DOI: 10.1002/ange.201006272

Microreactors

Safe and Efficient Tetrazole Synthesis in a Continuous-Flow Microreactor**

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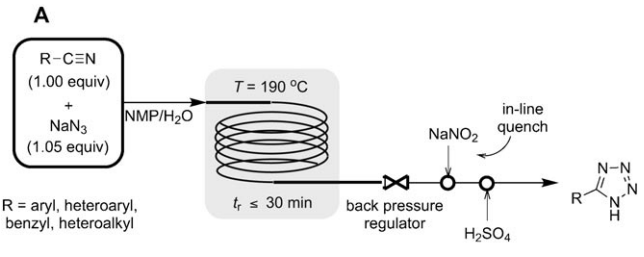
Tetrazoles are an important class of heterocycles in a wide range of applications, such as, organocatalysis and transition-metal catalysis, propellants, explosives, and perhaps most commonly, as non-classical isosteres of carboxylic acids in medicinal chemistry.[1,2] This broad utility has prompted significant effort toward tetrazole synthesis,[3] and notable among these is that of Sharpless, in which aqueous zinc bromide ($ZnBr_2$) facilitates the assembly of tetrazoles from nitriles and sodium azide (NaN_3).[3e] Nevertheless, the majority of reported methods are either less straightforward or generally not suited for large-scale synthesis; they require explosive and/or expensive reagents, toxic metal-containing compounds, or excess azide. The most significant hazard is the generation of hydrazoic acid (HN_3), particularly in reactions conducted in the presence of even trace amounts of Brønsted acids.[4]

Continuous-flow synthesis is emerging as a powerful technology complementary in several contexts to batch synthesis in flasks or vessel reactors.[5] As only small quantities of reagents and products are exposed to the reaction conditions at a given time, the risks associated with hazardous materials are minimized, and transformations using them are thus rendered much safer. Flow would thus appear to be an appropriate reaction format for the synthesis of tetrazoles from nitriles and an azide source. During the preparation of this manuscript a collaborative effort between Kappe and Lonza reported an exquisitely engineered system for the continuous-flow synthesis of tetrazoles using HN_3.[6] Generated in situ from NaN_3 and acetic acid, HN_3 (approximately 2.5 equiv at 1.6 M) may be used at elevated temperatures and pressures to prepare a range of tetrazoles from the corresponding nitriles.

From the outset of our investigations, described herein, we took a conceptually and technically different approach, establishing the following as fundamental requirements of our method: avoid the use and generation of HN_3,[7] require only a slight excess of azide (in any form), develop a system that can be assembled easily such that it may be implemented both in the laboratory (education and research) and, with straightforward modification, on manufacturing scale. In addition to being safer (no HN_3, minimal azide usage), easily assembled (see video provided in Supporting Information) and less expensive (syringes, syringe pumps, oil bath, standard tubing and fittings), this method is, perhaps unexpectedly, faster and higher yielding in many cases. Other features include the fact that neither a metal catalyst nor promoter is required and the inclusion of a simple in-line, post-reaction treatment with $NaNO_2$ to quench the vanishingly small traces of remaining azide.

We began our investigations by evaluating several reported methods of tetrazole synthesis with the aim of finding one that would be amenable to the requirements listed above. In early stages, small-scale microwave reactions provided a useful and informative bridging basis of comparison between batch and flow[8] (Table S1, Supporting Information). Nitrile **1** (Figure 1, R = *p*-anisyl) was chosen as the starting point as it is of moderate reactivity in most tetrazole syntheses, largely due to the electron-donating effect of the methoxy group.[9] The conditions reported by Sharpless et al.[3e] and later shown to be effective under microwave irradiation by Fang et al.[3h] (Table S1, entries 4–6) showed the greatest promise for development of a flow process. With nitrile **1** a reaction temperature of 140 °C provided the highest



B	feature	function
	• near 1:1 ratio of nitrile:azide	• minimizes azide usage
	• reaction pH 6.5 - 8.5	• minimizes HN_3 generation (< 0.006 M)
	• no headspace (flow reactor)	• avoids HN_3 accumulation and exposure
	• elevated temperature and pressure	• provides rate enhancement (safely)
	• absence of $ZnBr_2$ promoter	• suppresses nitrile hydration
	• in-line quench ($NaNO_2$)	• destroys residual azide traces

Figure 1. A) Continuous-flow synthesis of tetrazoles using our microreactor. See Supporting Information for parts list and instructions for assembly and operation (video). B) Summary of the function of each reactor feature. NMP = *N*-methyl-2-pyrrolidone.

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[**] We are grateful to the Novartis-MIT Center for Continuous Manufacturing for financial support and to several colleagues at MIT (Stephen L. Buchwald, Klavs F. Jensen, and their co-workers) and Novartis (Gerhard Penn, Berthold Schenkel, Oljan Repic, Thierry Schlama, Mike Girgis, Lukas Padeste, and Felix Kollmer) for insightful discussions.

Supporting information for this article is available on the WWW under http://dx.doi.org/10.1002/anie.201006272.

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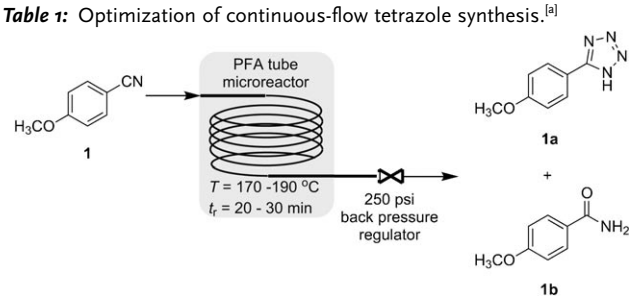
yield of desired tetrazole **1a** (65%) in 30 min. The solution mixture remained homogenous throughout the entire course of the reaction, but an undesired byproduct, carboxamide **1b** (see Supporting Information), resulting from nitrile hydration was also obtained in significant quantities (9% yield).[10]

Nevertheless, this lead result served as the starting point for the development of a straightforward flow process (Figure 1 and Table 1). Nitrile **1**, NaN_3, and $ZnBr_2$ in a clear, homogeneous organic/aqueous solution were pumped into a simplified microreactor assembly consisting of PFA (perfluoroalkoxyalkane) tubing immersed in an oil bath and equipped with a 250 psi back pressure regulator at the distal end. The lack of reactor headspace provided an immediate advantage over the batch microwave conditions: Much higher temperatures were possible, with no increased risk of explosion or exposure, thus providing significant acceleration of the desired transformation in a safe manner. We observed a considerable dependence of conversion on solvent selection, and a 9:1 mixture of NMP:water provided the best balance of rate and yield, while maintaining reaction homogeneity throughout (Table 1, entries 2–4).

Table 1: Optimization of continuous-flow tetrazole synthesis.[a]



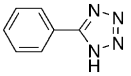
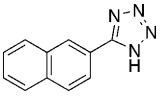
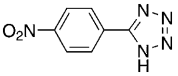
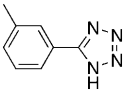
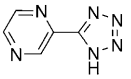
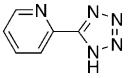
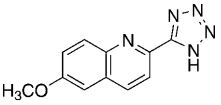
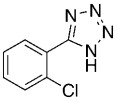
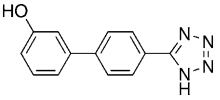
Entry	Solvent	NaN_3 (equiv)	$ZnBr_2$ (equiv)	Conv. [%][b]	Yield [%][b] 1a	1b
1[c]	THF:H_2O (1:4)	4	2	90	76	10
2	IPA:H_2O (1:4)	4	2	79	64	11
3	NMP:H_2O (1:4)	4	2	95	83	8
4	NMP:H_2O (1:4)	2	1	81	72	7
5	NMP:H_2O (1:4)	1.05	0.5	61	56	4
6	NMP:H_2O (9:1)	1.05	0.5	63	61	<1
7[d]	NMP:H_2O (9:1)	1.05	0.5	86	78	7
8[d]	NMP:H_2O (9:1)	1.05	0	83	81	<1

[a] See Supporting Information. Unless otherwise noted, substrate concentration $[\mathbf{1}]_0 = 0.2$ M; reaction temperature = 190 °C; residence time (t_r) = 20 min. [b] Determined by HPLC. [c] Reaction temperature = 170 °C. [d] $[\mathbf{1}]_0 = 0.4$ M; $t_r = 30$ min.

This observation and a few other modifications achieved one of the critical requirements that we had established for the process, namely, minimal use of azide (1.05 equiv relative to nitrile **1**). Moreover, as long as the solvent mixture was largely organic, the amount of NaN_3 and $ZnBr_2$ could be decreased to 1.05 and 0.50 equivalents, respectively, with no reduction in conversion or yield (Table 1, entries 5 and 6). Doubling the substrate concentration did increase conversion, but nitrile hydration to carboxamide **1b** reappeared as a significant competing process. However, omission of the $ZnBr_2$ suppressed this undesired pathway to below the limit of detection (HPLC, approximately 1%) with only a minimal decrease in conversion of desired tetrazole **1a** (Table 1, entries 7 and 8). Nitrile hydration is thus dependent upon $ZnBr_2$, whereas tetrazole formation is only minimally so.[3e,11]

Many nitriles underwent complete conversion to the corresponding tetrazoles under these optimized conditions (Table 2). Nitriles **2** and **3**, bearing no electron-donating or electron-withdrawing groups on the aromatic ring, were transformed to tetrazoles **2a** and **3a** in near-quantitative yield in 20 min. The electron-poor nitrile **4** behaved similarly, as did *m*-toluonitrile (**5**) and heteroaromatic nitriles **6**–**8**. Slightly reduced conversions were observed in case of sterically hindered nitrile **9** and biphenyl nitrile **10**.

Table 2: Scope of continuous-flow tetrazole synthesis.[a]

	Tetrazole product	Conv. [%][b]	Yield [%][b]
2a		100	98 (96)[c]
3a		99	95 (94)[c]
4a		98	95 (93)[c]
5a		90	85 (81)[c]
6a		94	93 (90)[c]
7a		100	96 (94)[c]
8a		99	98 (97)[c]
9a		80	77 (75)[c]
10a		81	79

[a] See text, Supporting Information. In all cases, nitrile concentration = 0.2 M; reaction temperature = 190 °C; $t_r = 20$ min. [b] Determined by HPLC. [c] Yield of isolated product.

The success with nitrile **1** prompted us to test the reactivity of other electron-rich nitriles under these conditions. Moderate conversion, yet excellent yield based thereon, was observed for electron-rich nitriles **11** and **13** (Table 3). As observed with the nitrile **1**, **11**–**17** showed higher conversion at substrate concentration = 0.4 M. Biphenyl nitriles **14** and **15** displayed both good conversion and good yield. Notably, chiral nitrile **16** provided **16a**, a derivative of which (no carbobenzyloxy (Cbz) group) has found utility as an organocatalyst,[1b] in greater than 99% *ee* and 92% yield based on

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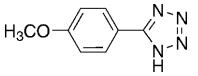
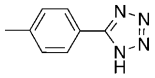
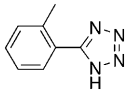
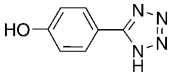
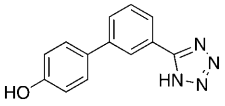
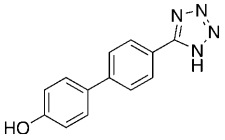
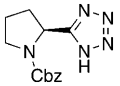
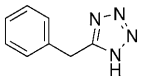
Table 3: Effects of concentration and residence time.[a]

	Tetrazole product	Conv. [%][b]	Yield [%][b]
1a		83[d]	81 (79)[c]
11a		61	57 (51)[c]
12a		25	25 (23)[c]
13a		49[d]	48 (45)[c]
14a		86	84 (81)[c]
15a		82	77
16a		71	65[e]
17a		51[f]	50[f] (48)[c]

[a] See Supporting Information. Unless otherwise noted nitrile concentration = 0.4 M; reaction temperature = 190 °C; t_r = 20 min. [b] Determined by HPLC. [c] Yield of isolated product. [d] t_r = 30 min. [e] *ee* > 99% (HPLC). [f] Determined by ^{1}H NMR spectroscopy.

conversion. The electron-rich as well as sterically hindered nitrile **12a** showed poor conversion and yield under these conditions. Most importantly, however, no carboxamide was observed in any case in the absence of $ZnBr_2$, even at extended residence times, and a ten-fold scale-up (10× longer tubing (same diameter), 10× faster flow rate) using these conditions proceeded as expected, affording 3.5 g of **3a** in 12 h.

To demonstrate the scale-up capabilities of our process beyond laboratory scale, we carried out the synthesis of **3a** on Uniqsis FlowSyn continuous-flow reactor. FlowSyn is an integrated continuous-flow reactor system that uses a pair of high-pressure pumps to deliver reagent solutions through a "T"-mixer into the electrically heated flow coil or column reactors.[12] The homogenous solution of reagents ([**3**] = 1 M; $[NaN_3]$ = 1.05 M) in NMP:H_2O (7:3) was pumped using a single pump through a coiled PFA tubing reactor (volume of heated zone ≈ 6.9 mL) with a flow rate of 0.35 mL min^{-1} (t_r = 20 min) at 190 °C (see Supporting Information). The flow process was run continuously for 2.5 h to obtain 9.7 g of **3a** in 96% yield. This corresponds to a product output of 4.85 g h^{-1} or 116 g day^{-1} for the tetrazole **3a**.

Overall, this flow synthesis of 5-substituted tetrazoles is safe, practical, efficient, and straightforward. It enjoys a broad scope, and in all cases the yield based on conversion is greater than 90%, in many cases nearly quantitative. The hazards associated with HN_3 are essentially eliminated, shock-sensitive metal azides such as $Zn(N_3)_2$ are eschewed, and any residual NaN_3 is quenched in-line with $NaNO_2$. Given these features and the widespread applications of tetrazoles, this method may find use on any scale, from laboratory to manufacturing.

Finally, it should be emphasized that the most important attributes of this process (high yield, near-equimolar nitrile:azide ratio, no $ZnBr_2$-promoted nitrile hydration, minimal HN_3 generation,[13] and short reaction time) are collectively possible only because the reactions can be conducted at elevated temperature (190 °C). This critical reaction variable is in turn feasible only because the reaction format is flow, wherein there is no headspace in which HN_3 could accumulate to an explosive level. That there is no headspace therefore not only obviates several hazards, but also improves the method. A closed-system batch process at 190 °C (microwave or otherwise) would be far too hazardous, and without elevation of the reaction temperature, the reaction rate would be well below a usable level. It is thus demonstrated in this case that flow not only is far safer than batch, but also is the necessary and enabling technology for this process.

Received: October 6, 2010
Revised: February 9, 2011
Published online: March 8, 2011

Keywords: azides · continuous-flow synthesis · microreactors · synthetic methods · tetrazoles

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[10] In the cases of nitriles **3** and **10**, formation of the carboxamide byproduct was also observed under the same conditions.

[11] For detailed comparisons of the effects of $ZnBr_2$ (presence vs. absence) in this transformations, please see the Supporting Information.

[12] http://www.uniqsis.com.

[13] Ferric chloride strip test was performed for detection of HN_3 in the post-reaction stream (see Ref. [3e] and references therein). The test gave negative results (no HN_3 detected) for reactions run up to 1M concentration of NaN_3. The test also gave negative results for a control reaction run without the addition of substrate at 1M NaN_3 concentration.

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