possible pathway, d-1, which results in the formation of only HCN.

![Figure 7. Pyrolytic reaction pathways based on the ind-OH-C3-H interaction.](image)

The initial ind-OH-C3-H interaction leads to the formation of intermediate d-1-1m through transition state d-1-1t, with an energy barrier of 293.1 kJ/mol. Then, d-1-1m forms intermediate d-1-2m via transition state d-1-2t with an energy barrier of 140.1 kJ/mol. In this reaction, the hydrogen at N position migrates to the adjacent C4 position. Intermediate d-1-2m further generates intermediate d-1-3m through transition state d-1-3t, with an energy barrier of 349.4 kJ/mol. Afterwards, intermediate d-1-3m undergoes hydrogen transfer reaction via transition state d-1-4t to form intermediate d-1-4m, with an energy barrier of 326.1 kJ/mol. Finally, intermediate d-1-4m decomposes into HCN and d-1-5m, with an energy barrier of 205.6 kJ/mol. The rate-determining step is the last step, and the overall energy barrier of pathway d-1 is 413.9 kJ/mol. Notably, both pathways following interactions ind-OH-C1-H and ind-OH-C3-H do not lead to the formation of NH3, implying that NH3 cannot be formed when the hydroxyl group of H2O attacks the C3 position.
3. Discussion

The above calculation clearly indicates that H₂O plays a vital role in the pyrolysis of pyrrole. The type of N products will be determined by the initial interaction of H₂O and pyrrole. Based on the calculation results, the optional pathways following each initial interaction of H₂O and pyrrole are summarized in Table 1. Following the initial adj-OH-C₂-H interaction, the optimal pathway is a-3, with an overall energy barrier of 362.3 kJ/mol, and the N product is NH₃. Within the initial adj-OH-N-H interaction, pathways a-3 and b-1 are the optimal pathways for the formation of NH₃. The overall energy barriers are 362.2 and 361.4 kJ/mol, respectively. Starting from the initial ind-OH-C₁-H interaction, the optimal pathway is c-4, with an overall energy barrier of 455.4 kJ/mol, and HCN is the final product. Following the initial ind-OH-C₃-H interaction, there is only one possible pathway (pathways d-1) for HCN formation, with an overall energy barrier of 413.9 kJ/mol. Compared with the HCN formation from pure pyrrole pyrolysis process (shown in Figure 1), generation of HCN in the presence of H₂O needs to overcome a higher energy barrier [12,17]. Hence, the presence of H₂O in pyrrole pyrolysis inhibits the formation of HCN, while promotes the formation of NH₃. For the two N products of NH₃ and HCN, the formation pathways of NH₃ need to overcome lower overall energy barriers than those of HCN. Therefore, it can be concluded that formation of NH₃ is easier than that of HCN during the pyrrole pyrolysis process in the presence of H₂O. The research result is consistent with previous experimental results [24], which found that the formation of NH₃ would be promoted by increasing the concentration of H₂O in the feeding gas. Moreover, Tian et al. [28] proposed that the high NH₃ yield from char-N (pyrrolic-nitrogen) gasification in steam resulted from the increased availability of H radical derived from the steam. According to our calculations, it is the initial interaction of H₂O and pyrrole that determines the final formation of NH₃, especially based on the adj-OH-C₂-H and adj-OH-N-H interactions, since H₂O will attack the C₂ position of pyrrole with its hydroxyl group in both interactions.

<table>
<thead>
<tr>
<th>Initial Interaction Way</th>
<th>Optimal Pathway</th>
<th>Overall Energy Barrier (kJ/mol)</th>
<th>Products</th>
</tr>
</thead>
<tbody>
<tr>
<td>adj-OH-C₂-H</td>
<td>a-3</td>
<td>362.3</td>
<td>NH₃</td>
</tr>
<tr>
<td>adj-OH-N-H</td>
<td>b-1</td>
<td>361.4</td>
<td>NH₃</td>
</tr>
<tr>
<td>ind-OH-C₁-H</td>
<td>c-4</td>
<td>455.4</td>
<td>HCN</td>
</tr>
<tr>
<td>ind-OH-C₃-H</td>
<td>d-1</td>
<td>413.9</td>
<td>HCN</td>
</tr>
</tbody>
</table>

The mechanisms discussed in this paper only indicate the thermal decomposition of pyrrole to form HCN and NH₃. However, according to the previous study [29], N-containing compounds might also undergo polymerization to form solid residues. Therefore, the effects of both solid residues and H₂O during pyrrole pyrolysis are worthy of investigation in a future work.

4. Materials and Methods

4.1. Materials

Pyrrole is a heterocyclic organic compound containing a five-membered ring with the formula C₄H₅NH. The optimized molecular structure and main parameters (bond length, bond angle) of pyrrole are shown in Figure 8. All carbon atoms are marked with numbers for convenient expression. Due to the symmetrical structure, there is no difference between the C₁ group and C₄ group, or between the C₂ group and C₃ group.
In this study, the formation mechanisms of HCN and NH$_3$ during pyrrole pyrolysis in the presence of H$_2$O are investigated by DFT calculation. The results show that H$_2$O and pyrrole can interact in four ways, followed by 13 possible pyrolysis pathways. Six pathways will result in the formation of NH$_3$ (a-1, a-2, a-3, b-1, b-2, b-3), and another six pathways will lead to the HCN (a-4, a-5, c-2, c-3, c-4, d-1), while pathway c-1 does not lead to the formation of either HCN or NH$_3$. Among all these pathways, pathways a-3 and b-1 are the most favorable ones, with an overall energy barrier of 362.3 and 361.4 kJ/mol, respectively. Starting from the initial ind-OH-C$_1$-H interaction, the optimal pathway is a-3, with an overall energy barrier of 362.3 kJ/mol, and the N product is NH$_3$. Within the initial adj-OH-C$_2$-H interaction, the optimal pathway is a-3, with an overall energy barrier of 362.3 kJ/mol, and the N product is NH$_3$.

The formation of NH$_3$ or HCN is determined by the different initial interactions of H$_2$O with pyrrole. When H$_2$O attacks the C$_2$ position of pyrrole, there are two possible interactions (adj-OH-C$_2$-H and adj-OH-N-H). In the following pathways based on the two interactions, NH$_3$ will be formed while the formation of HCN is inhibited. When H$_2$O attacks the C$_3$ position of pyrrole with its hydroxyl group, it leads to another two interactions (ind-OH-C$_1$-H and ind-OH-C$_3$-H). In the following pathways, HCN will be generated instead of NH$_3$. Meanwhile, the formation of HCN is inhibited compared to in reactions without H$_2$O.

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