Microfluidic Synthesis of Energetic Materials

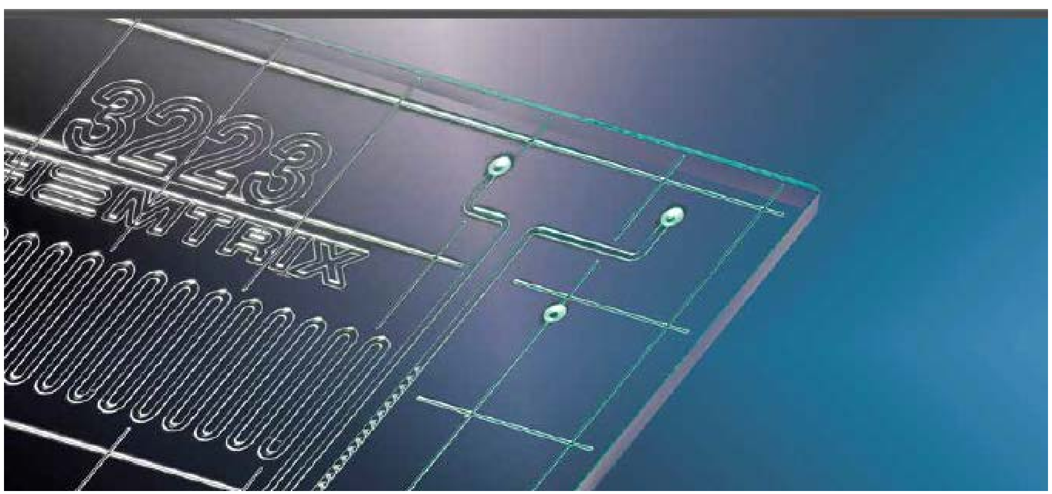
Joe Scavuzzo, PhD
Melissa Mileham, PhD

April 2018

Abstract # 20271

What is Microfluidic Synthesis?

- **Microfluidics:** "Microfluidic systems manipulate and control fluids that are geometrically constrained within environments having internal dimensions, or hydrodynamic diameters, on a scale of micrometers" – Nature Chemistry, 2003
- **Microfluidic Synthesis** uses microfluidic technology to manipulate reactive liquids or solutions to produce chemical transformations



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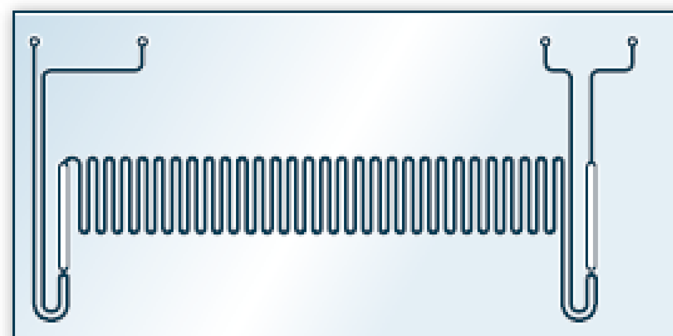


~1 in

Advantages Of Microfluidic Reactors

- Efficient heat exchange between reactor and environment
  - Highly exothermic, reactions are common in energetic synthesis (nitration, oxidation, acid neutralizations, etc.). If exotherms are not properly managed, run-away reactions can occur.
- Low reactive volume (microliters of solution)
  - Low consequence hazard
- Easy scale-up
  - Very high throughput at lab scale (20 conditions/day)
  - Scale is increased by lengthening reactor path or including parallel reactors
  - ~5µL reactor can produce ~ 50 g of material/day
    - ~200 µL reactor can produce at pilot scale levels

Lab Scale Work Station

Kilo Scale Work Station

Chemical Synthesis Methods

Batch Operation	Continuous Operation	Microfluidic Operation
High flexibility; preferred for multi-product/purpose operation, useful for a large range of reaction scale	Low flexibility; designed for a single process, not practical for development-scale production	Mid flexibility; lab and pilot scale reactor modifications are simple, reactors cannot handle all types of reaction media, useful for development to pilot plant scale
Low capital cost	High capital cost	Low capital cost
High consequence hazard; Large volumes of energetic materials being processed	High consequence hazard; large volumes of energetic materials being processed	**Low consequence hazard; µL to mL volumes of energetic materials being processed**
Reasonable scale-up from lab scale	Reasonable scale-up from lab scale – involves engineering/modeling	**Simple scale-up from lab scale**
Not suitable for unattended operation → labor intensive → high operating cost	Simple conversion to unattended operations → low operating cost	**Simple conversion to unattended operations → low operating cost**

Development Path

Goal: Build a microfluidic reactor from lab materials and use it to perform a two step reaction and make compound NO2-X2

1. Reaction Step 1; Nitrate X1

Optimize nitration conditions

$$HO{-}X_1 \xrightarrow[\text{Solvent}]{HNO_3\ (98\%)} O_2N{-}X_1$$

2. Reaction Step 2; Transform NO2-X1 to NO2-X2

Optimize transformation conditions

$$\xrightarrow{NaOH} O_2N{-}X_2$$

3. Combine 1 &2

Reconfigure and optimize reactor to perform both steps in series

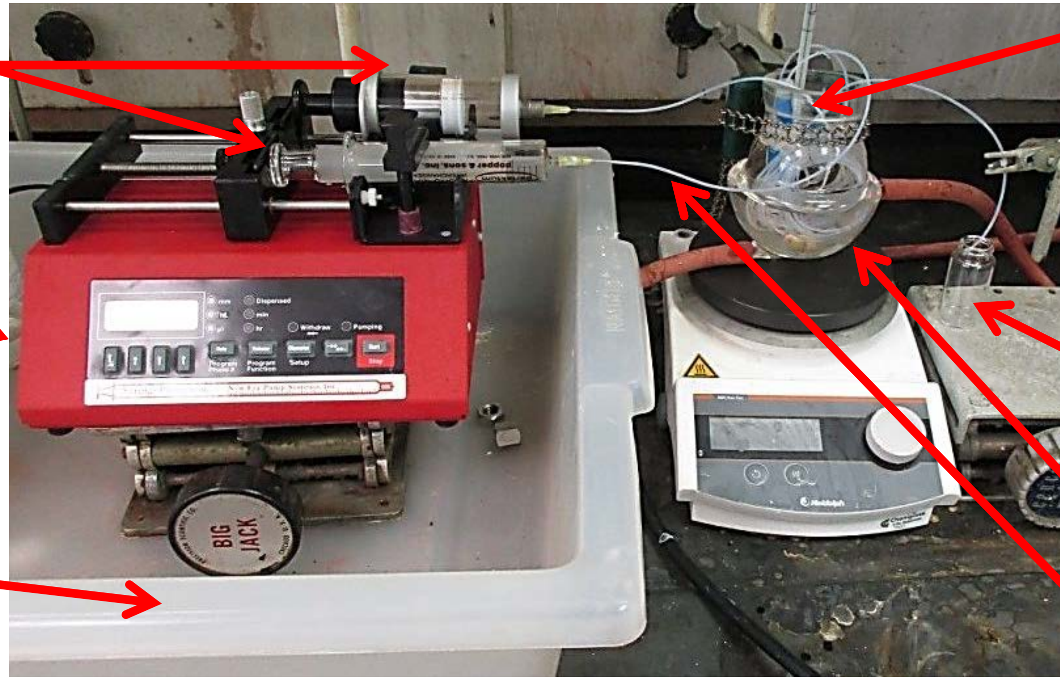
Reactor Design

Orbital ATK

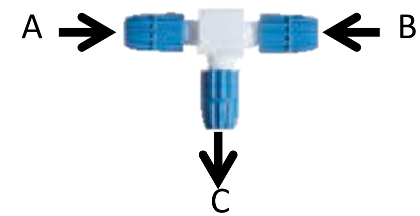
Syringes with no wetted metal

Dual syringe pump

Secondary containment



Tefzel T-joint used as mixer



Glass vial with ice quenches reaction product

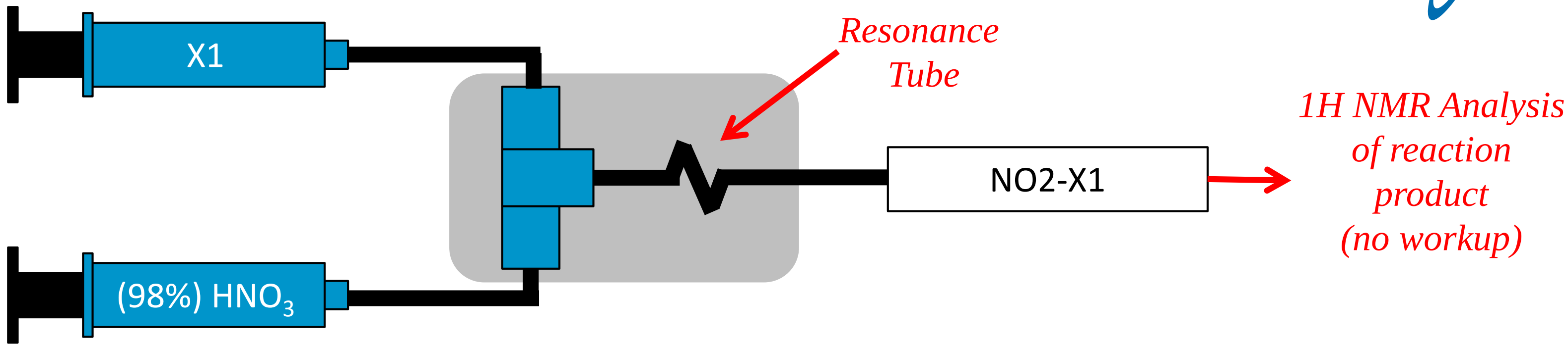
Glycol temperature bath

1/32-in. ID PTFE tubing 30cm

Process Controls

- Reagent feed ratios controlled by syringe size or dilution
- Reaction temperature controlled by temp bath
- Resonance time controlled by plunger rate or reactor tube length

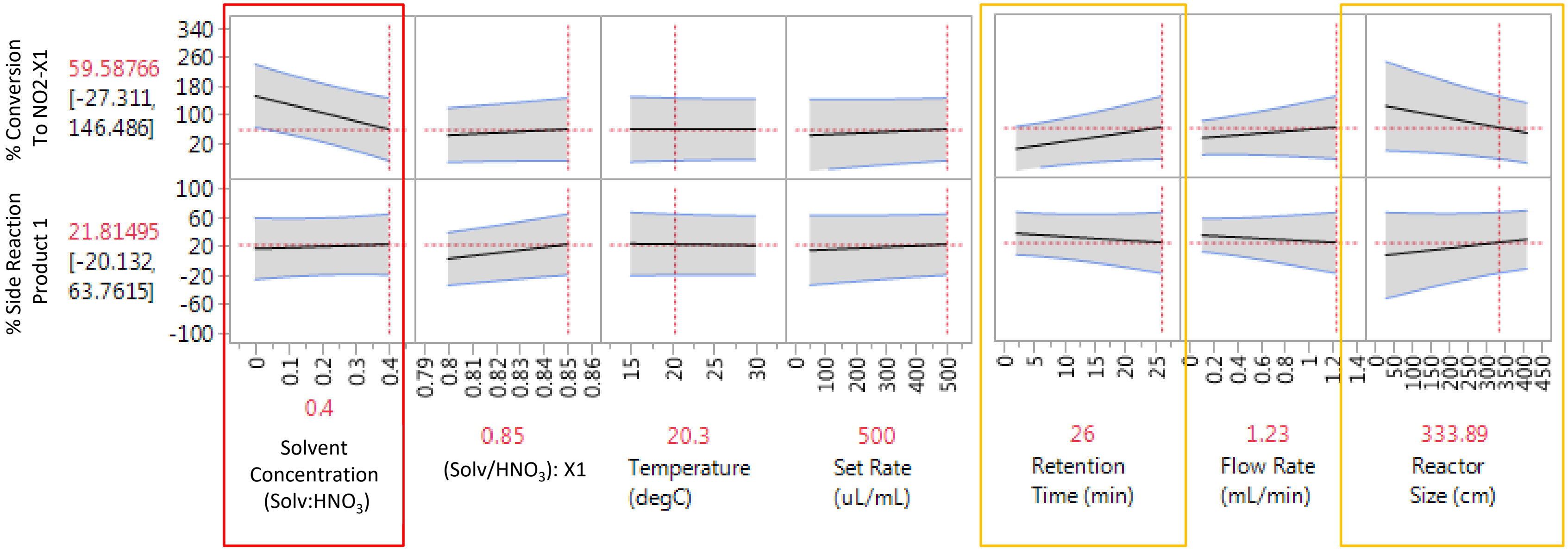
Nitration



Experiment	Temp (°C)	Acid Concentration (Solvent:HNO_3)	Acid:X1	Flow Rate (mL/min)	Retention Time (min)	Molar % Conversion	% Side Rxn Product 1
1	15	2:3	4:1	0.11	2.05	0	0
2	25	2:3	4:1	0.11	2.05	0	0
3	30	2:3	4:1	0.11	5.65	0	0
4	20	1:3	4:1	0.15	21.6	19	14
5	20	1:5	4:1	1.23	2.68	13	12
6	20	1:5	4:1	0.25	13.4	14	12
7	20	1:5	4:1	0.125	26.0	54	13
8	27	1:5	4:1	1.23	2.68	22	13
9	20	0:1	4:1	1.23	2.68	68	14
10	20	0:1	4:1	0.25	13.4	43	7
11	20	0:1	4:0.68	0.76	4.23	78	39
12	20	0:1	4:0.68	0.152	21.0	74	18
11b	20	0:1	4:0.68	0.76	4.23	80	41
12b	20	0:1	4:0.68	0.152	21.0	75	27

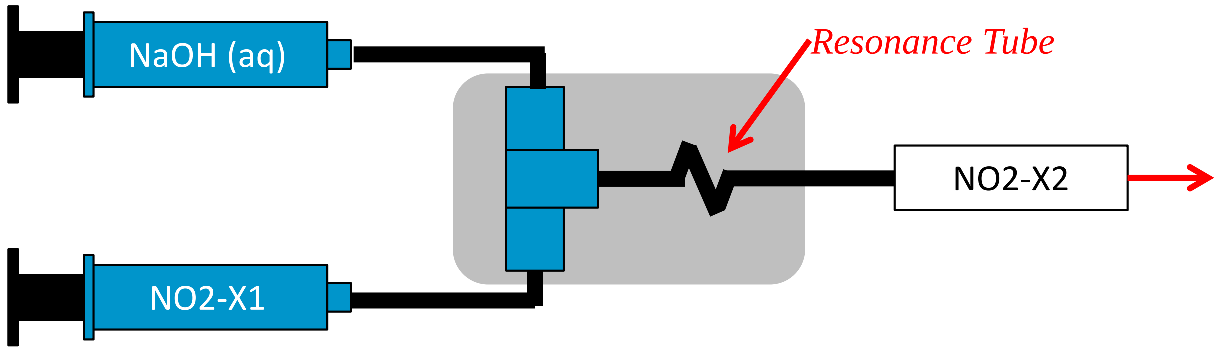
This method is capable of producing NO2-X1 at conversions and purity levels similar to batch

Nitration Statistical Analysis



Acid concentration, reactor size, and retention time are the most significant variables

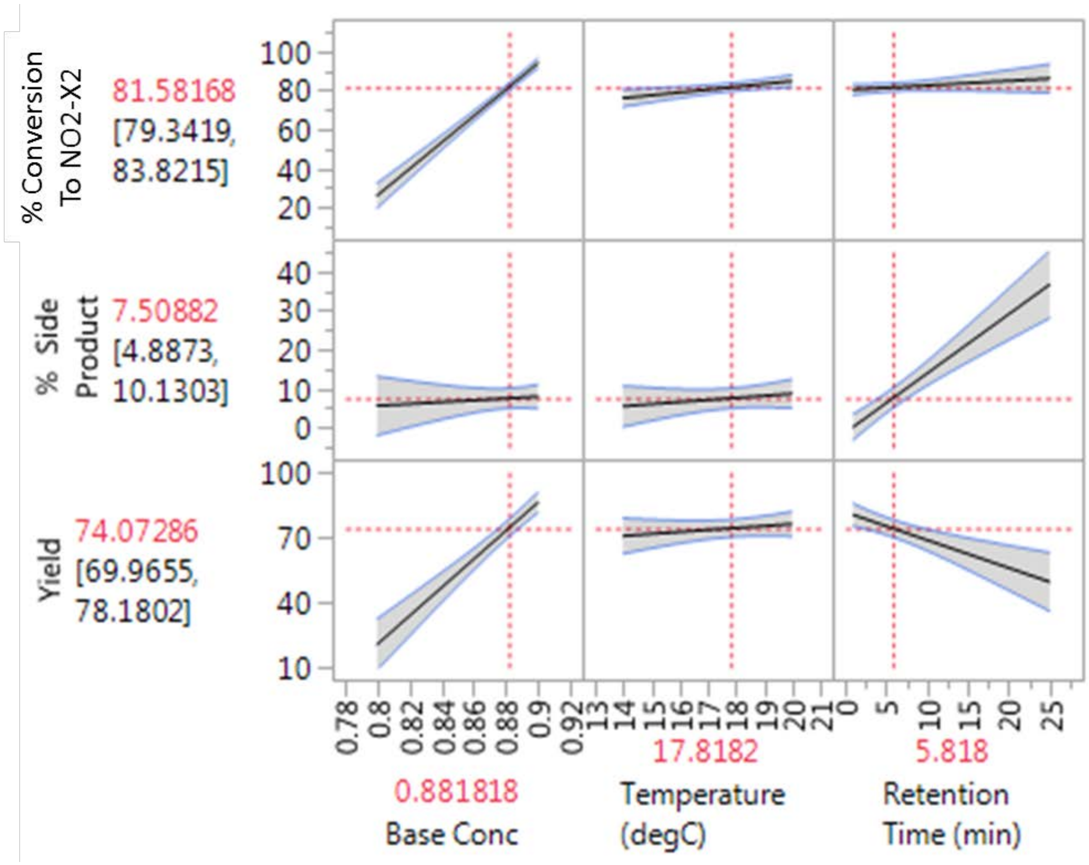
Step 2 (Caustic) Reaction



Experiment	*NaOH:(NO2-X1)*	*Temp (°C)*	*Actual Flow Rate (mL/min)*	*Retention Time (min)*	*%Conversion From NO2-X1*	*%Side Products*	*% Reaction Yield*
1	4:1	14	0.57	1.13	20	0	20
2	4:1	14	0.11	5.65	20	0	20
3	2.7:1	14	0.63	1.02	83	0.6	82.4
4	2.7:1	14	0.126	5.10	92.4	2.6	89.8
5	2.7:1	20	0.63	1.02	94.7	2.2	92.5
6	2.7:1	20	0.126	5.10	97.3	3.9	93.4
7	2.7:1	20	0.63	5.10	100	5	95
8	2.7:1	20	0.31	7.30	100	9.3	90.7
9	2.7:1	20	0.126	25.0	100	40	60
10	2.7:1	20	0.95	2.50	93	6	87
11	2.7:1	20	0.63	5.10	97	13	84

This method is capable of neutralizing all acid and producing NO2-X2 with complete conversion

Caustic Reaction Statistical Analysis



Increased base concentration increases conversion and yield without increasing side reaction

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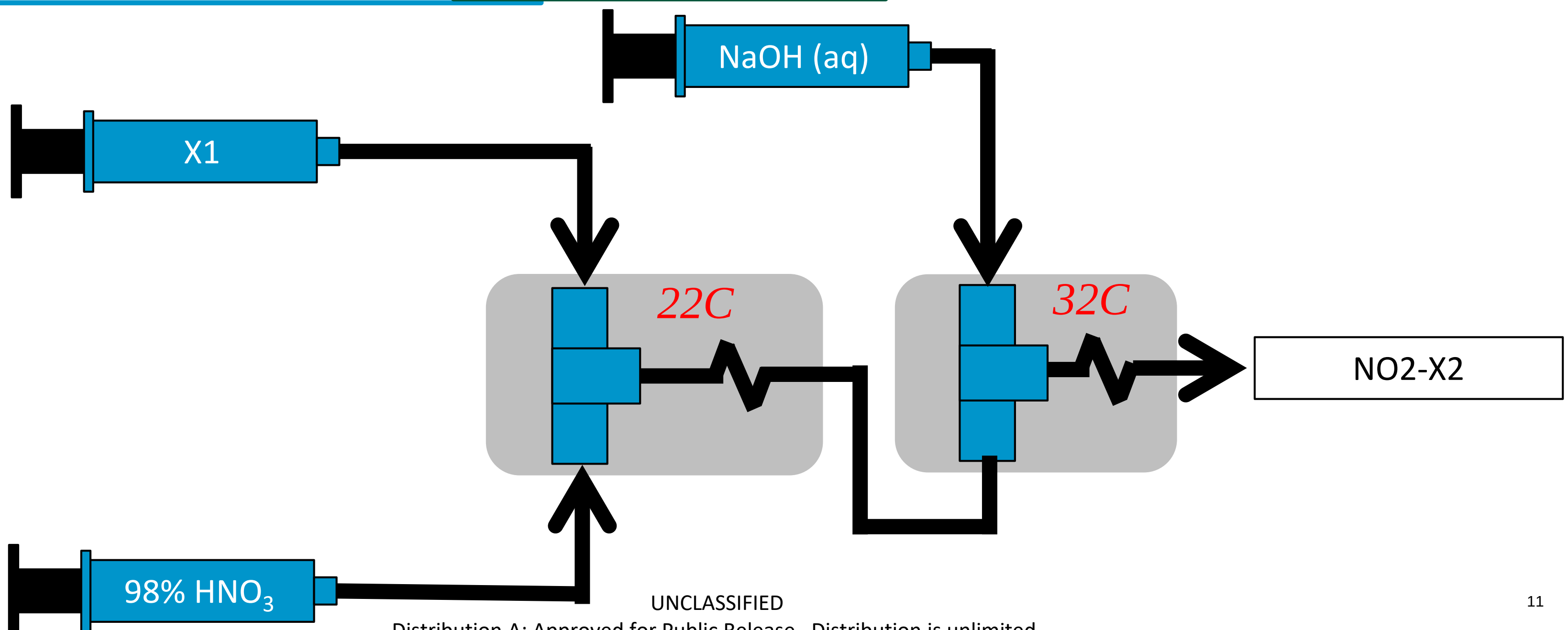
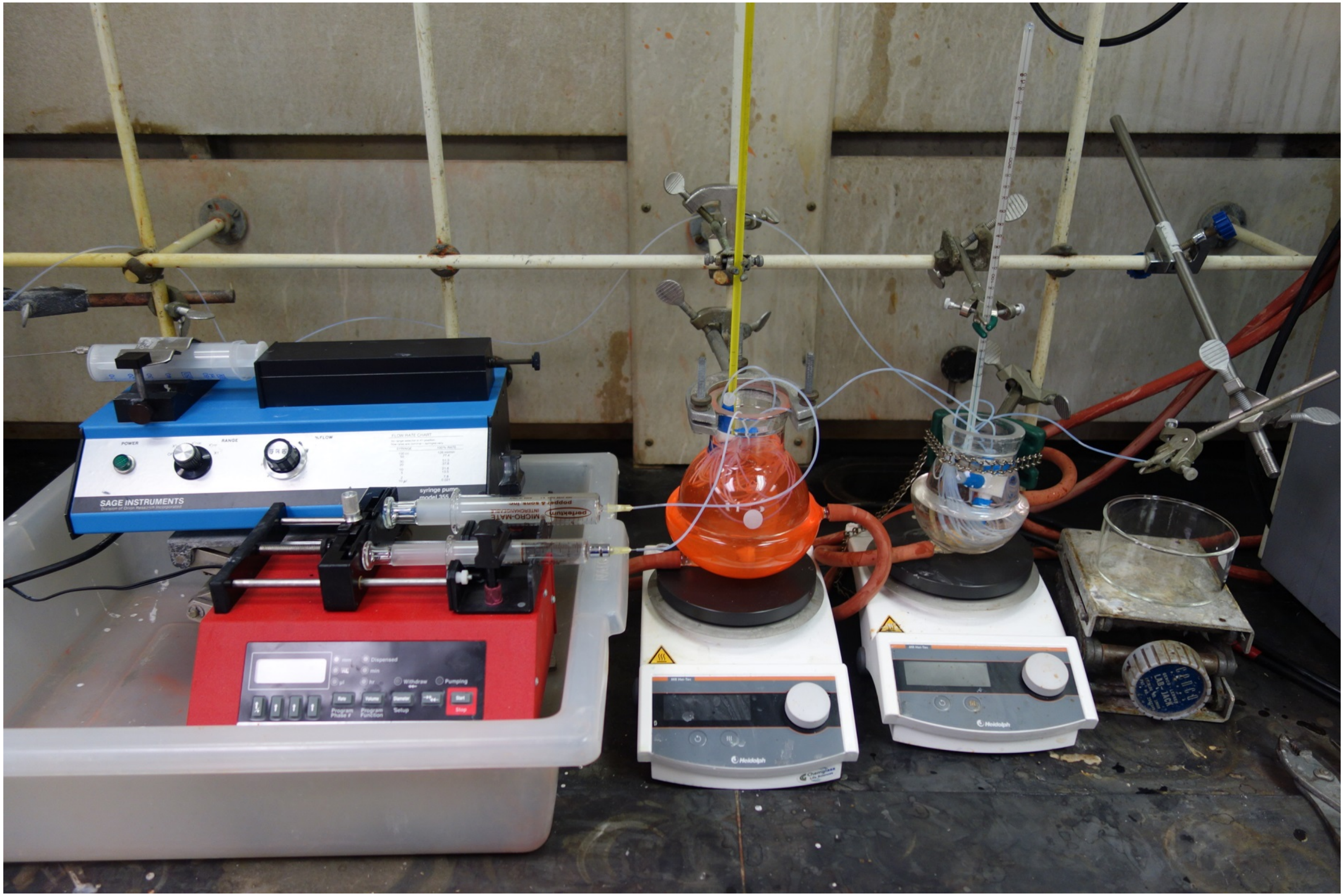


Two Step Reaction

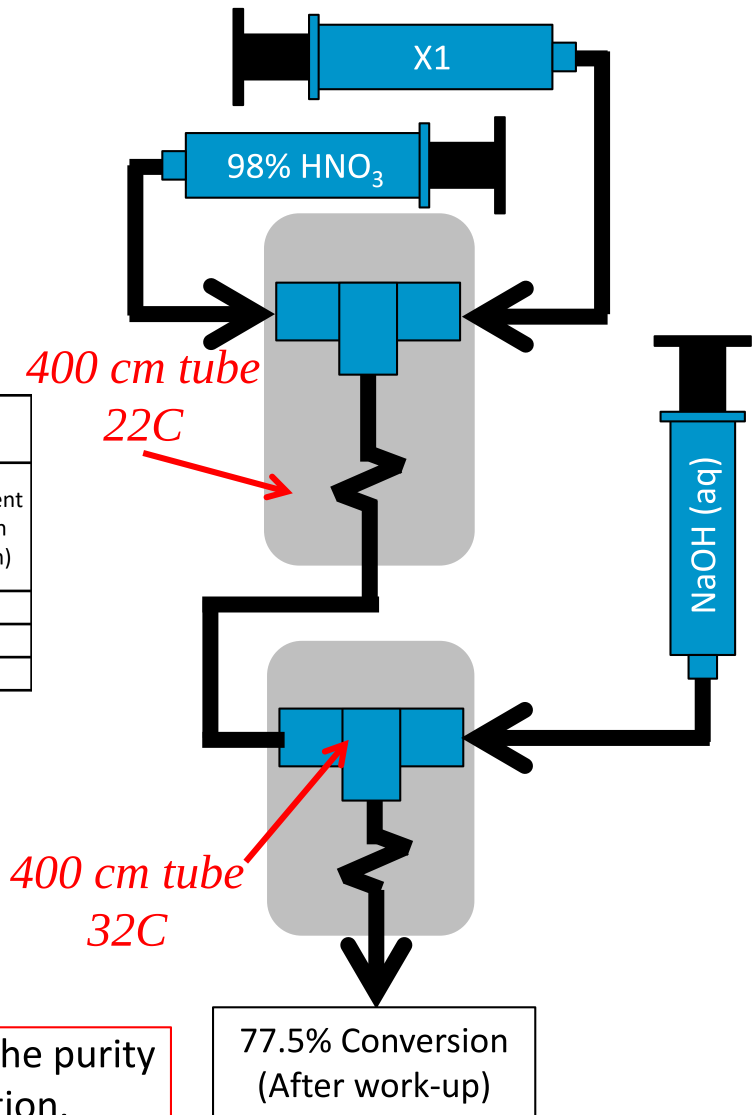


Two Step Reaction

Nitration Step Reactor Conditions (1st Segment)					
Experiment	HNO3:X1	Temperature (°C)	1st Segment Retention Time (min)	1st Segment Flow Rate (mL/min)	1st Segment Length (cm)
1	4:0.68	21	2.68	0.76	400
2	4:0.68	22	2.68	0.76	400
3	4:0.68	22	5.36	0.38	400

Ring Closure Reactor Conditions (2nd Segment)						
Experiment	NaOH Concentration	Temperature (°C)	NaOH Flow Rate (mL/mL)	2nd Segment Length (cm)	2nd Segment Flow Rate (mL/min)	2nd Segment Retention Time (min)
1	3.4	22	0.774	400	1.7	1.2
2	7.2	22	0.774	400	1.7	1.2
3	7.2	32	2.4	400	2.9	0.7

Experimental Results			
Experiment	% Conversion to X2-NO2	% Side Product	Yield/Notes
1	NA	NA	Insufficient Base
2	NA	NA	Inorganic Precipitates
3	83	5.5	77.5



NO2-X2 was produced with a two step microfluidic reactor. The purity and yield were similar to that expected for a batch reaction.

Conclusion

- A microfluidic reactor was successfully built with inexpensive lab materials and could withstand nitration conditions
- The two step synthesis of NO2-X2 was carried out on the microfluidic reactor successfully
- Very useful for optimization because of quick variable adjustments and high throughput
  - 28 conditions in several days
  - Less exposure of equipment and personnel to hazardous processes (14 batch nitrations vs 14 microflow conditions)

Questions?