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GEN IV integrated oxide fuels recycling strategies

Challenges in implementing separation processes – moving from lab to plant scale

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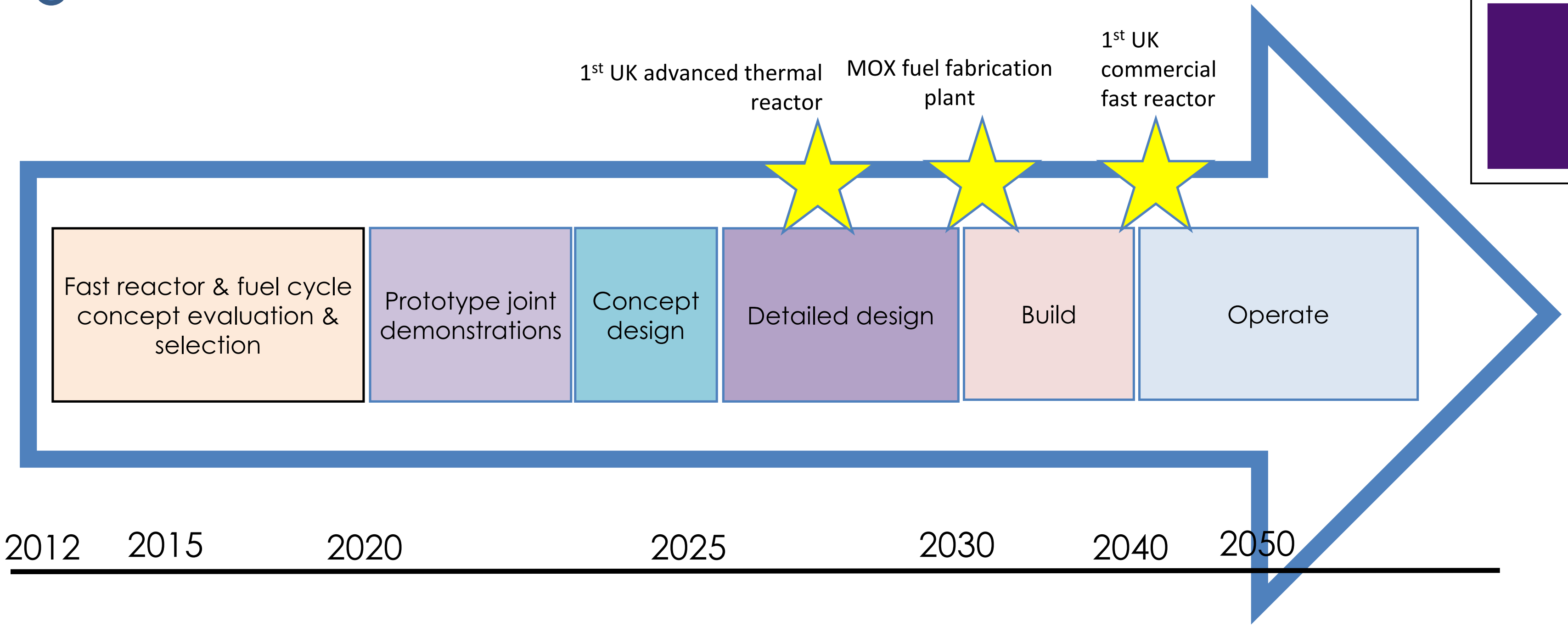
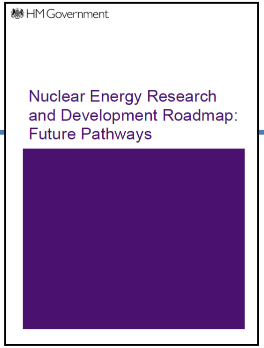
Context

- No advanced reprocessing of MA partitioning plants planned in Europe or North America
  - No government policies to deploy
  - No industry pull
  - But widespread interest in advanced fuel cycles for sustainability reasons
- We are in an R&D phase
  - Developing options
  - National Lab led
  - Technology push
- How do we transition from lab to plant?

Nuclear energy pathway – closed cycle





- Long timescale to transition from research to operating plant
- Need R&D now to deploy mid-century
- A fully closed cycle requires integration of different technologies

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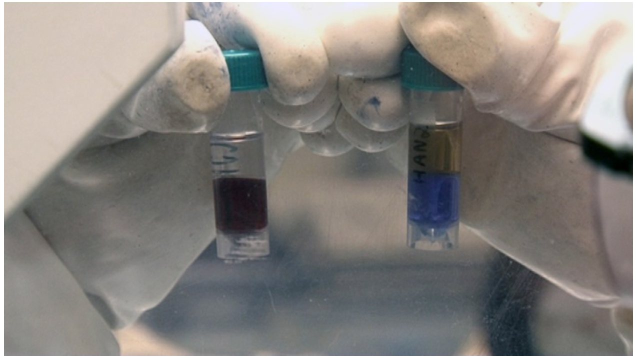
Contents

- Context
- R&D goals
  - Research led development stages
- Testing
  - Example from Thorp development
- Design & engineering
  - Moving to the design-led process
  - Space batteries example



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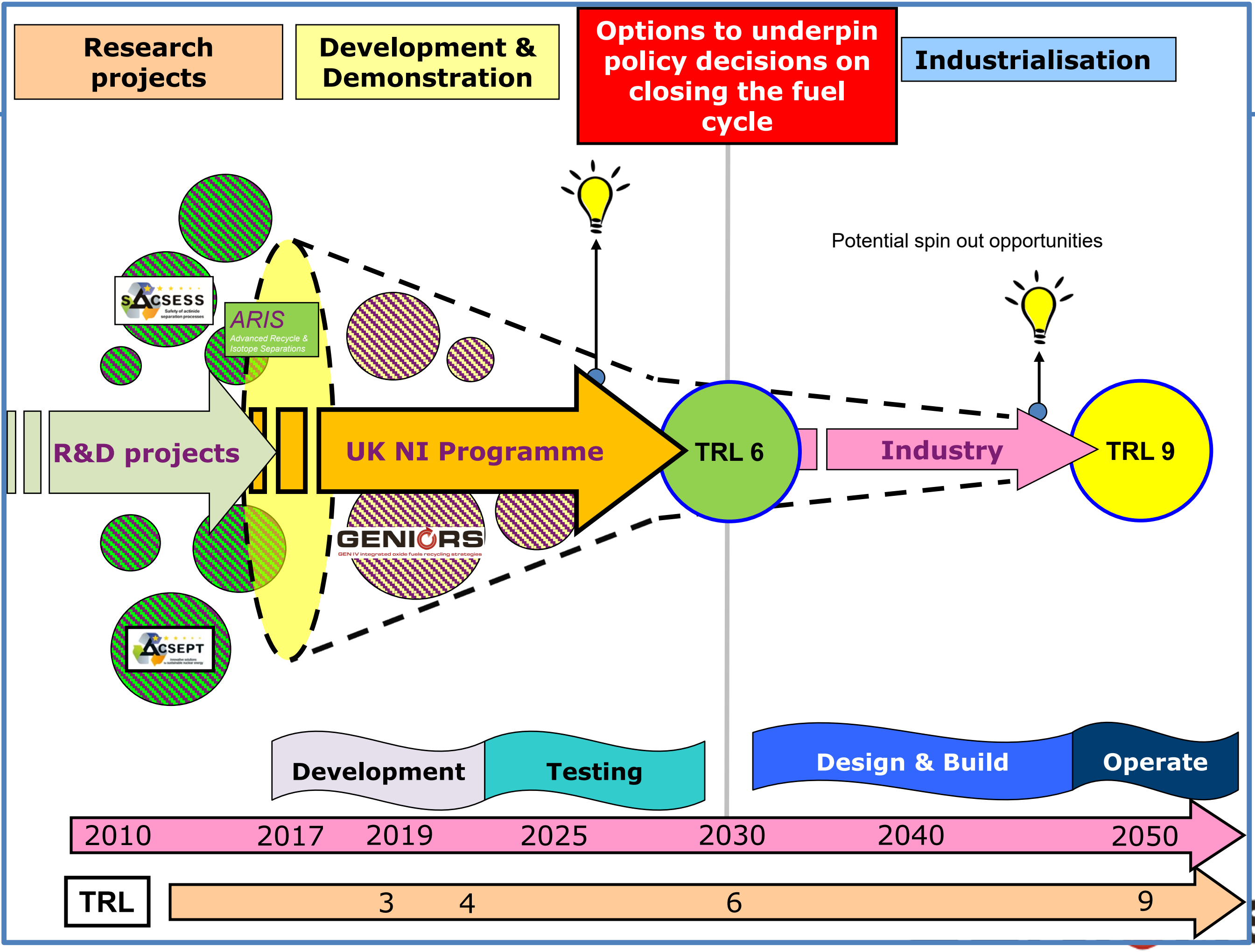
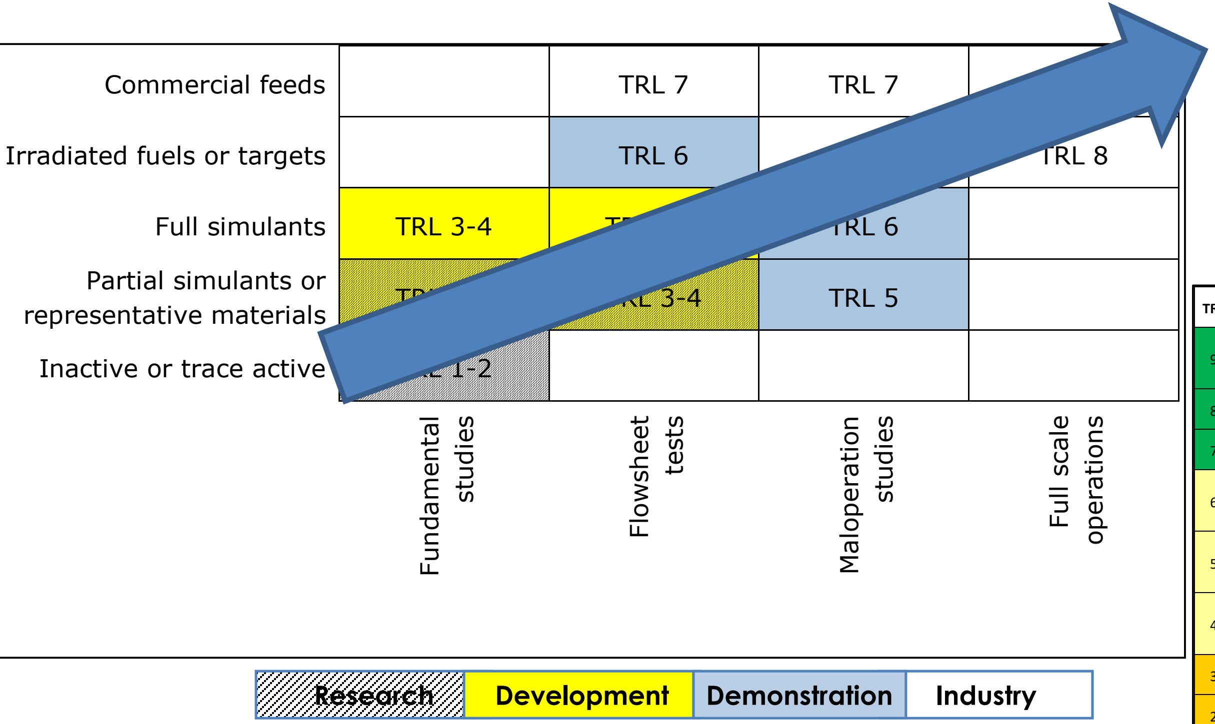
R&D pathway

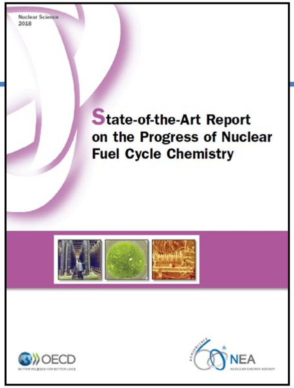
- Coordination of R&D
- Down-selection of processes
- R&D goal is demonstration
- ~TRL 6
- Develop credible options
- Address perceived problems
- Prove benefits
- Collaborate
- Integrate into fuel cycle
- Be ready to transition to industry



GEN IV integrated oxide fuels recycling strategies

Use of TRLs





TRL	Function	Definition
9	Proof of performance	Multiple years of operational experience established at industrial scale. Processing and recycle of minor actinide fuels / targets.
8		Full scale process demonstrated in a limited operational environment.
7		Prototype system demonstrated under conditions fully representative of operations.
6	Proof of principle	Engineering or pilot scale testing of technology component or process step. Process flowsheets proven through hot tests using spent fuel. Process models validated.
5		Technology component or process step validated at bench scale under relevant conditions. Process models developed. Proof of principle hot tests using spent fuel.
4		Technology component or process step validated under laboratory conditions. Tests performed using active materials in simulated feeds. Fundamental properties measured.
3	Proof of concept	Lab scale tests to prove concepts, fundamental data obtained
2		Technology application developed and options investigated
1		Initial concepts are proposed and basic principles established

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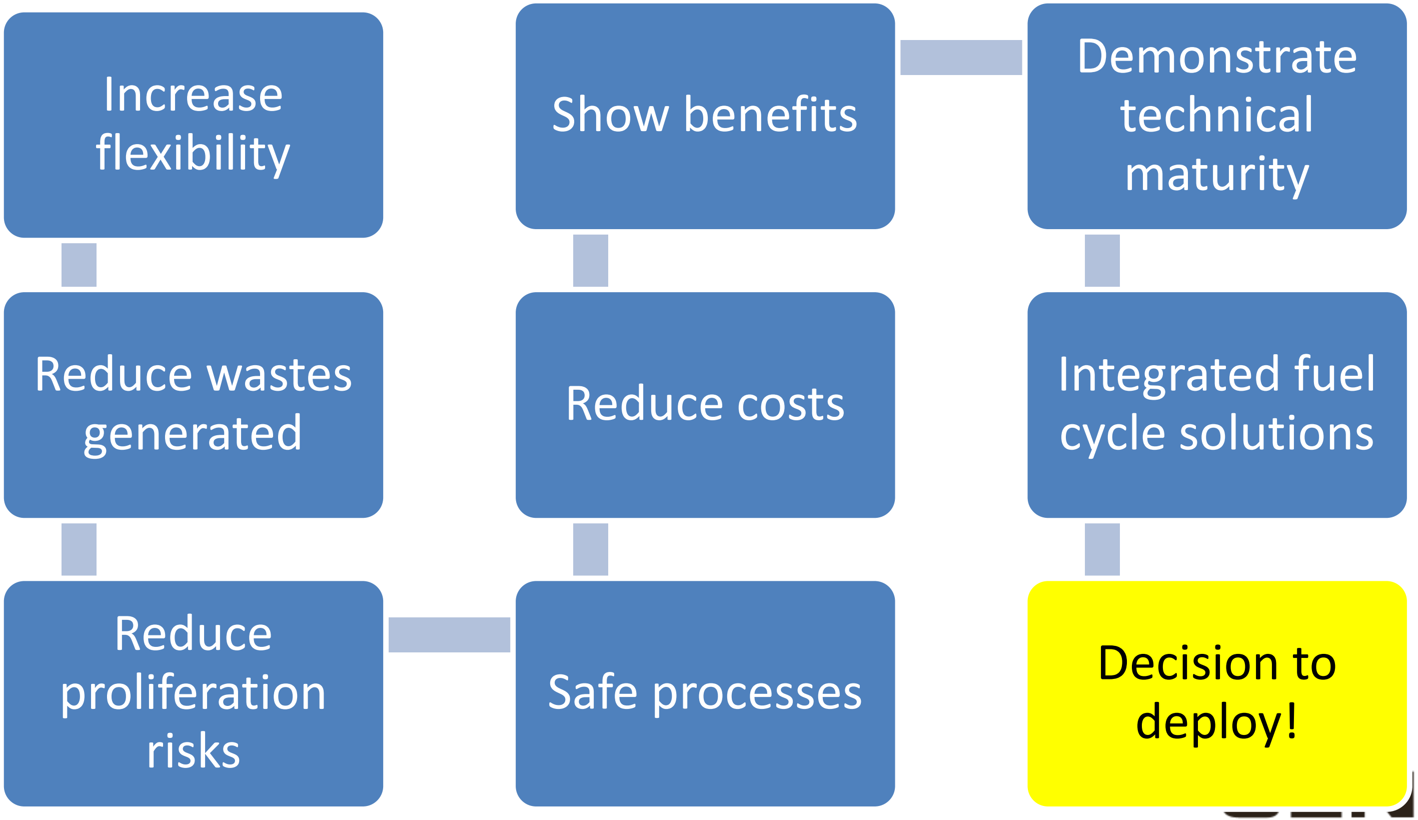
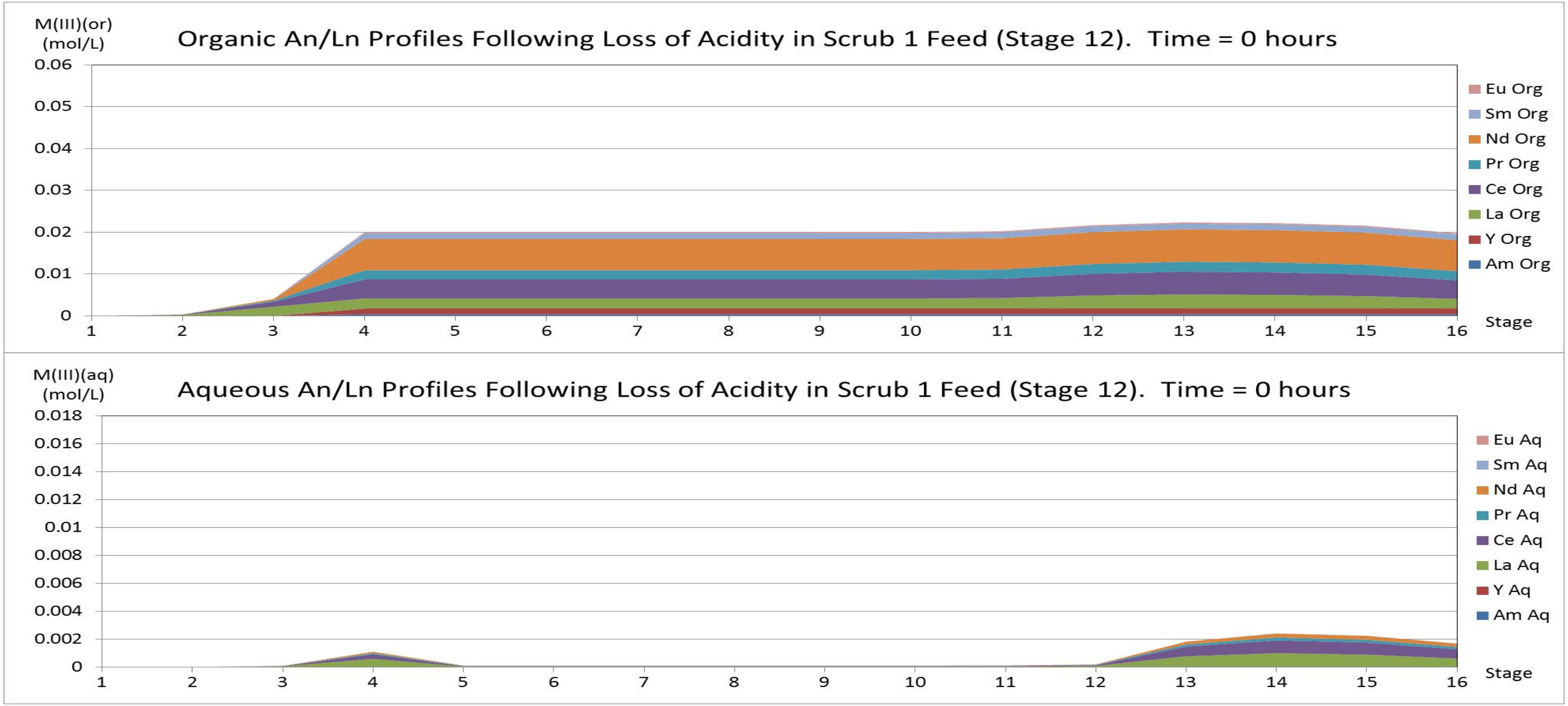
Research focused on what's important to decision makers



GEN IV integrated oxide fuels recycling strategies

Modelling & simulation

- Explain basic data & direct new experiments
- Useful in flowsheet design
- Essential in maloperations & sensitivity analyses
- Example malop – dynamic simulation:
  - recycle & accumulation of An/Ln in i-SANEX process
  - Addition of water to scrub acid feed
    - F. McLachlan et al., Modelling of Innovative SANEX Process Maloperations, Procedia Chemistry 21, 2016, pp. 109-116



M(III)(or) (mol/L)
Organic An/Ln Profiles Following Loss of Acidity in Scrub 1 Feed (Stage 12). Time = 0 hours
0.06
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Stage
Eu Org
Sm Org
Nd Org
Pr Org
Ce Org
La Org
Y Org
Am Org
M(III)(aq) (mol/L)
Aqueous An/Ln Profiles Following Loss of Acidity in Scrub 1 Feed (Stage 12). Time = 0 hours
0.018
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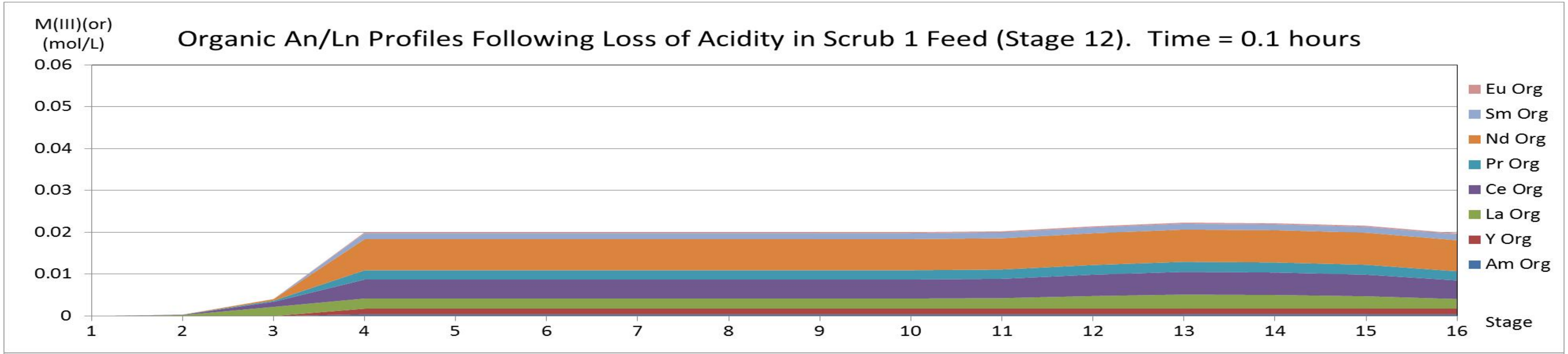

Organic An/Ln Profiles Following Loss of Acidity in Scrub 1 Feed (Stage 12). Time = 0.1 hours
M(III)(or) (mol/L)
0
0.01
0.02
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0.04
0.05
0.06
Stage
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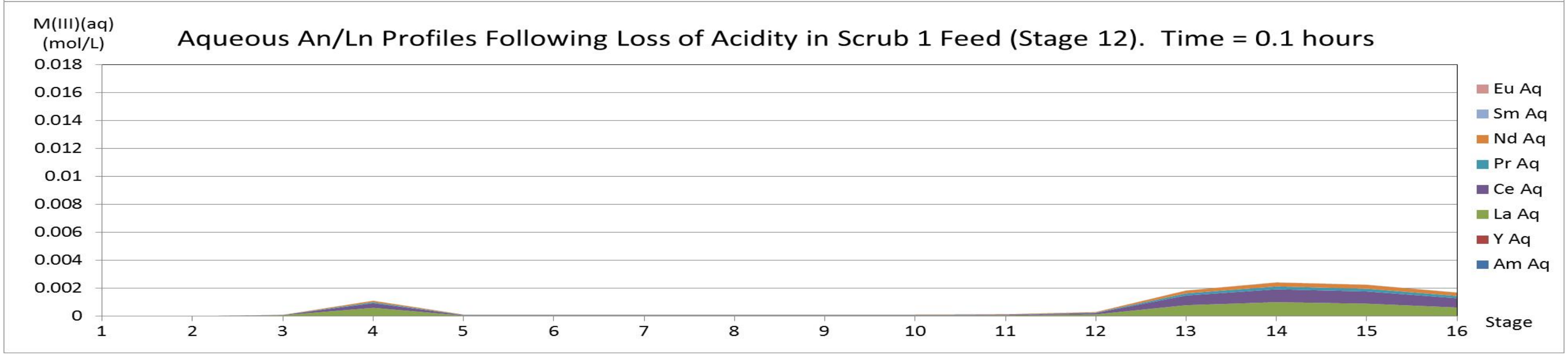

Aqueous An/Ln Profiles Following Loss of Acidity in Scrub 1 Feed (Stage 12). Time = 0.1 hours
M(III)(aq) (mol/L)
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0.002
0.004
0.006
0.008
0.01
0.012
0.014
0.016
0.018
Stage
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Pr Aq
Ce Aq
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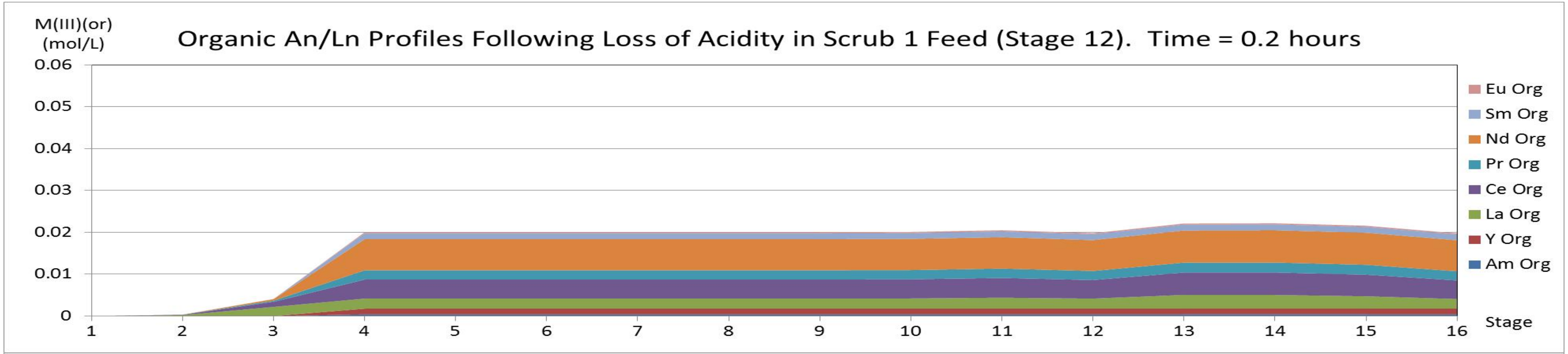
Am Aq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(mol/L)
Organic An/Ln Profiles Following Loss of Acidity in Scrub 1 Feed (Stage 12). Time = 0.2 hours
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0.05
0.04
0.03
0.02
0.01
0
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15
16
Stage
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Sm Org
Nd Org
Pr Org
Ce Org
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Y Org
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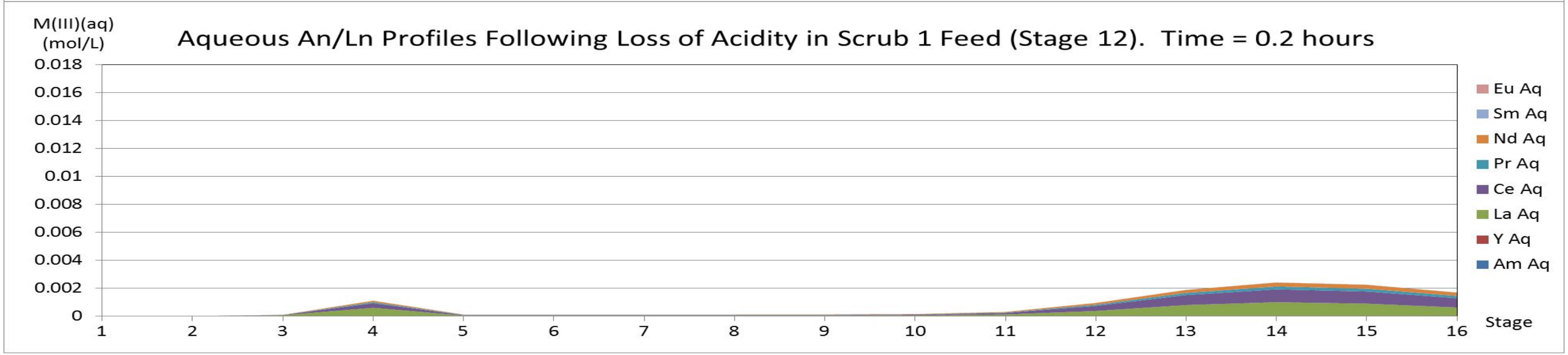
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Aqueous An/Ln Profiles Following Loss of Acidity in Scrub 1 Feed (Stage 12). Time = 0.2 hours
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0.01
0.008
0.006
0.004
0.002
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Stage
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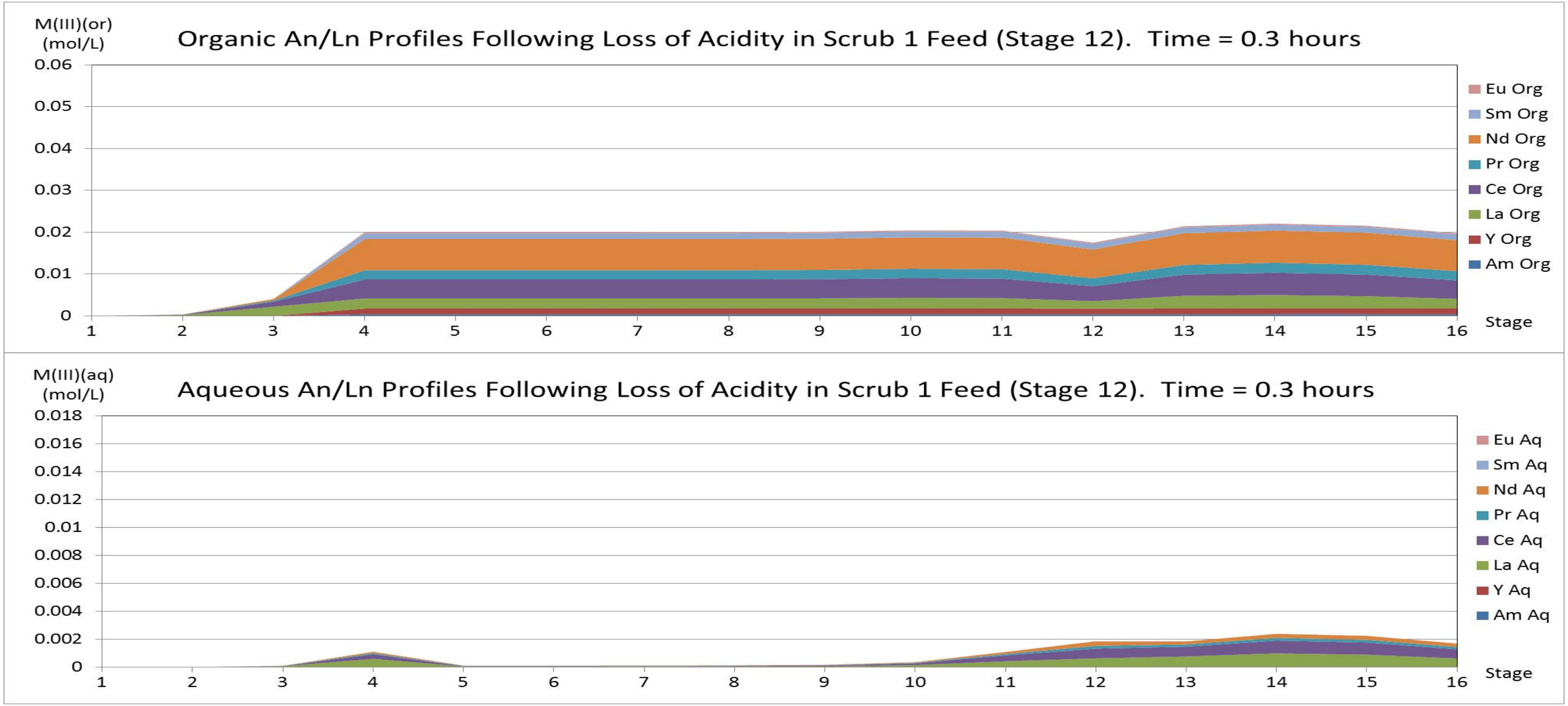
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0.05
0.04
0.03
0.02
0.01
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Stage
Eu Org
Sm Org
Nd Org
Pr Org
Ce Org
La Org
Y Org
Am Org
M(III)(aq) (mol/L)
Aqueous An/Ln Profiles Following Loss of Acidity in Scrub 1 Feed (Stage 12). Time = 0.3 hours
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
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Stage
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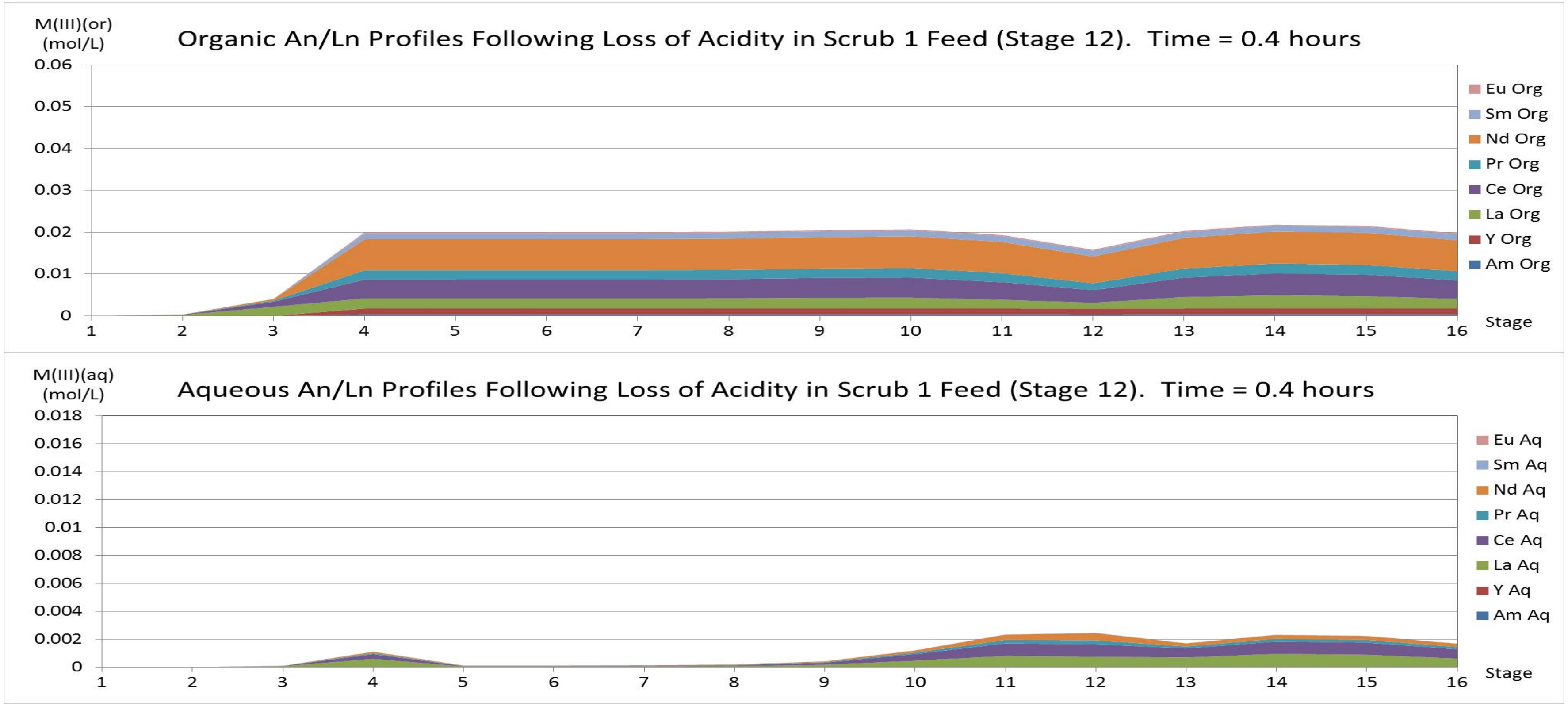
Y Aq
Am Aq



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0.02
0.01
0
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Stage
Eu Org
Sm Org
Nd Org
Pr Org
Ce Org
La Org
Y Org
Am Org
M(III)(aq) (mol/L)
Aqueous An/Ln Profiles Following Loss of Acidity in Scrub 1 Feed (Stage 12). Time = 0.4 hours
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
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Stage
Eu Aq
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Nd Aq
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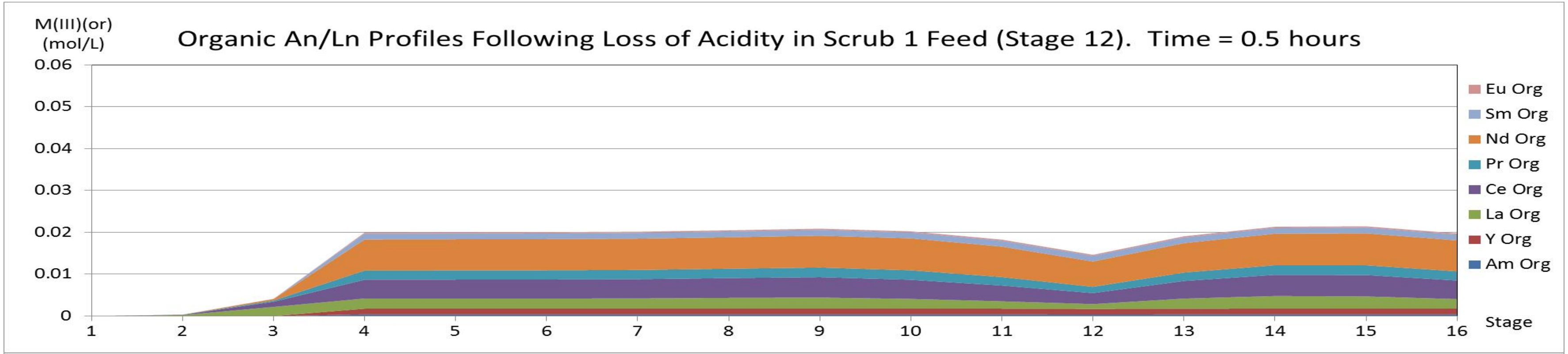
La Aq
Y Aq
Am Aq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(mol/L)
Organic An/Ln Profiles Following Loss of Acidity in Scrub 1 Feed (Stage 12). Time = 0.5 hours
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0.05
0.04
0.03
0.02
0.01
0
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Stage
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Pr Org
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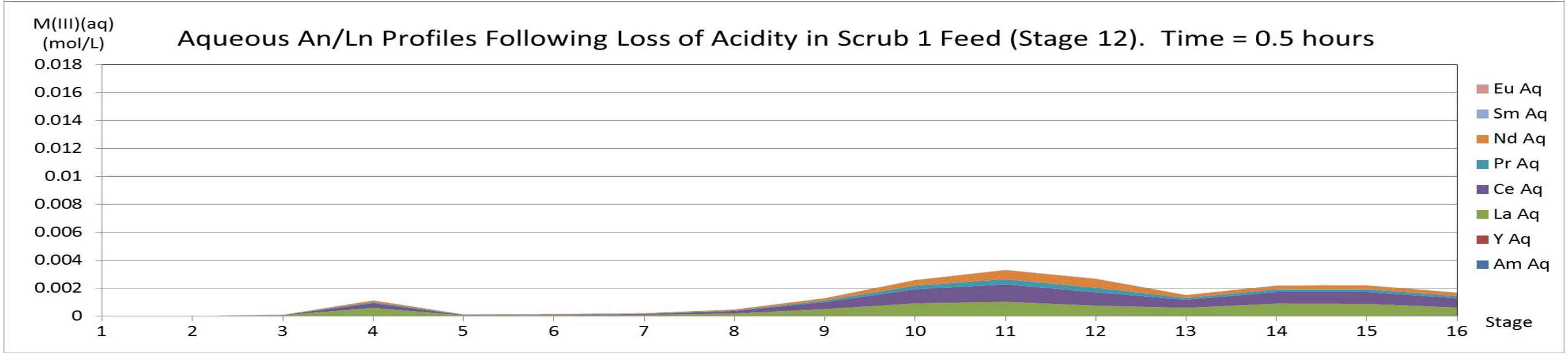
La Org
Y Org
Am Org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0.012
0.01
0.008
0.006
0.004
0.002
0
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Stage
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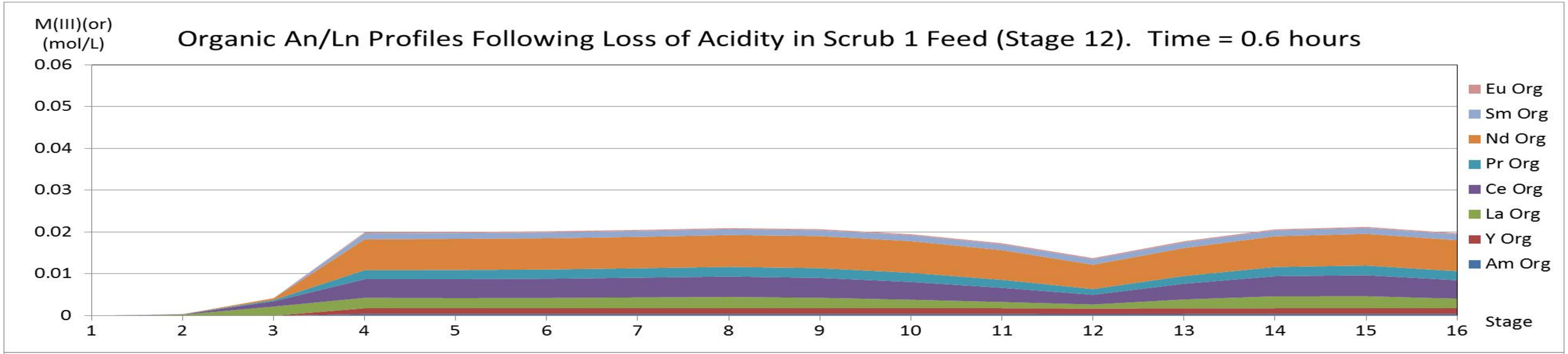
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(mol/L)
Organic An/Ln Profiles Following Loss of Acidity in Scrub 1 Feed (Stage 12). Time = 0.6 hours
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0.05
0.04
0.03
0.02
0.01
0
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Stage
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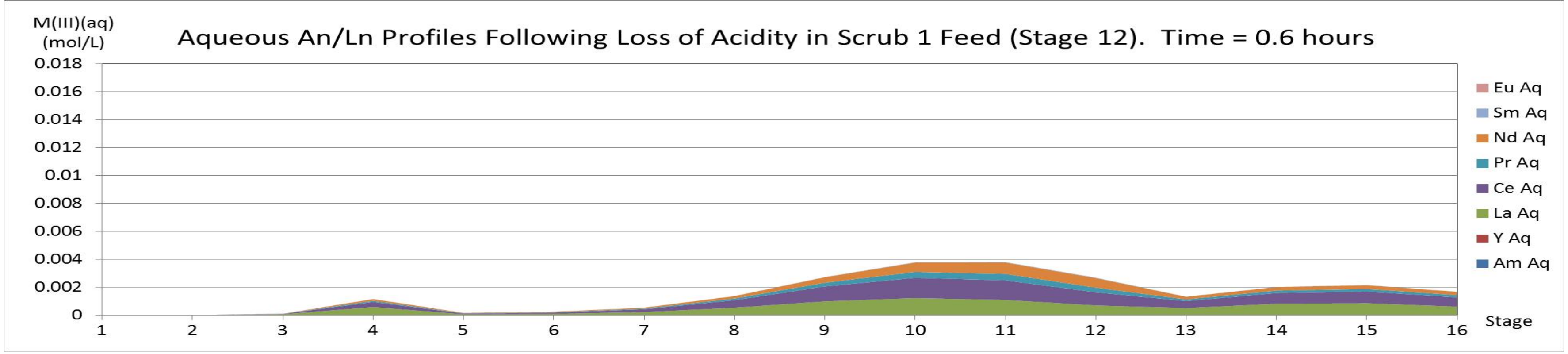
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0.008
0.006
0.004
0.002
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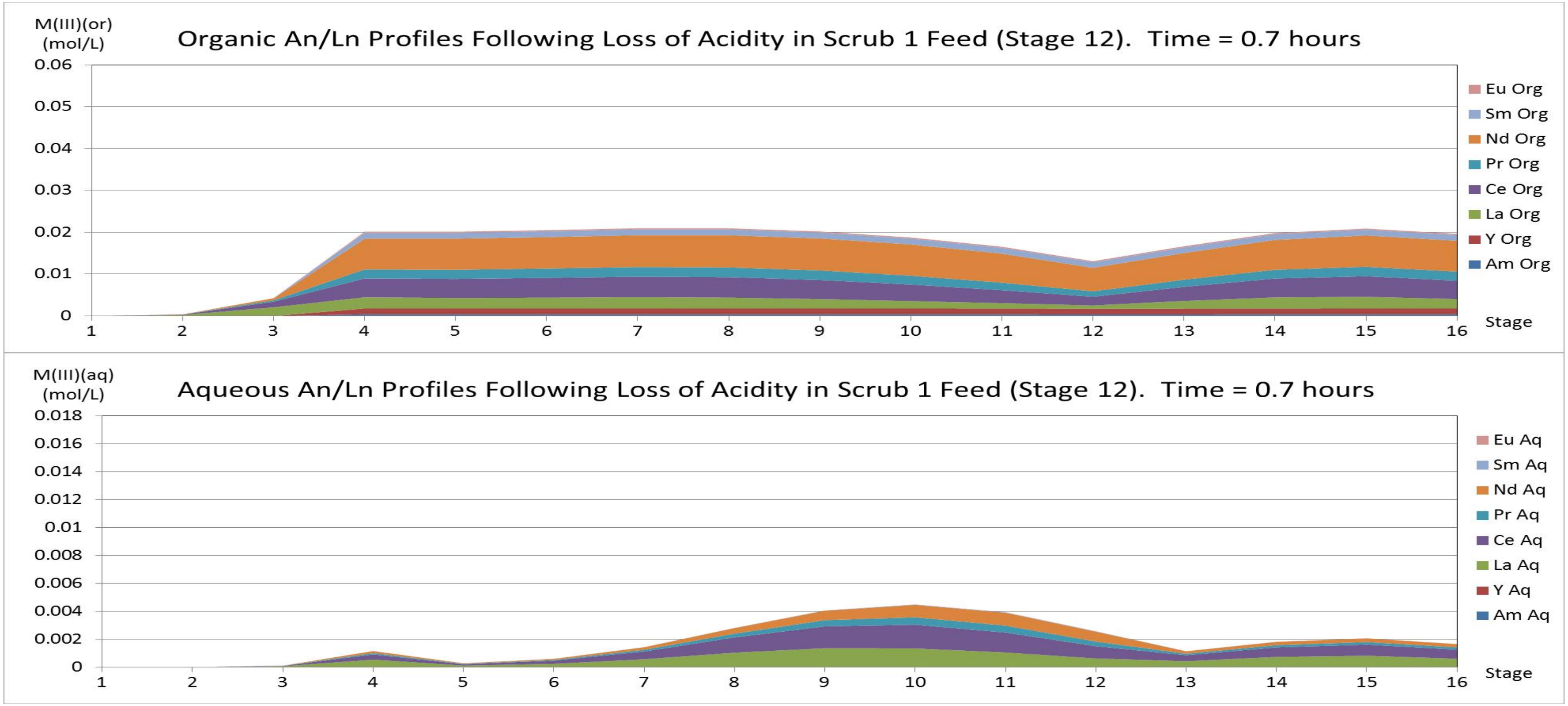
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Stage
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Pr Org
Ce Org
La Org
Y Org
Am Org
M(III)(aq)
(mol/L)
Aqueous An/Ln Profiles Following Loss of Acidity in Scrub 1 Feed (Stage 12). Time = 0.7 hours
0.018
0.016
0.014
0.012
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0.006
0.004
0.002
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1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Stage
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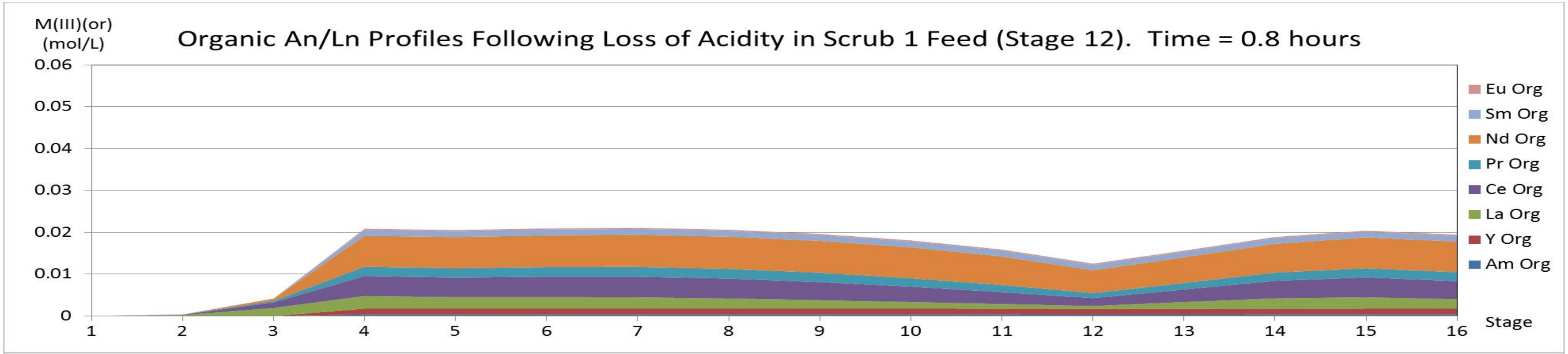

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0.02
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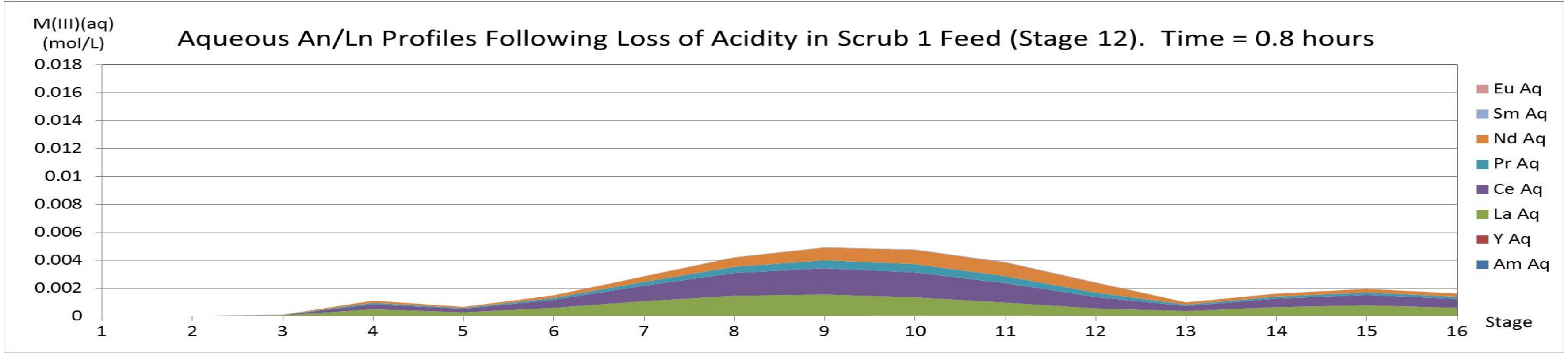

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Aqueous An/Ln Profiles Following Loss of Acidity in Scrub 1 Feed (Stage 12). Time = 0.8 hours
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Stage
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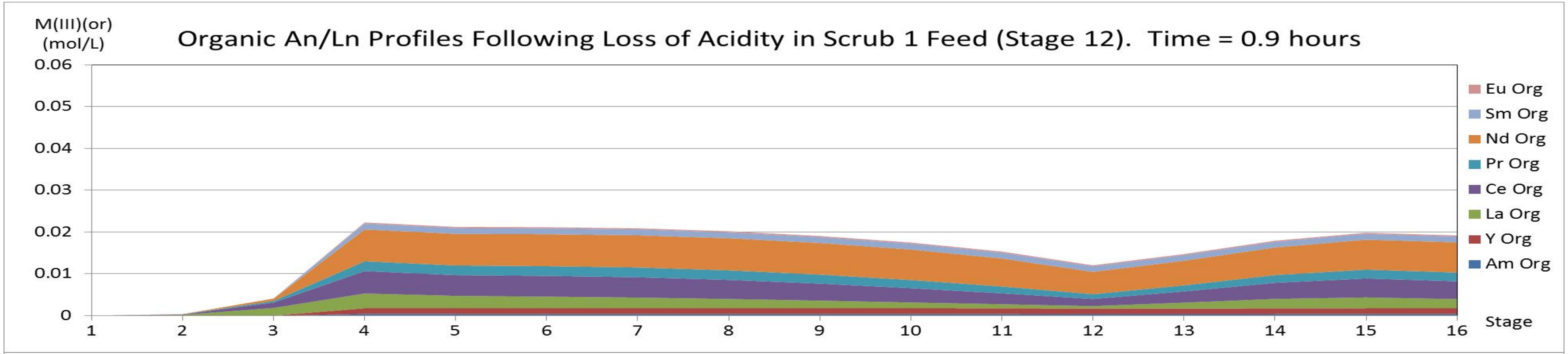
Am Aq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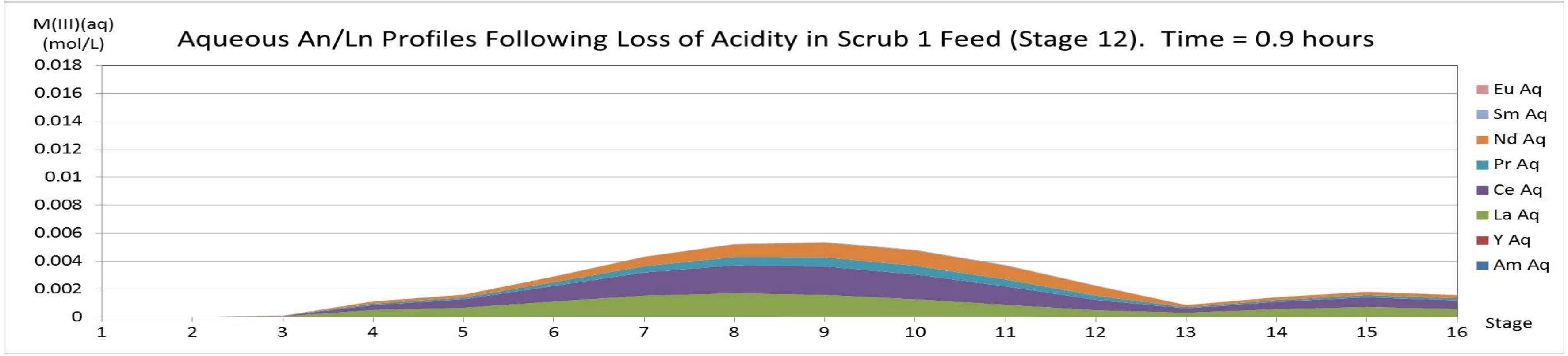
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Stage
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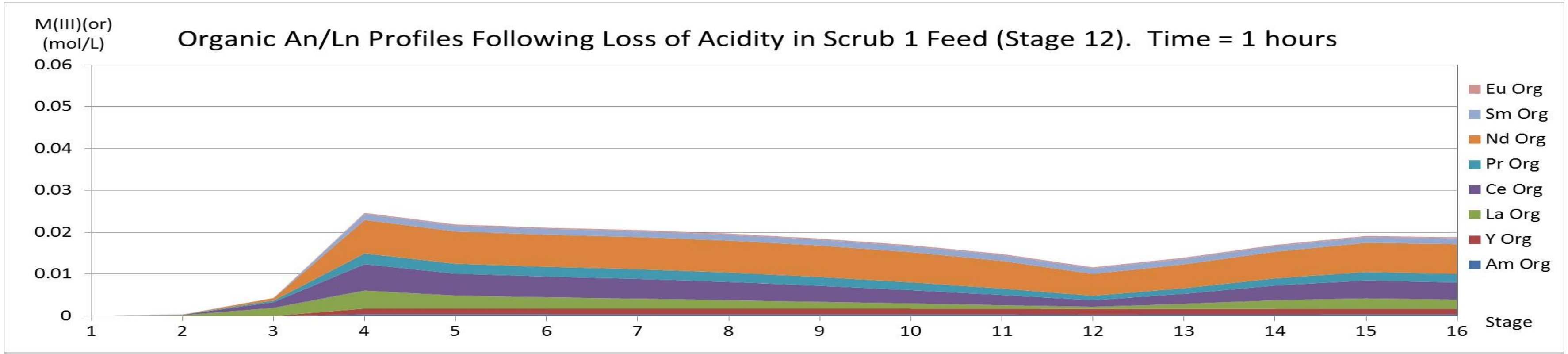

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Stage
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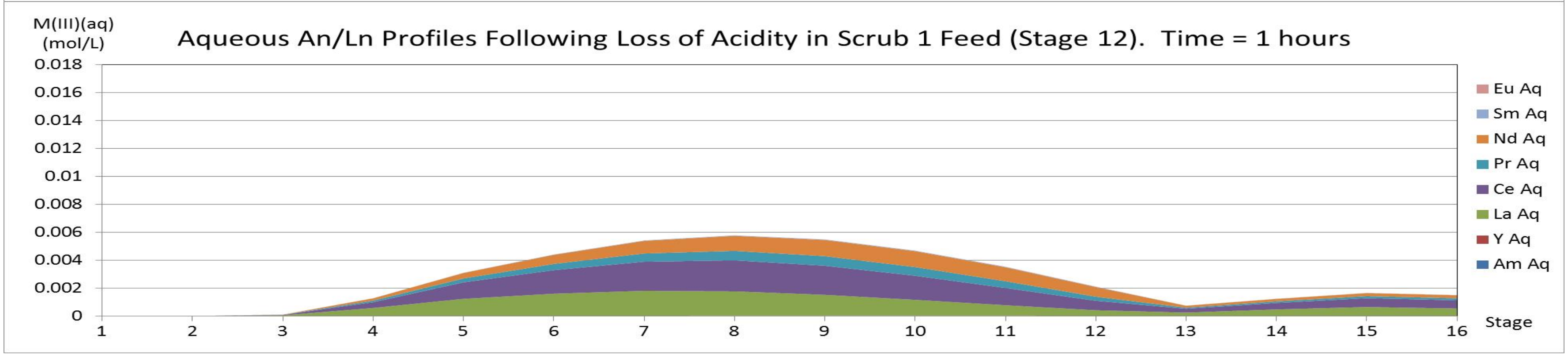

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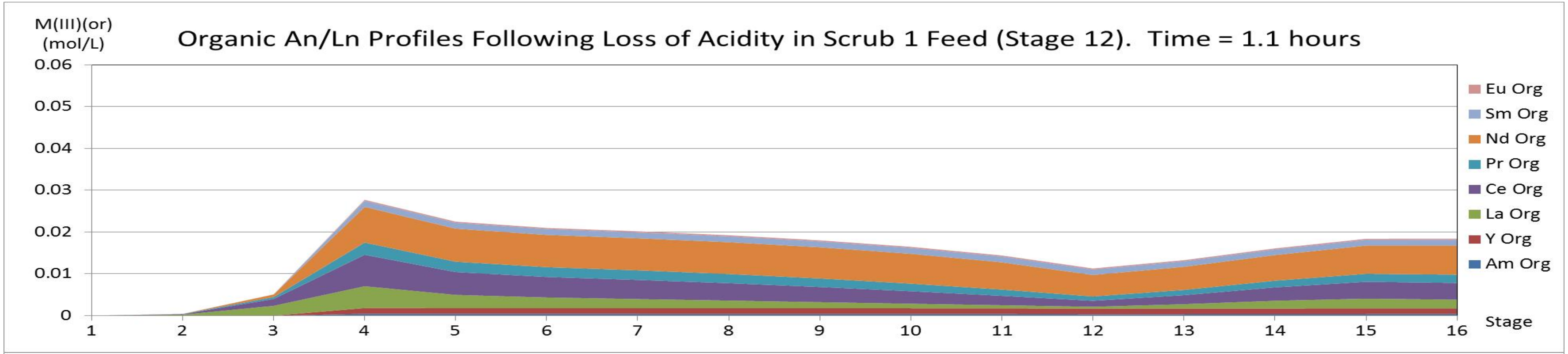
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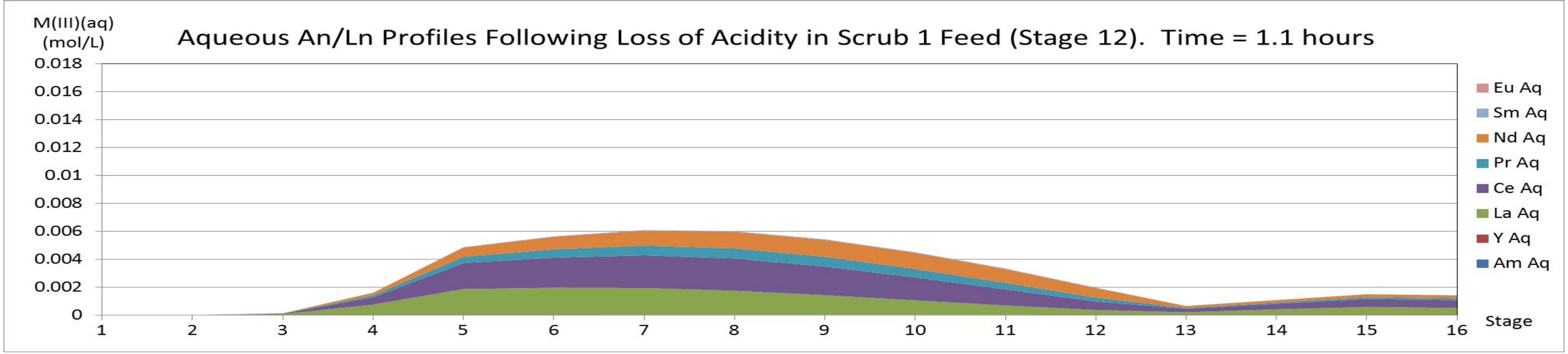
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Aqueous An/Ln Profiles Following Loss of Acidity in Scrub 1 Feed (Stage 12). Time = 1.1 hours
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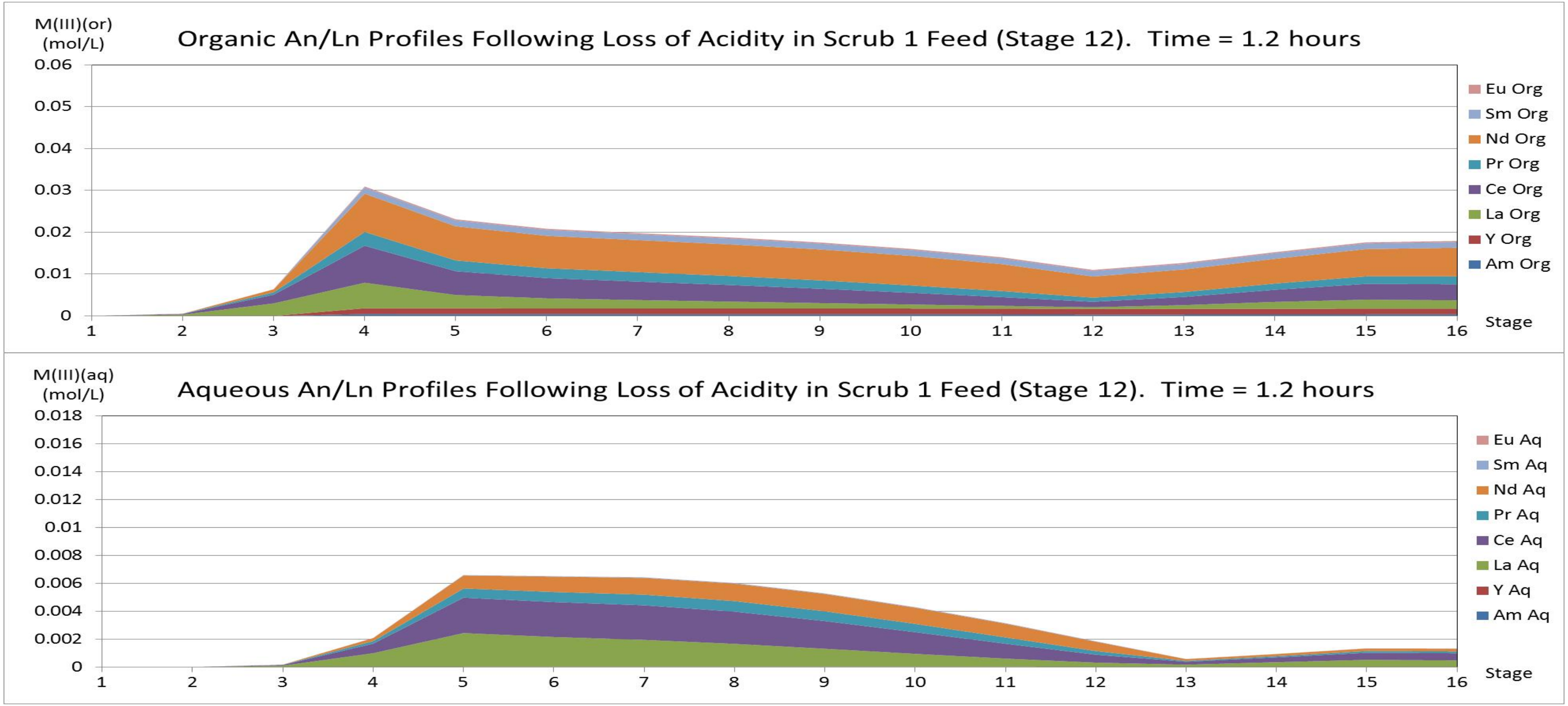
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0.03
0.02
0.01
0
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Stage
Eu Org
Sm Org
Nd Org
Pr Org
Ce Org
La Org
Y Org
Am Org
M(III)(aq) (mol/L)
Aqueous An/Ln Profiles Following Loss of Acidity in Scrub 1 Feed (Stage 12). Time = 1.2 hours
0.018
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0.008
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0.004
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Stage
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Y Aq
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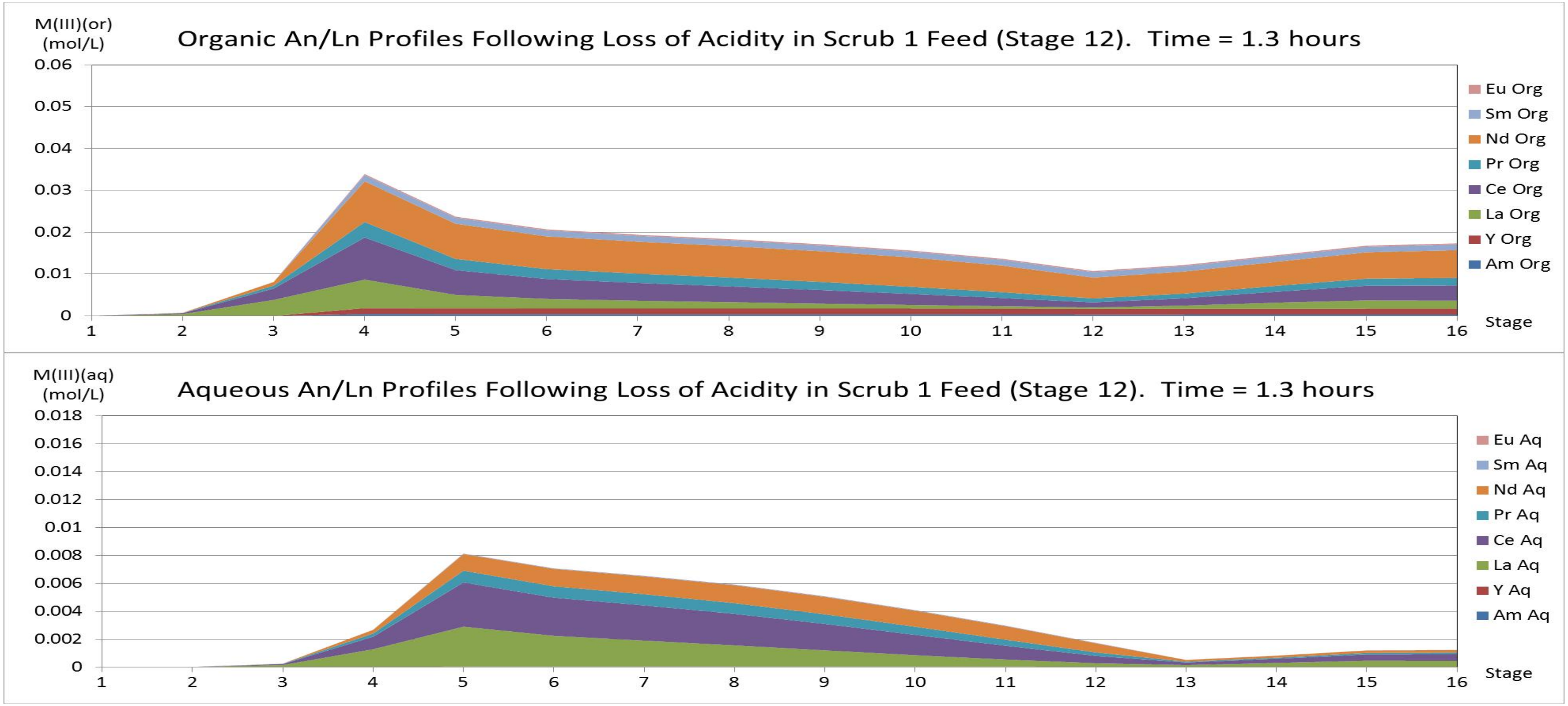
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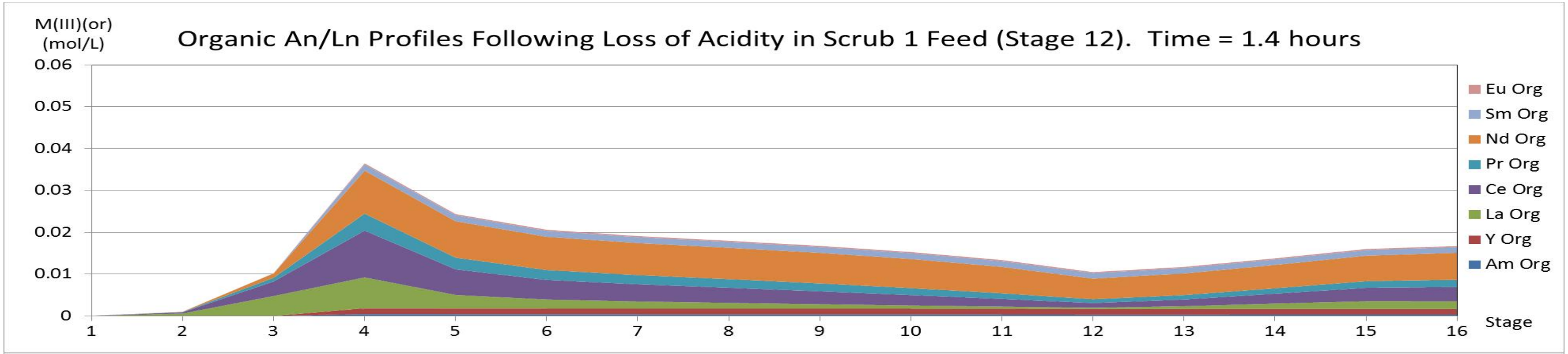
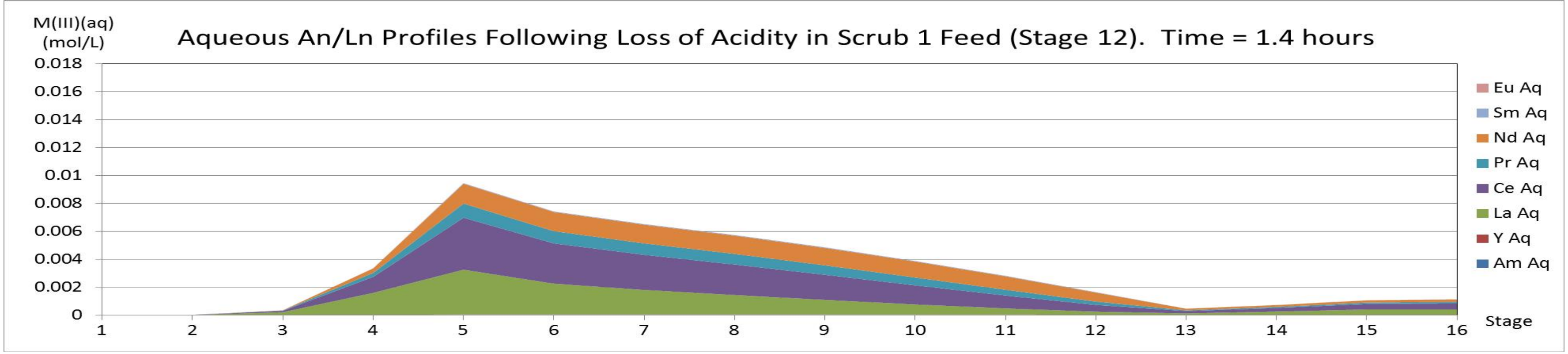
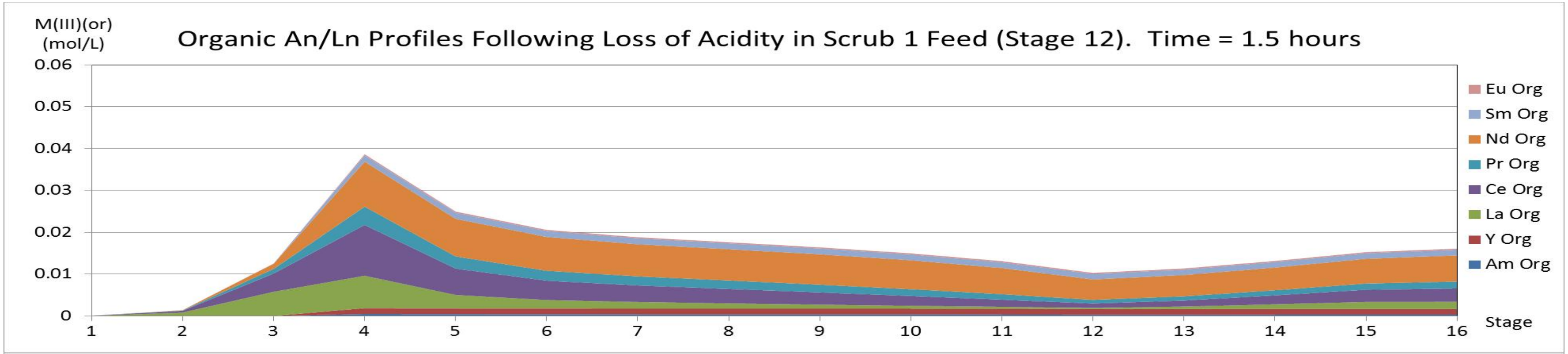
12
13
14
15
16
Stage
Eu Org
Sm Org
Nd Org
Pr Org
Ce Org
La Org
Y Org
Am Org
M(III)(aq)
(mol/L)
Aqueous An/Ln Profiles Following Loss of Acidity in Scrub 1 Feed (Stage 12). Time = 1.3 hours
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
Stage
Eu Aq
Sm Aq
Nd Aq
Pr Aq
Ce Aq
La Aq
Y Aq
Am Aq


M(III)(or)
(mol/L)
Organic An/Ln Profiles Following Loss of Acidity in Scrub 1 Feed (Stage 12). Time = 1.4 hours
0.06
0.05
0.04
0.03
0.02
0.01
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Stage
Eu Org
Sm Org
Nd Org
Pr Org
Ce Org
La Org
Y Org
Am Org


M(III)(aq)
(mol/L)
Aqueous An/Ln Profiles Following Loss of Acidity in Scrub 1 Feed (Stage 12). Time = 1.4 hours
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Stage
Eu Aq
Sm Aq
Nd Aq
Pr Aq
Ce Aq
La Aq
Y Aq
Am Aq


M(III)(or)
(mol/L)
Organic An/Ln Profiles Following Loss of Acidity in Scrub 1 Feed (Stage 12). Time = 1.5 hours
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0.05
0.04
0.03
0.02
0.01
0
1
2
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6
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8
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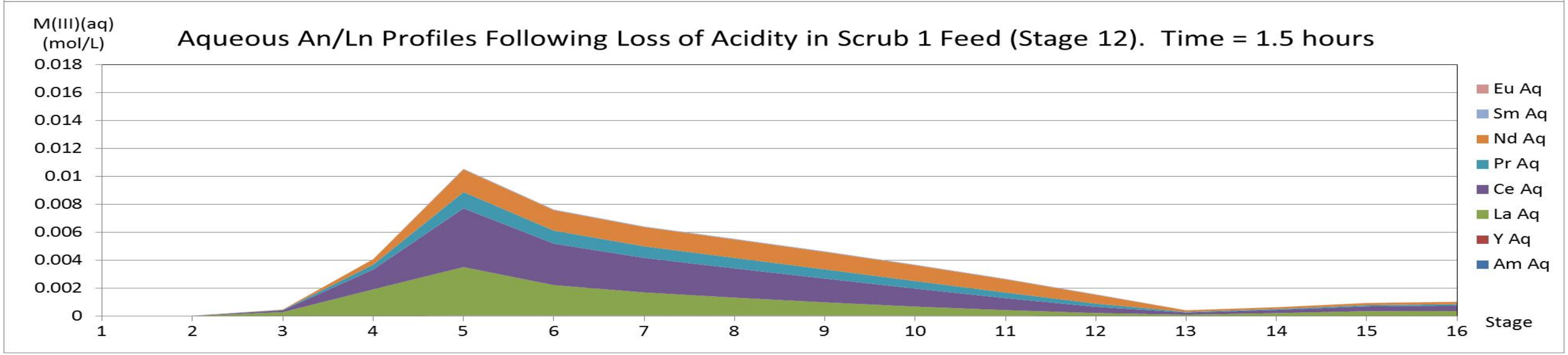
10
11
12
13
14
15
16
Stage
Eu Org
Sm Org
Nd Org
Pr Org
Ce Org
La Org
Y Org
Am Org


M(III)(aq)
(mol/L)
Aqueous An/Ln Profiles Following Loss of Acidity in Scrub 1 Feed (Stage 12). Time = 1.5 hours
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
1
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7
8
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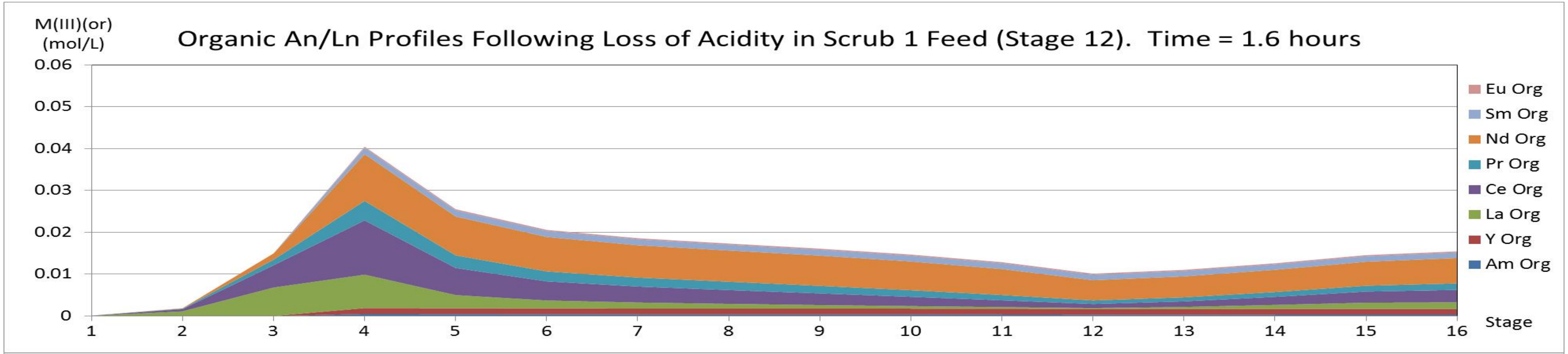
11
12
13
14
15
16
Stage
Eu Aq
Sm Aq
Nd Aq
Pr Aq
Ce Aq
La Aq
Y Aq
Am Aq


M(III)(or) (mol/L)
Organic An/Ln Profiles Following Loss of Acidity in Scrub 1 Feed (Stage 12). Time = 1.6 hours
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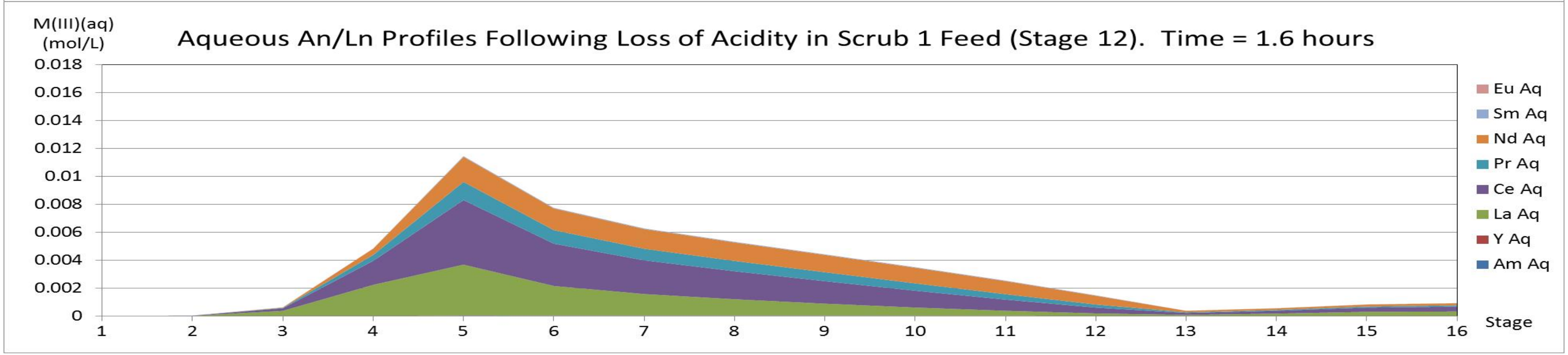
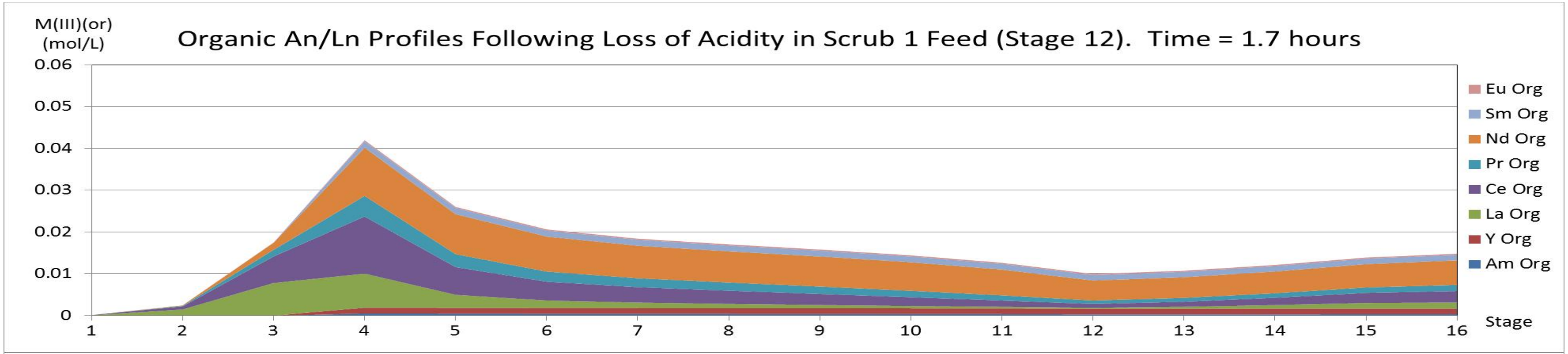
0.05
0.04
0.03
0.02
0.01
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Stage
Eu Org
Sm Org
Nd Org
Pr Org
Ce Org
La Org
Y Org
Am Org


M(III)(aq) (mol/L)
Aqueous An/Ln Profiles Following Loss of Acidity in Scrub 1 Feed (Stage 12). Time = 1.6 hours
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Stage
Eu Aq
Sm Aq
Nd Aq
Pr Aq
Ce Aq
La Aq
Y Aq
Am Aq


Organic An/Ln Profiles Following Loss of Acidity in Scrub 1 Feed (Stage 12). Time = 1.7 hours
M(III)(or)
(mol/L)
0.06
0.05
0.04
0.03
0.02
0.01
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1
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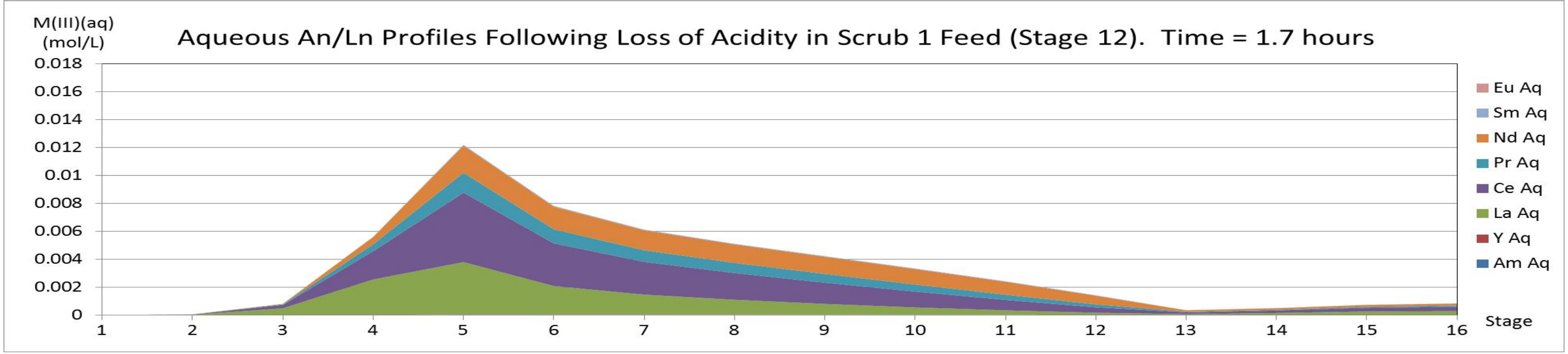
8
9
10
11
12
13
14
15
16
Stage
Eu Org
Sm Org
Nd Org
Pr Org
Ce Org
La Org
Y Org
Am Org


Aqueous An/Ln Profiles Following Loss of Acidity in Scrub 1 Feed (Stage 12). Time = 1.7 hours
M(III)(aq)
(mol/L)
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
1
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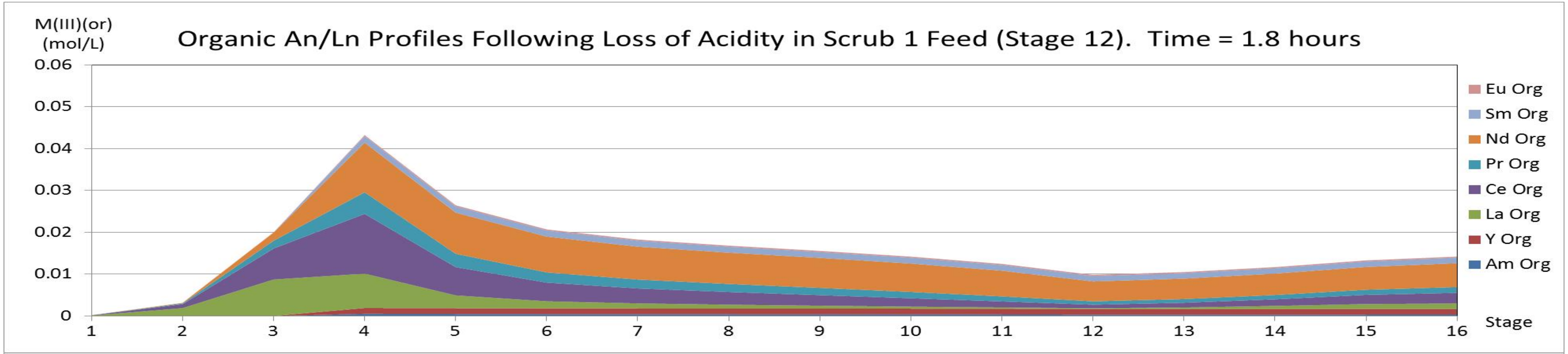
11
12
13
14
15
16
Stage
Eu Aq
Sm Aq
Nd Aq
Pr Aq
Ce Aq
La Aq
Y Aq
Am Aq


M(III)(or)
(mol/L)
Organic An/Ln Profiles Following Loss of Acidity in Scrub 1 Feed (Stage 12). Time = 1.8 hours
0.06
0.05
0.04
0.03
0.02
0.01
0
1
2
3
4
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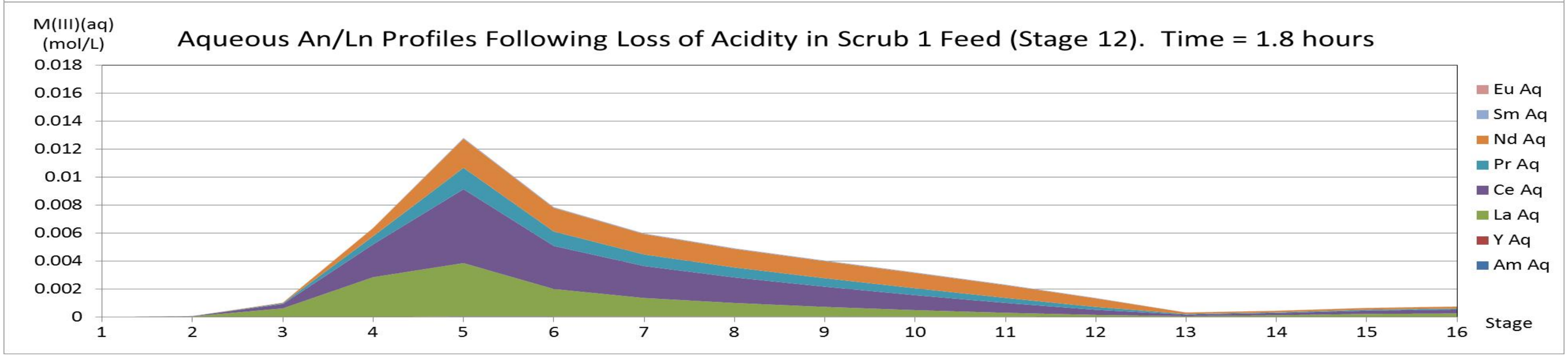
6
7
8
9
10
11
12
13
14
15
16
Stage
Eu Org
Sm Org
Nd Org
Pr Org
Ce Org
La Org
Y Org
Am Org


M(III)(aq)
(mol/L)
Aqueous An/Ln Profiles Following Loss of Acidity in Scrub 1 Feed (Stage 12). Time = 1.8 hours
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
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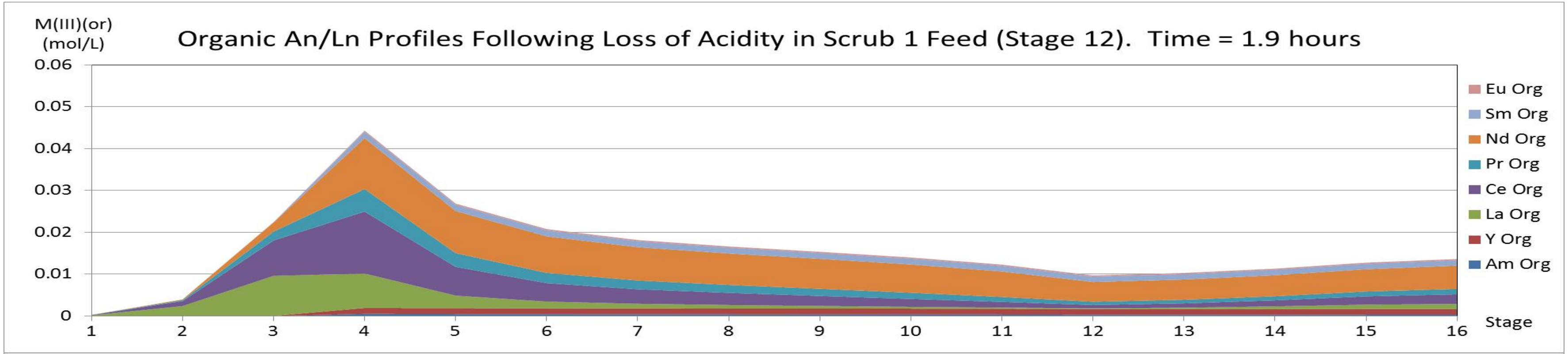
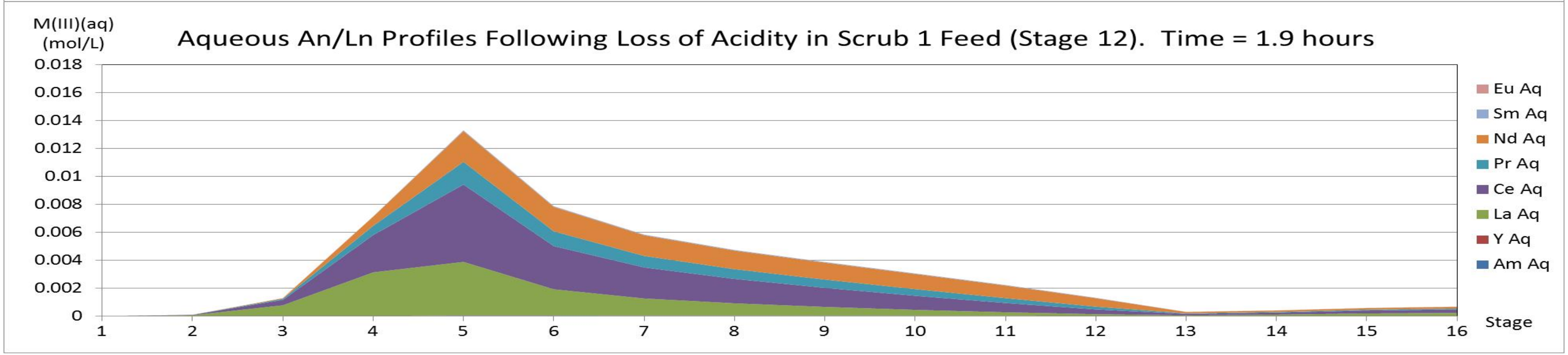
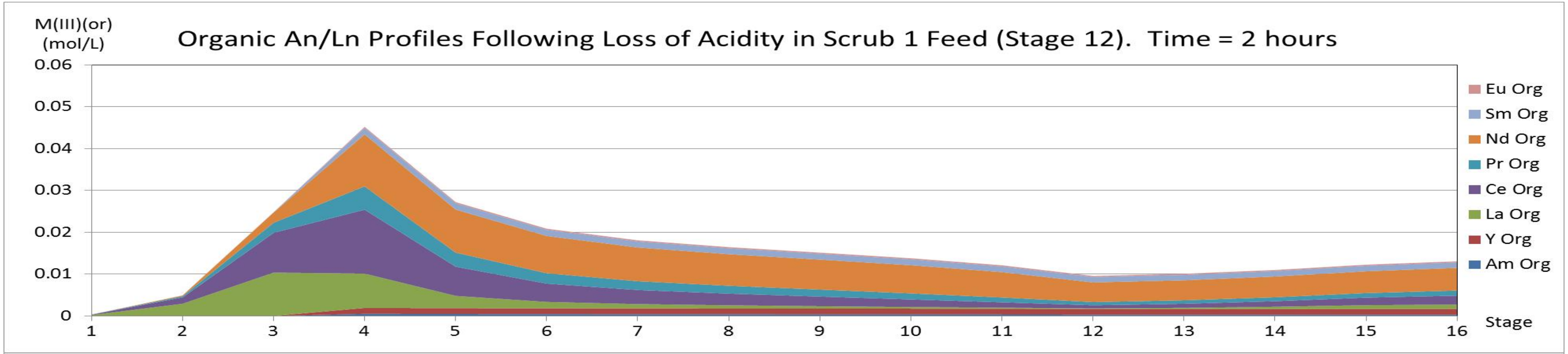
13
14
15
16
Stage
Eu Aq
Sm Aq
Nd Aq
Pr Aq
Ce Aq
La Aq
Y Aq
Am Aq



M(III)(or)
(mol/L)
Organic An/Ln Profiles Following Loss of Acidity in Scrub 1 Feed (Stage 12). Time = 1.9 hours
0.06
0.05
0.04
0.03
0.02
0.01
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Stage
Eu Org
Sm Org
Nd Org
Pr Org
Ce Org
La Org
Y Org
Am Org



M(III)(aq)
(mol/L)
Aqueous An/Ln Profiles Following Loss of Acidity in Scrub 1 Feed (Stage 12). Time = 1.9 hours
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Stage
Eu Aq
Sm Aq
Nd Aq
Pr Aq
Ce Aq
La Aq
Y Aq
Am Aq



M(III)(or) (mol/L)
Organic An/Ln Profiles Following Loss of Acidity in Scrub 1 Feed (Stage 12). Time = 2 hours
0.06
0.05
0.04
0.03
0.02
0.01
0
1
2
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5
6
7
8
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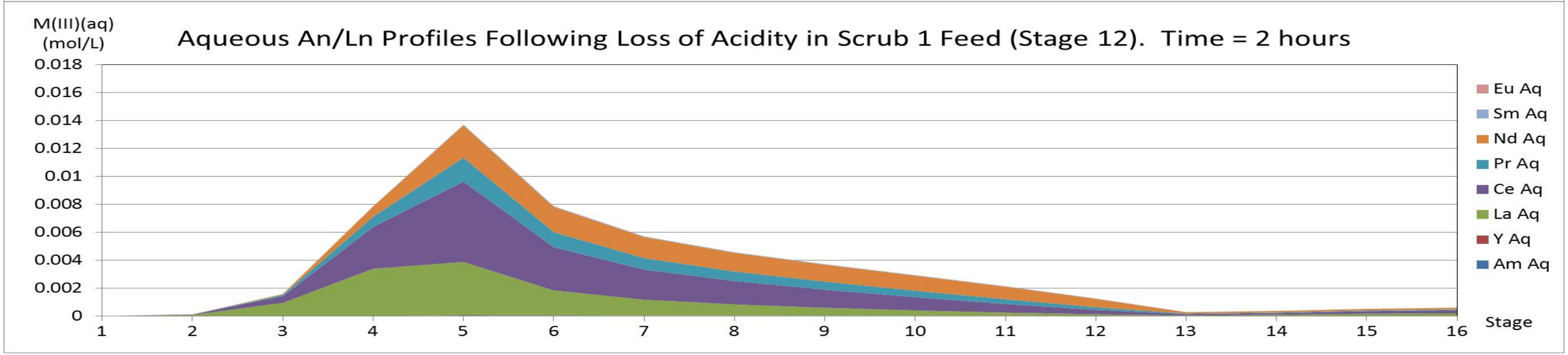
10
11
12
13
14
15
16
Stage
Eu Org
Sm Org
Nd Org
Pr Org
Ce Org
La Org
Y Org
Am Org



M(III)(aq) (mol/L)
Aqueous An/Ln Profiles Following Loss of Acidity in Scrub 1 Feed (Stage 12). Time = 2 hours
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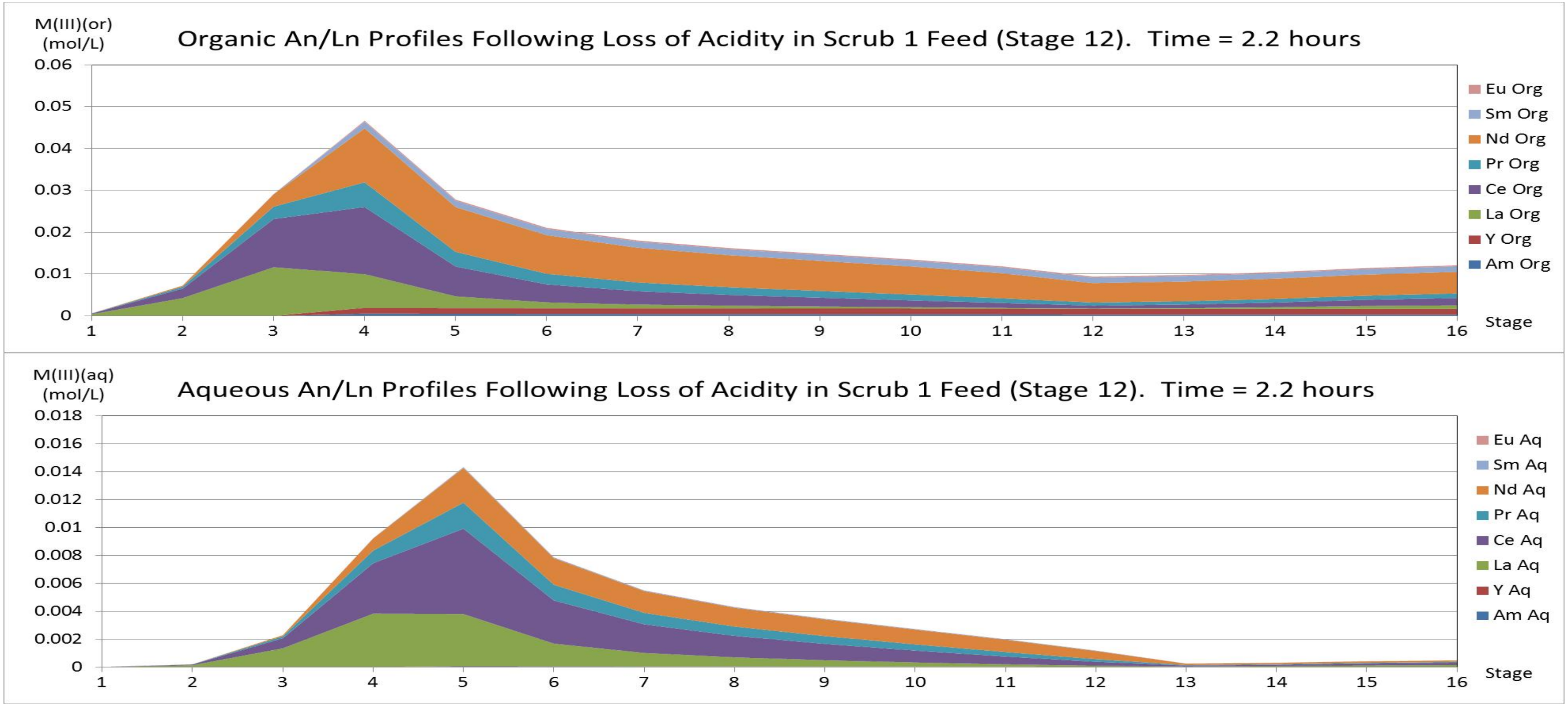
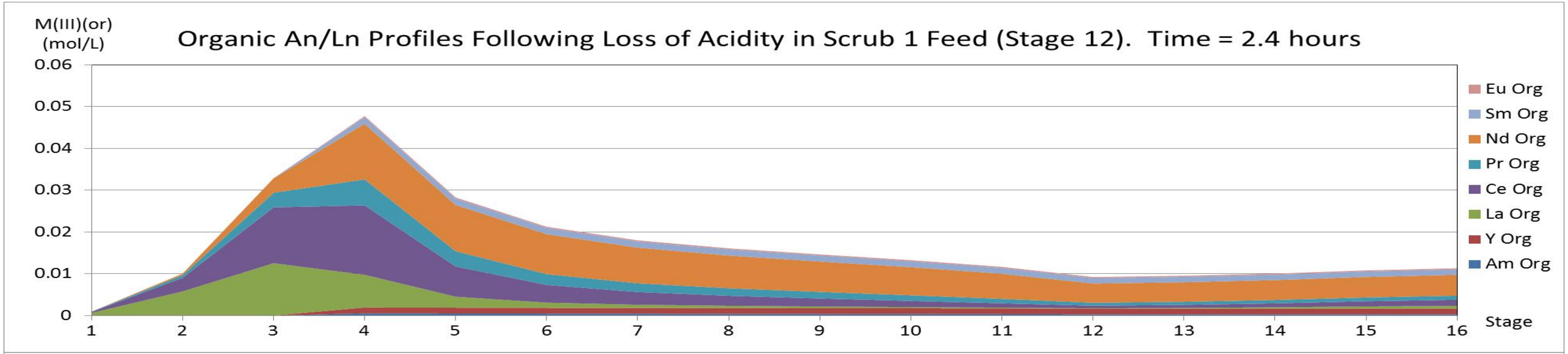
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
Stage
Eu Aq
Sm Aq
Nd Aq
Pr Aq
Ce Aq
La Aq
Y Aq
Am Aq



M(III)(or) (mol/L)
Organic An/Ln Profiles Following Loss of Acidity in Scrub 1 Feed (Stage 12). Time = 2.2 hours
0.06
0.05
0.04
0.03
0.02
0.01
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Stage
Eu Org
Sm Org
Nd Org
Pr Org
Ce Org
La Org
Y Org
Am Org
M(III)(aq) (mol/L)
Aqueous An/Ln Profiles Following Loss of Acidity in Scrub 1 Feed (Stage 12). Time = 2.2 hours
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Stage
Eu Aq
Sm Aq
Nd Aq
Pr Aq
Ce Aq
La Aq
Y Aq
Am Aq


M(III)(or)
(mol/L)
Organic An/Ln Profiles Following Loss of Acidity in Scrub 1 Feed (Stage 12). Time = 2.4 hours
0.06
0.05
0.04
0.03
0.02
0.01
0
1
2
3
4
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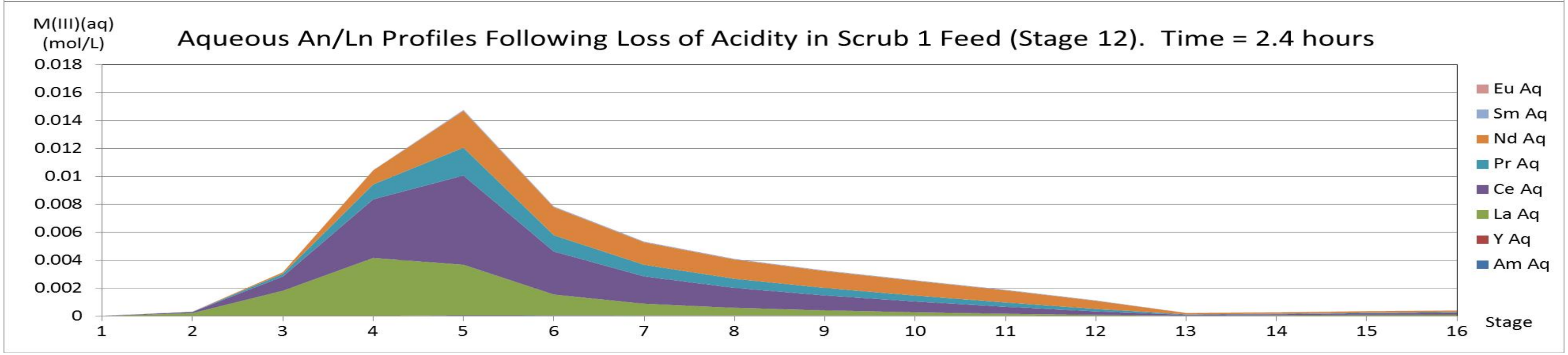
6
7
8
9
10
11
12
13
14
15
16
Stage
Eu Org
Sm Org
Nd Org
Pr Org
Ce Org
La Org
Y Org
Am Org


M(III)(aq)
(mol/L)
Aqueous An/Ln Profiles Following Loss of Acidity in Scrub 1 Feed (Stage 12). Time = 2.4 hours
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0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
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8
9
10
11
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Stage
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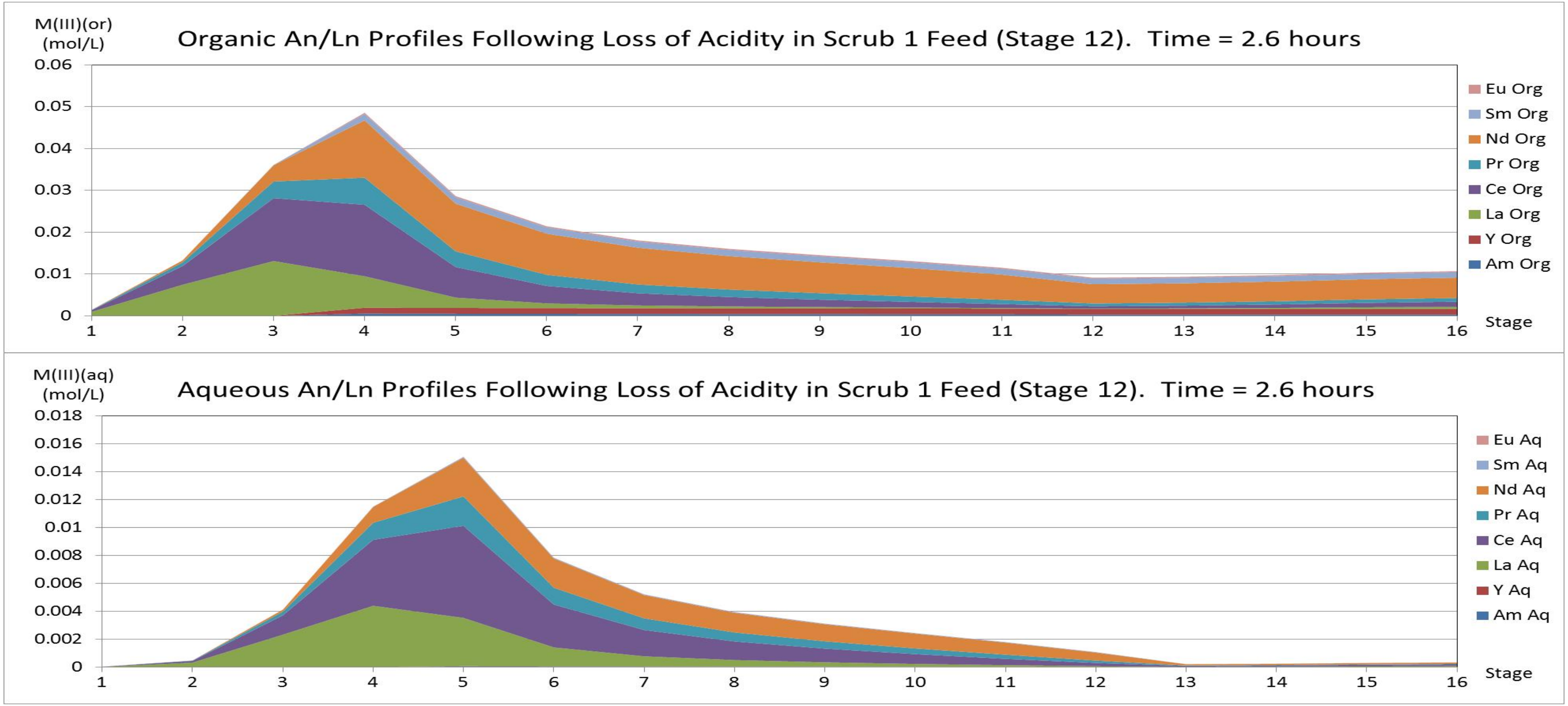
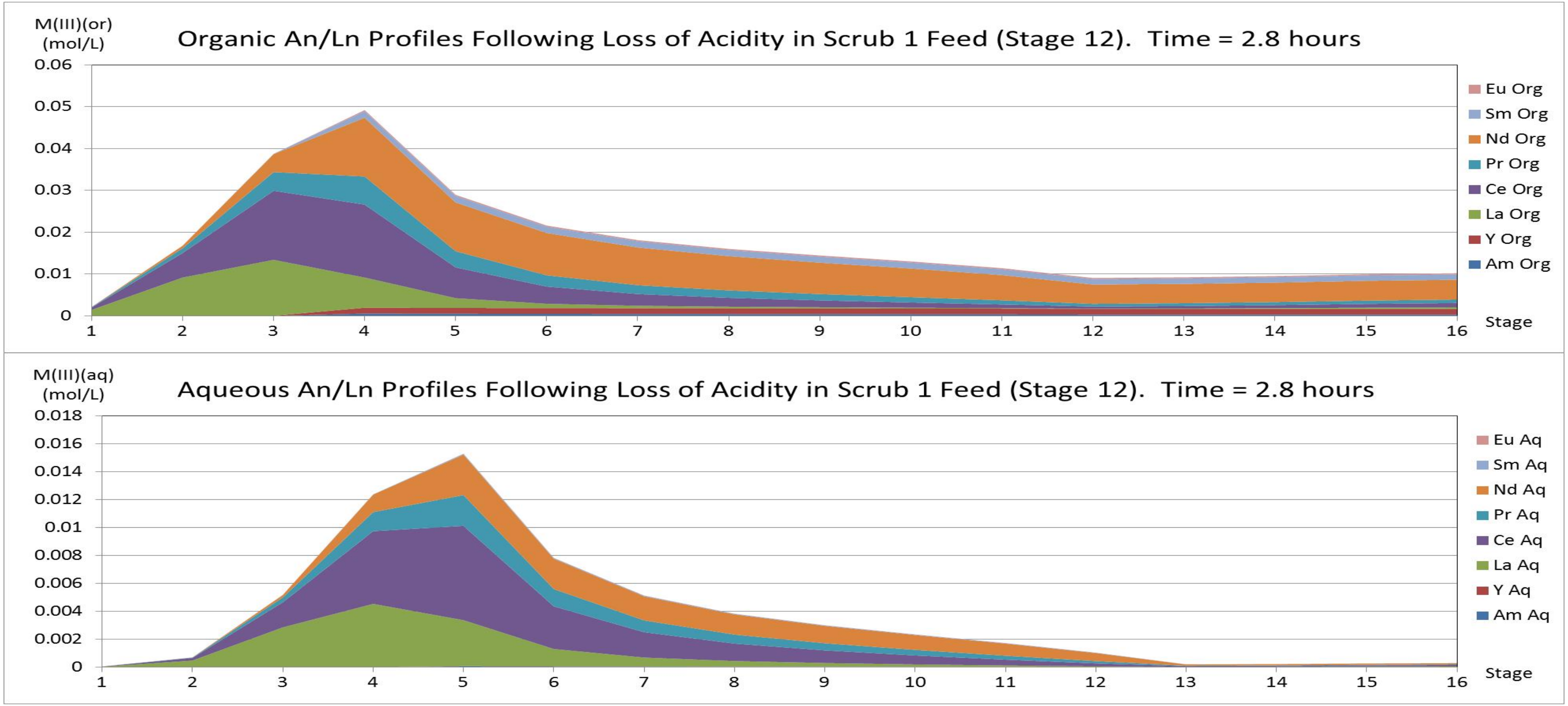
Sm Aq
Nd Aq
Pr Aq
Ce Aq
La Aq
Y Aq
Am Aq



M(III)(or) (mol/L)
Organic An/Ln Profiles Following Loss of Acidity in Scrub 1 Feed (Stage 12). Time = 2.6 hours
0.06
0.05
0.04
0.03
0.02
0.01
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Stage
Eu Org
Sm Org
Nd Org
Pr Org
Ce Org
La Org
Y Org
Am Org
M(III)(aq) (mol/L)
Aqueous An/Ln Profiles Following Loss of Acidity in Scrub 1 Feed (Stage 12). Time = 2.6 hours
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Stage
Eu Aq
Sm Aq
Nd Aq
Pr Aq
Ce Aq
La Aq
Y Aq
Am Aq



M(III)(or)
(mol/L)
Organic An/Ln Profiles Following Loss of Acidity in Scrub 1 Feed (Stage 12). Time = 2.8 hours
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0.04
0.03
0.02
0.01
0
1
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5
6
7
8
9
10
11
12
13
14
15
16
Stage
Eu Org
Sm Org
Nd Org
Pr Org
Ce Org
La Org
Y Org
Am Org
M(III)(aq)
(mol/L)
Aqueous An/Ln Profiles Following Loss of Acidity in Scrub 1 Feed (Stage 12). Time = 2.8 hours
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
1
2
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4
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15
16
Stage
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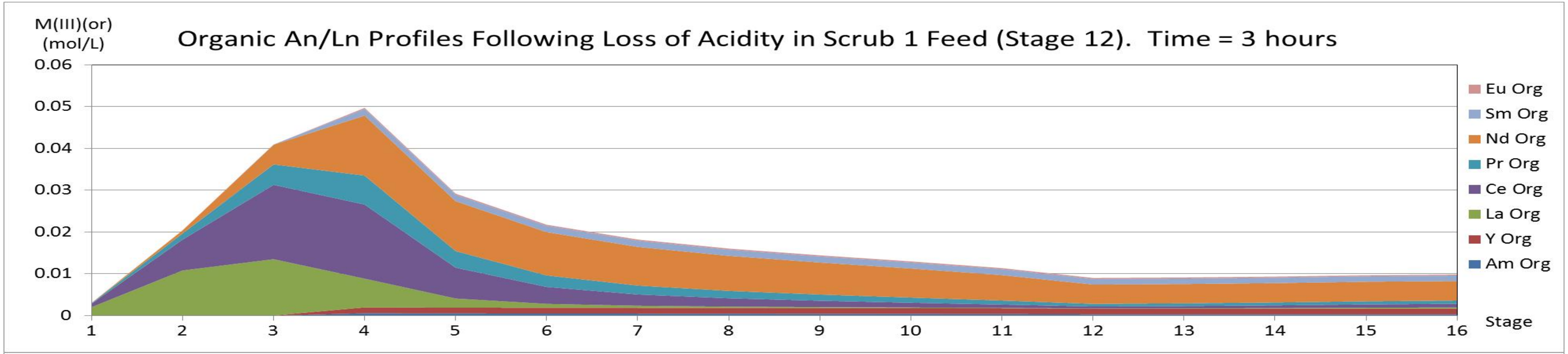
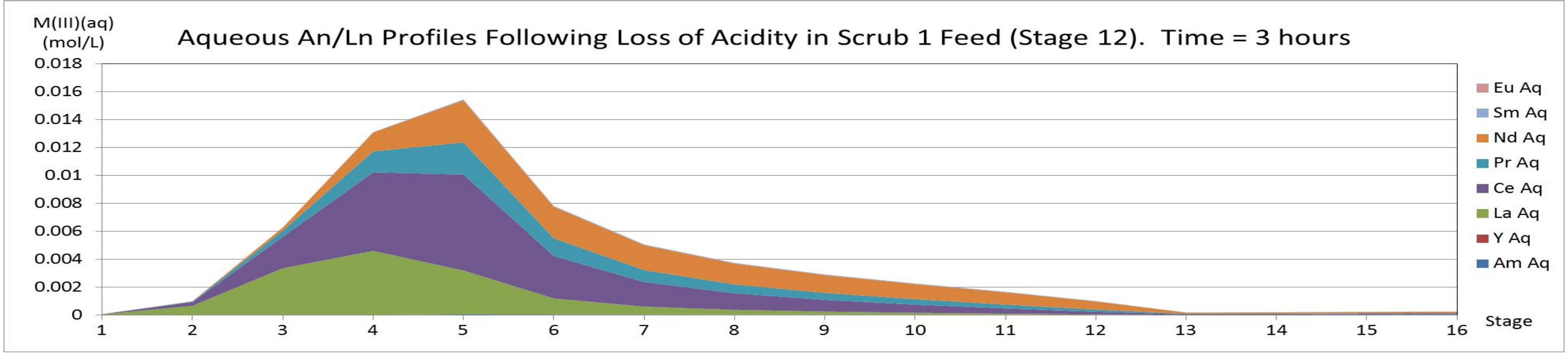
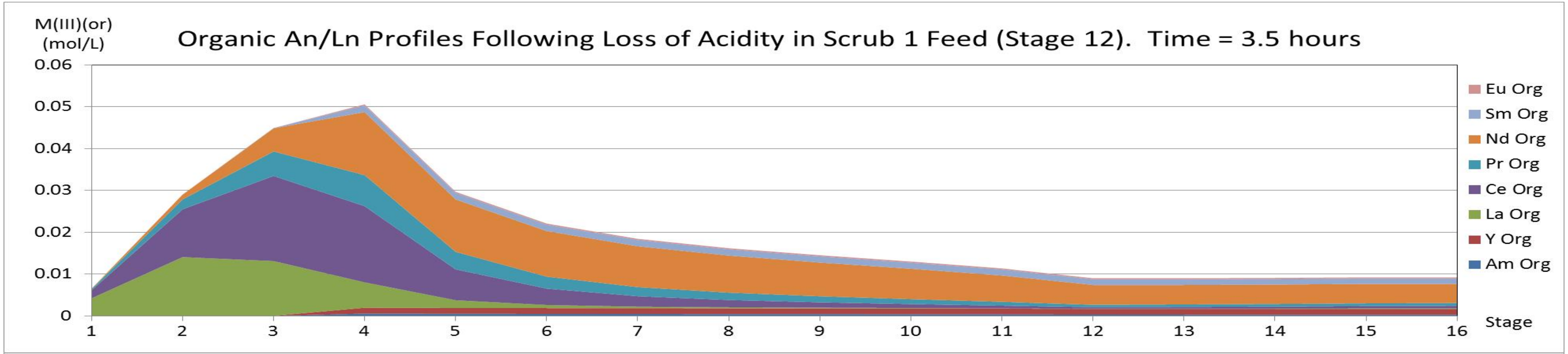
Sm Aq
Nd Aq
Pr Aq
Ce Aq
La Aq
Y Aq
Am Aq

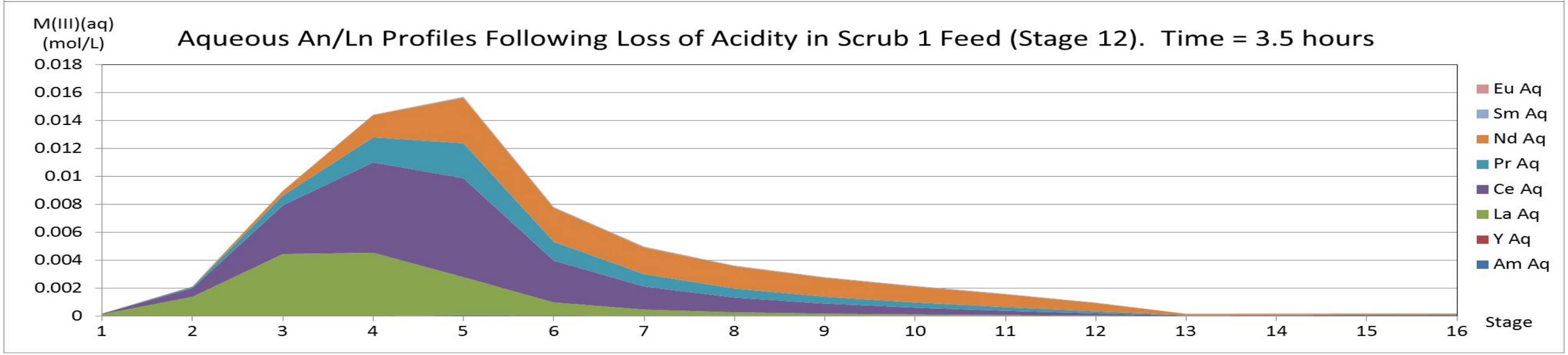


M(III)(or)
(mol/L)
Organic An/Ln Profiles Following Loss of Acidity in Scrub 1 Feed (Stage 12). Time = 3 hours
0.06
0.05
0.04
0.03
0.02
0.01
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
Stage
Eu Org
Sm Org
Nd Org
Pr Org
Ce Org
La Org
Y Org
Am Org



M(III)(aq)
(mol/L)
Aqueous An/Ln Profiles Following Loss of Acidity in Scrub 1 Feed (Stage 12). Time = 3 hours
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
Stage
Eu Aq
Sm Aq
Nd Aq
Pr Aq
Ce Aq
La Aq
Y Aq
Am Aq


M(III)(or)
(mol/L)
Organic An/Ln Profiles Following Loss of Acidity in Scrub 1 Feed (Stage 12). Time = 3.5 hours
0.06
0.05
0.04
0.03
0.02
0.01
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Stage
Eu Org
Sm Org
Nd Org
Pr Org
Ce Org
La Org
Y Org
Am Org


M(III)(aq)
(mol/L)
Aqueous An/Ln Profiles Following Loss of Acidity in Scrub 1 Feed (Stage 12). Time = 3.5 hours
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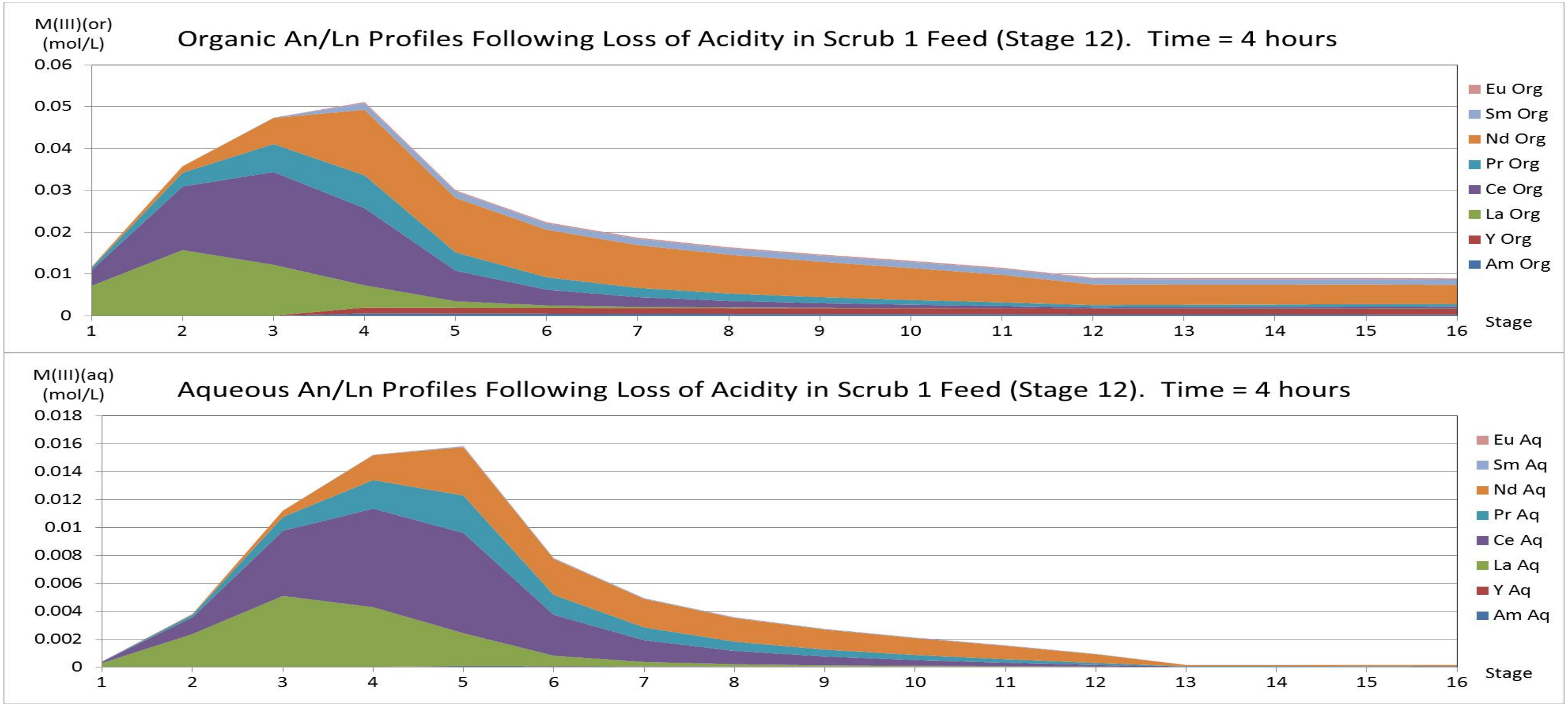
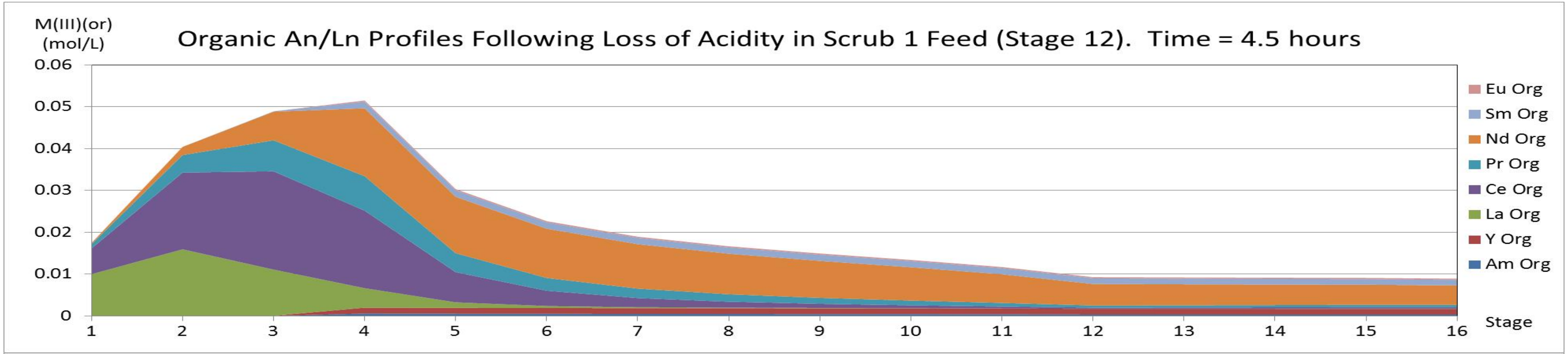
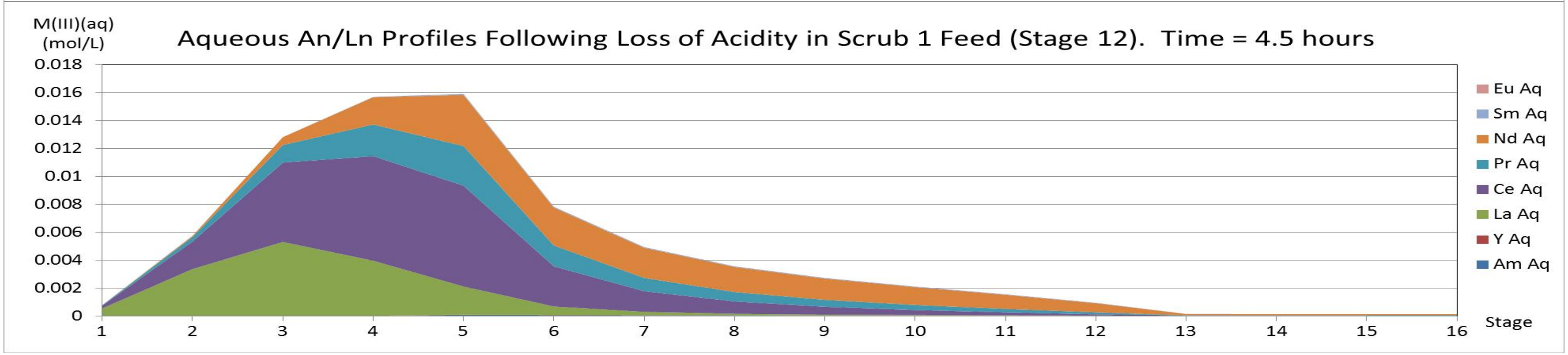
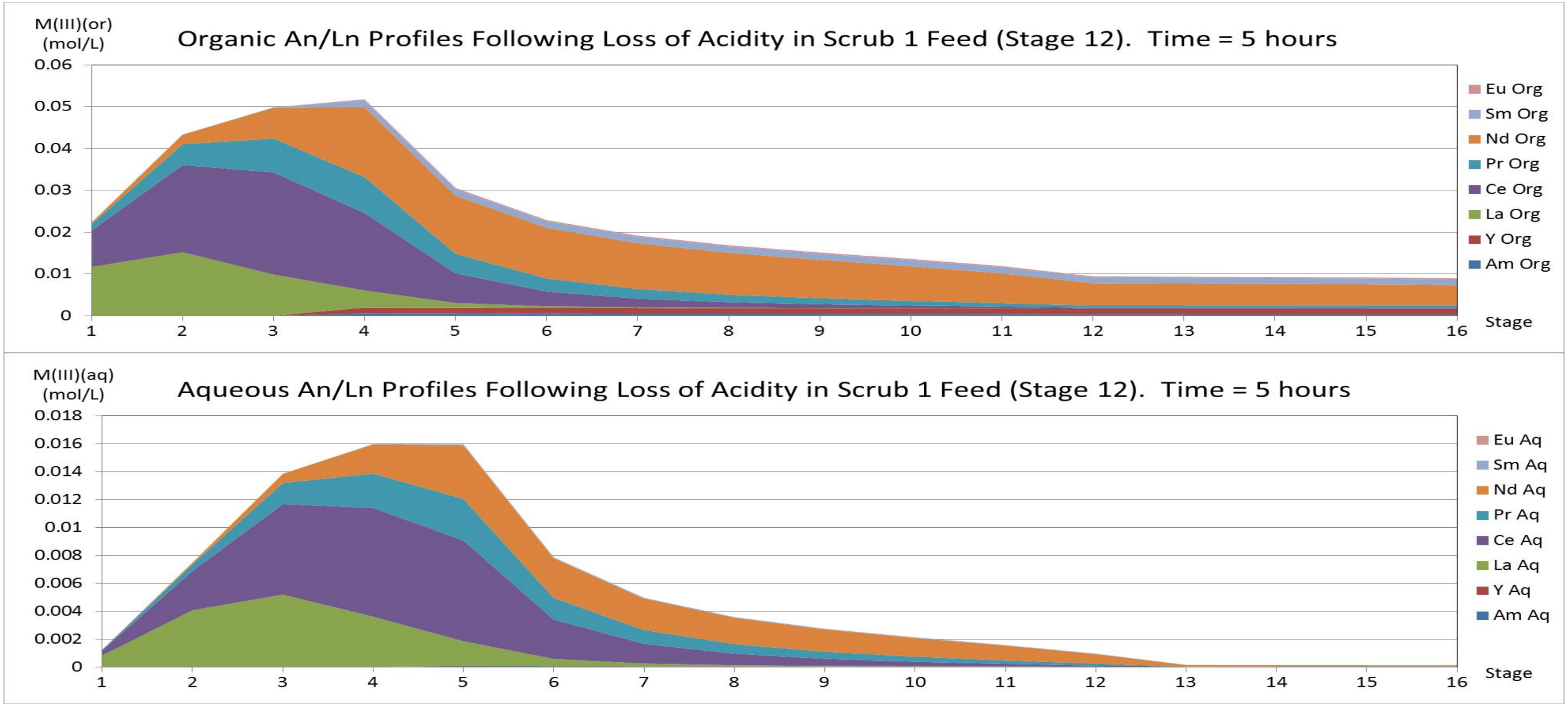
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Stage
Eu Aq
Sm Aq
Nd Aq
Pr Aq
Ce Aq
La Aq
Y Aq
Am Aq

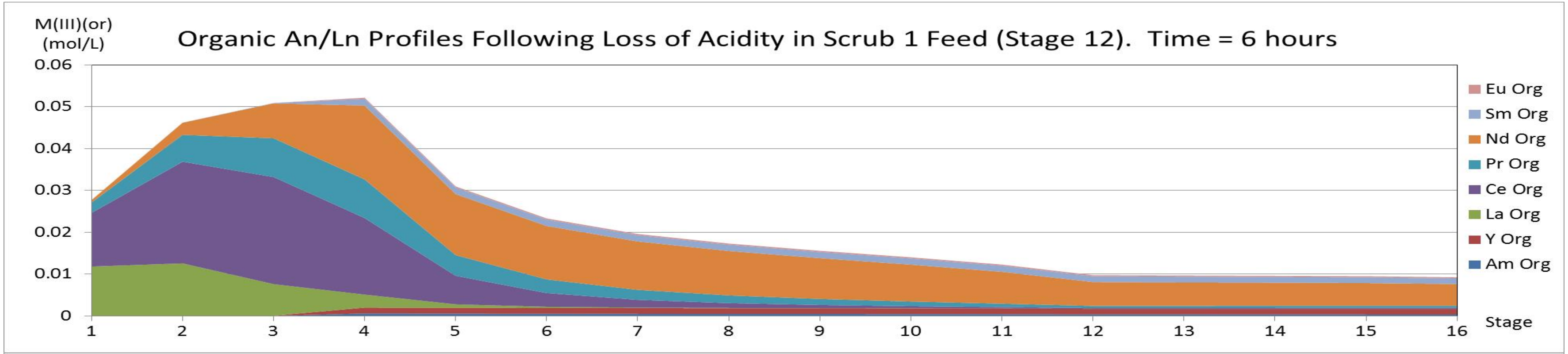

M(III)(or) (mol/L)
Organic An/Ln Profiles Following Loss of Acidity in Scrub 1 Feed (Stage 12). Time = 4 hours
0.06
0.05
0.04
0.03
0.02
0.01
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Stage
Eu Org
Sm Org
Nd Org
Pr Org
Ce Org
La Org
Y Org
Am Org
M(III)(aq) (mol/L)
Aqueous An/Ln Profiles Following Loss of Acidity in Scrub 1 Feed (Stage 12). Time = 4 hours
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Stage
Eu Aq
Sm Aq
Nd Aq
Pr Aq
Ce Aq
La Aq
Y Aq
Am Aq

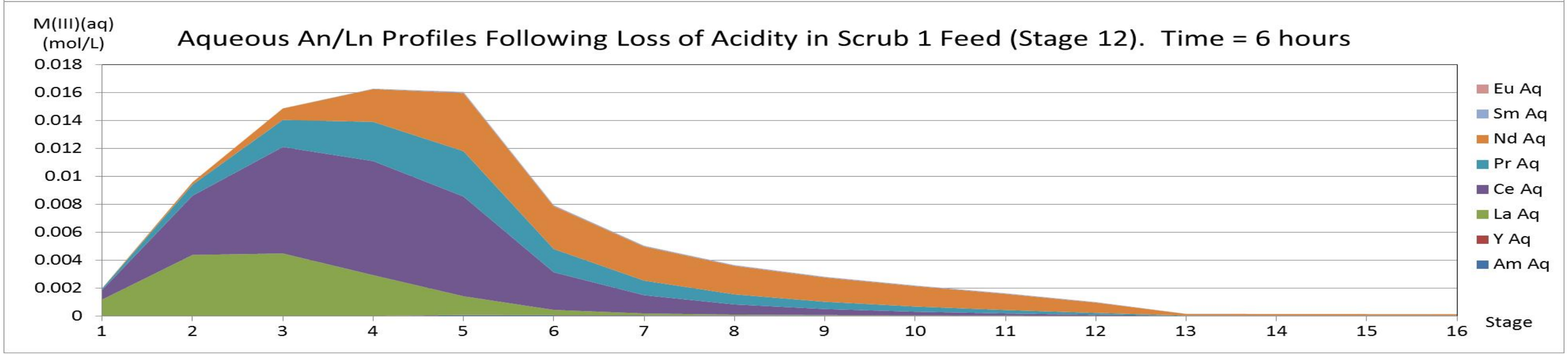

M(III)(or)
(mol/L)
Organic An/Ln Profiles Following Loss of Acidity in Scrub 1 Feed (Stage 12). Time = 4.5 hours
0.06
0.05
0.04
0.03
0.02
0.01
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
Stage
Eu Org
Sm Org
Nd Org
Pr Org
Ce Org
La Org
Y Org
Am Org


M(III)(aq)
(mol/L)
Aqueous An/Ln Profiles Following Loss of Acidity in Scrub 1 Feed (Stage 12). Time = 4.5 hours
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
Stage
Eu Aq
Sm Aq
Nd Aq
Pr Aq
Ce Aq
La Aq
Y Aq
Am Aq



M(III)(or)
(mol/L)
Organic An/Ln Profiles Following Loss of Acidity in Scrub 1 Feed (Stage 12). Time = 5 hours
0.06
0.05
0.04
0.03
0.02
0.01
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Stage
Eu Org
Sm Org
Nd Org
Pr Org
Ce Org
La Org
Y Org
Am Org
M(III)(aq)
(mol/L)
Aqueous An/Ln Profiles Following Loss of Acidity in Scrub 1 Feed (Stage 12). Time = 5 hours
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Stage
Eu Aq
Sm Aq
Nd Aq
Pr Aq
Ce Aq
La Aq
Y Aq
Am Aq


M(III)(or)
(mol/L)
Organic An/Ln Profiles Following Loss of Acidity in Scrub 1 Feed (Stage 12). Time = 6 hours
0.06
0.05
0.04
0.03
0.02
0.01
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
Stage
Eu Org
Sm Org
Nd Org
Pr Org
Ce Org
La Org
Y Org
Am Org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(mol/L)
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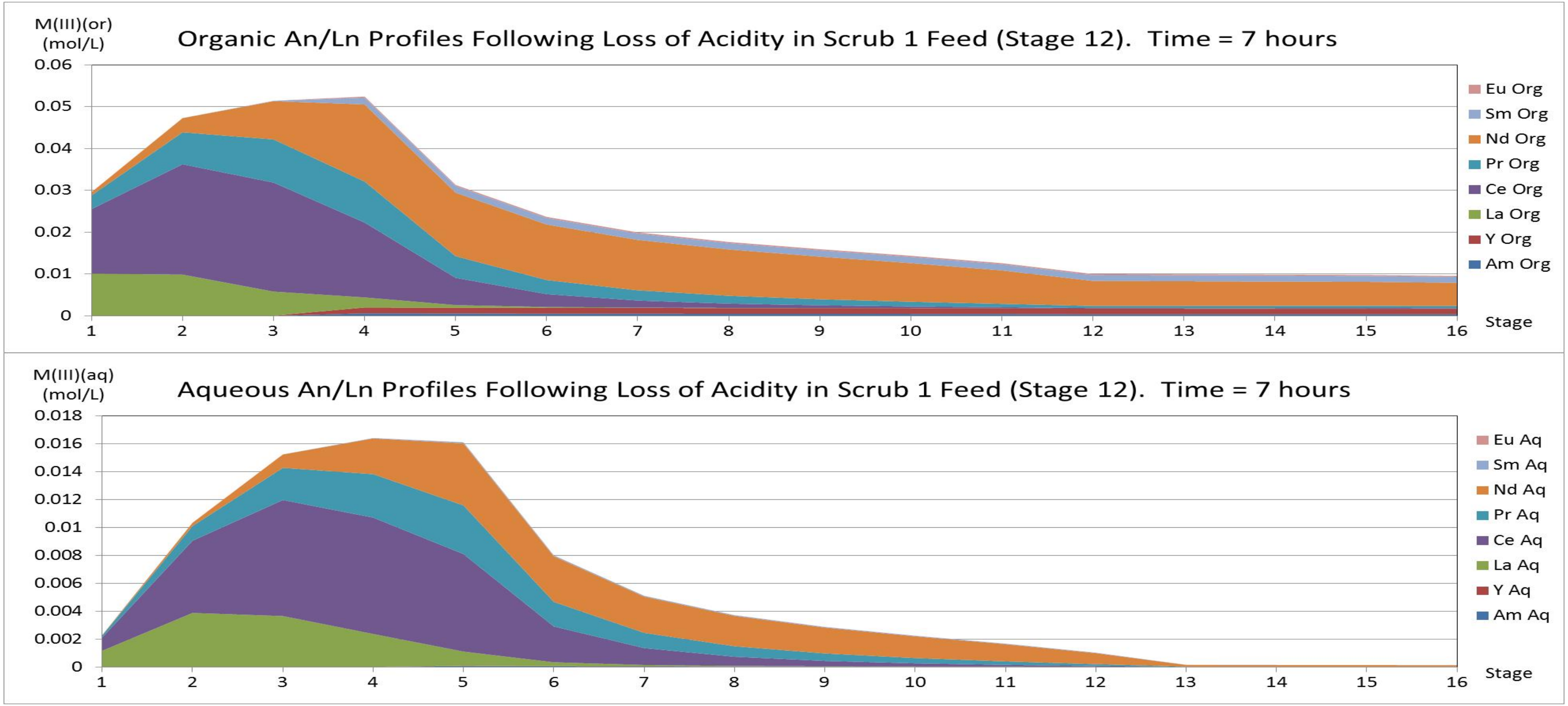
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
Stage
Eu Aq
Sm Aq
Nd Aq
Pr Aq
Ce Aq
La Aq
Y Aq
Am Aq


M(III)(or)
(mol/L)
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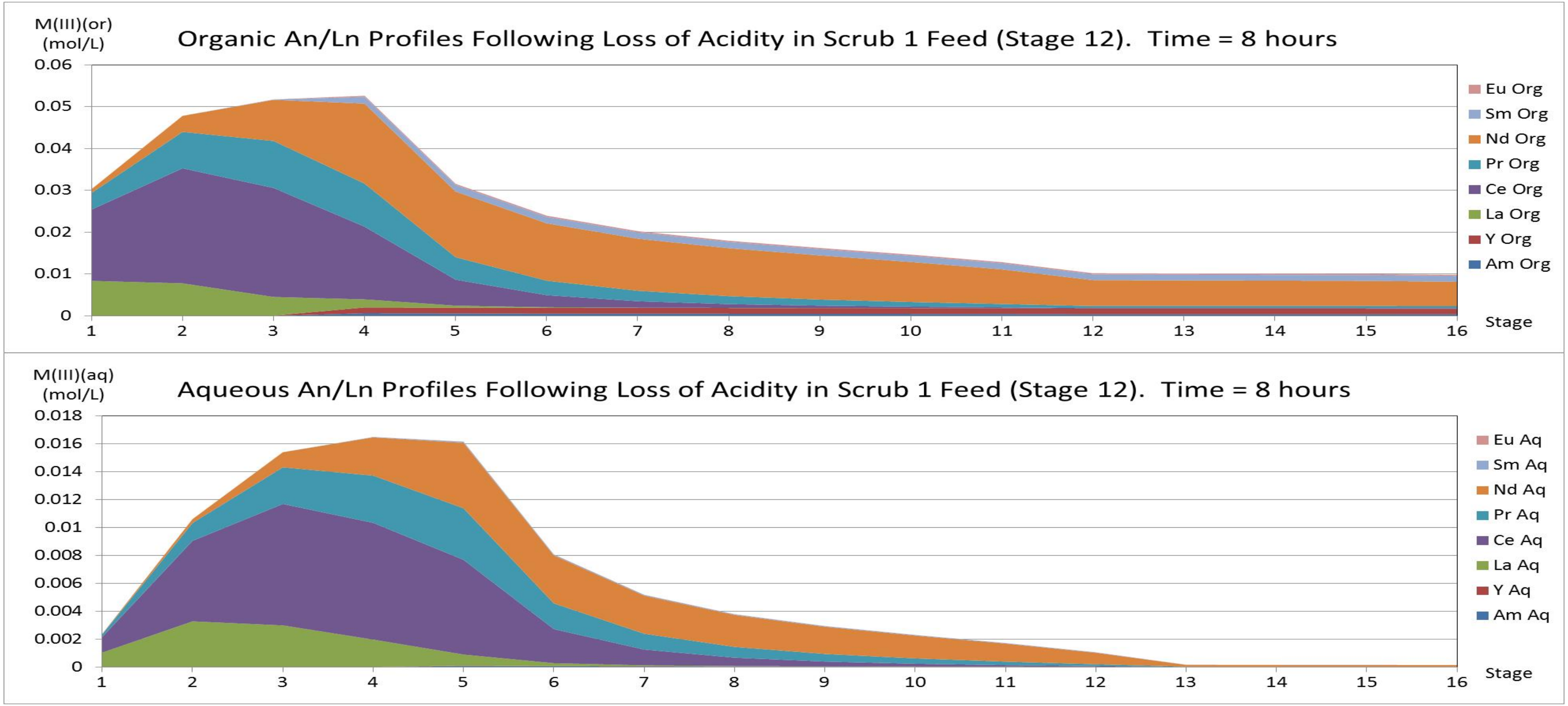
0.06
0.05
0.04
0.03
0.02
0.01
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Stage
Eu Org
Sm Org
Nd Org
Pr Org
Ce Org
La Org
Y Org
Am Org
M(III)(aq)
(mol/L)
Aqueous An/Ln Profiles Following Loss of Acidity in Scrub 1 Feed (Stage 12). Time = 7 hours
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Stage
Eu Aq
Sm Aq
Nd Aq
Pr Aq
Ce Aq
La Aq
Y Aq
Am Aq



M(III)(or) (mol/L)
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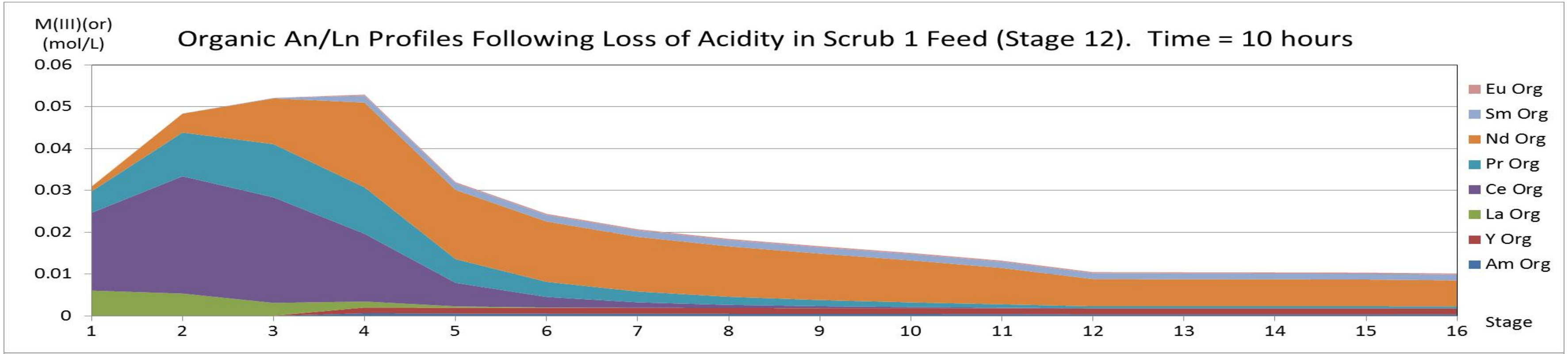
0.04
0.03
0.02
0.01
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Stage
Eu Org
Sm Org
Nd Org
Pr Org
Ce Org
La Org
Y Org
Am Org
M(III)(aq) (mol/L)
Aqueous An/Ln Profiles Following Loss of Acidity in Scrub 1 Feed (Stage 12). Time = 8 hours
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Stage
Eu Aq
Sm Aq
Nd Aq
Pr Aq
Ce Aq
La Aq
Y Aq
Am Aq


M(III)(or) (mol/L)
Organic An/Ln Profiles Following Loss of Acidity in Scrub 1 Feed (Stage 12). Time = 10 hours
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0.05
0.04
0.03
0.02
0.01
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Stage
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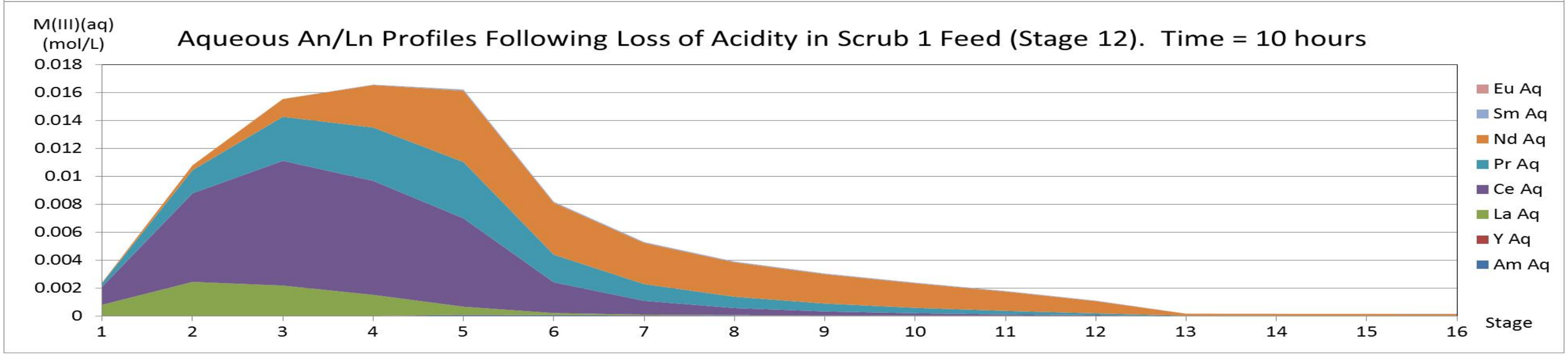
Sm Org
Nd Org
Pr Org
Ce Org
La Org
Y Org
Am Org


M(III)(aq) (mol/L)
Aqueous An/Ln Profiles Following Loss of Acidity in Scrub 1 Feed (Stage 12). Time = 10 hours
0.018
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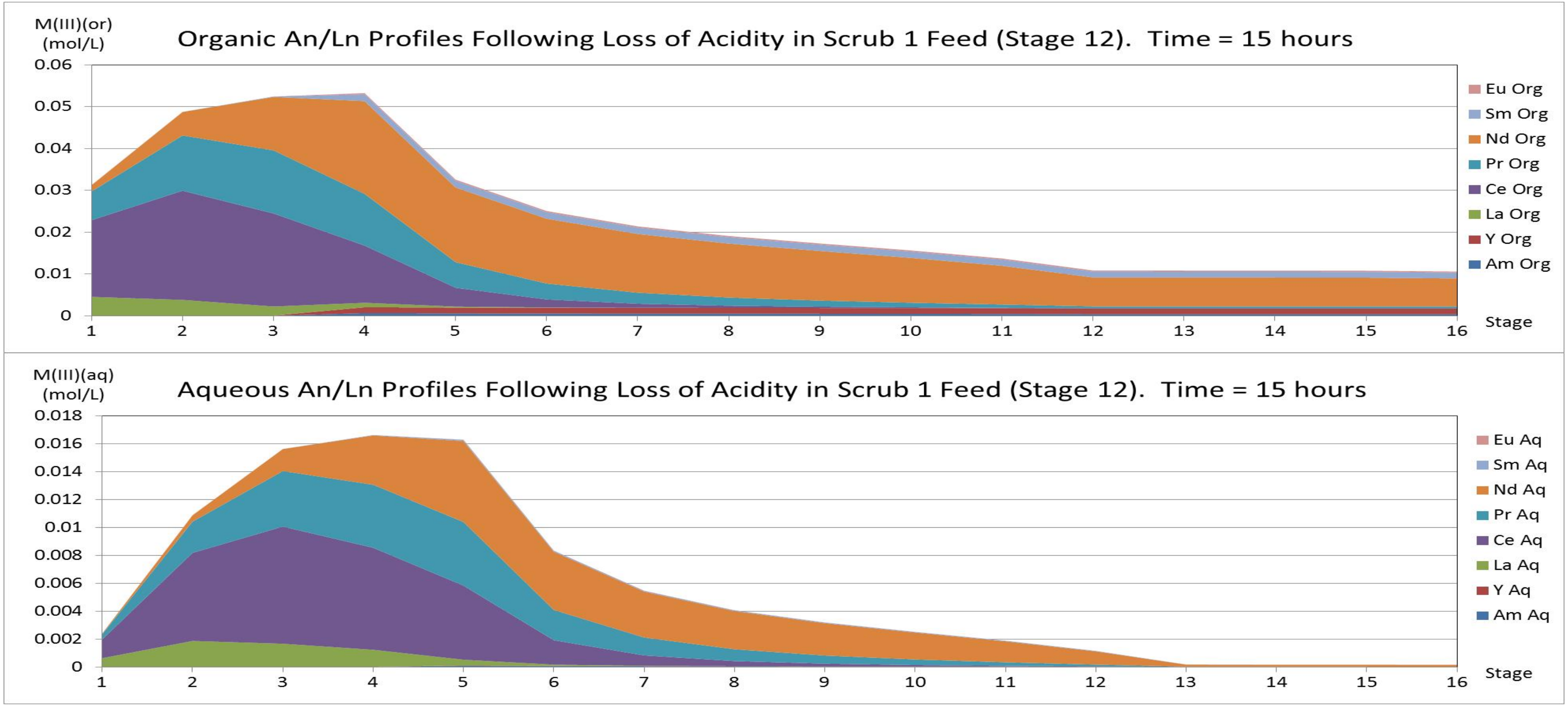
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Stage
Eu Aq
Sm Aq
Nd Aq
Pr Aq
Ce Aq
La Aq
Y Aq
Am Aq



M(III)(or) (mol/L)
Organic An/Ln Profiles Following Loss of Acidity in Scrub 1 Feed (Stage 12). Time = 15 hours
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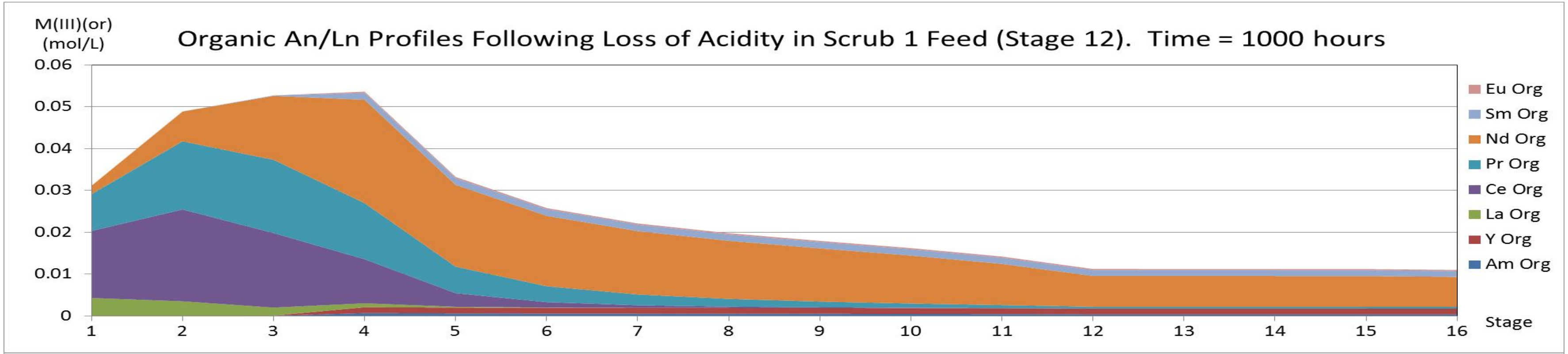
0.04
0.03
0.02
0.01
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Stage
Eu Org
Sm Org
Nd Org
Pr Org
Ce Org
La Org
Y Org
Am Org
M(III)(aq) (mol/L)
Aqueous An/Ln Profiles Following Loss of Acidity in Scrub 1 Feed (Stage 12). Time = 15 hours
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Stage
Eu Aq
Sm Aq
Nd Aq
Pr Aq
Ce Aq
La Aq
Y Aq
Am Aq


M(III)(or)
(mol/L)
Organic An/Ln Profiles Following Loss of Acidity in Scrub 1 Feed (Stage 12). Time = 1000 hours
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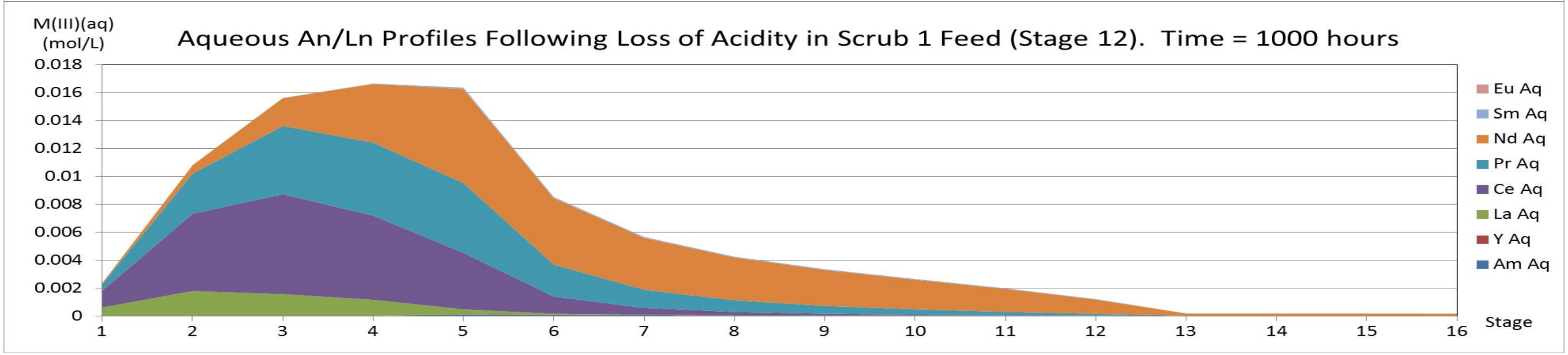
0.05
0.04
0.03
0.02
0.01
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Stage
Eu Org
Sm Org
Nd Org
Pr Org
Ce Org
La Org
Y Org
Am Org


M(III)(aq)
(mol/L)
Aqueous An/Ln Profiles Following Loss of Acidity in Scrub 1 Feed (Stage 12). Time = 1000 hours
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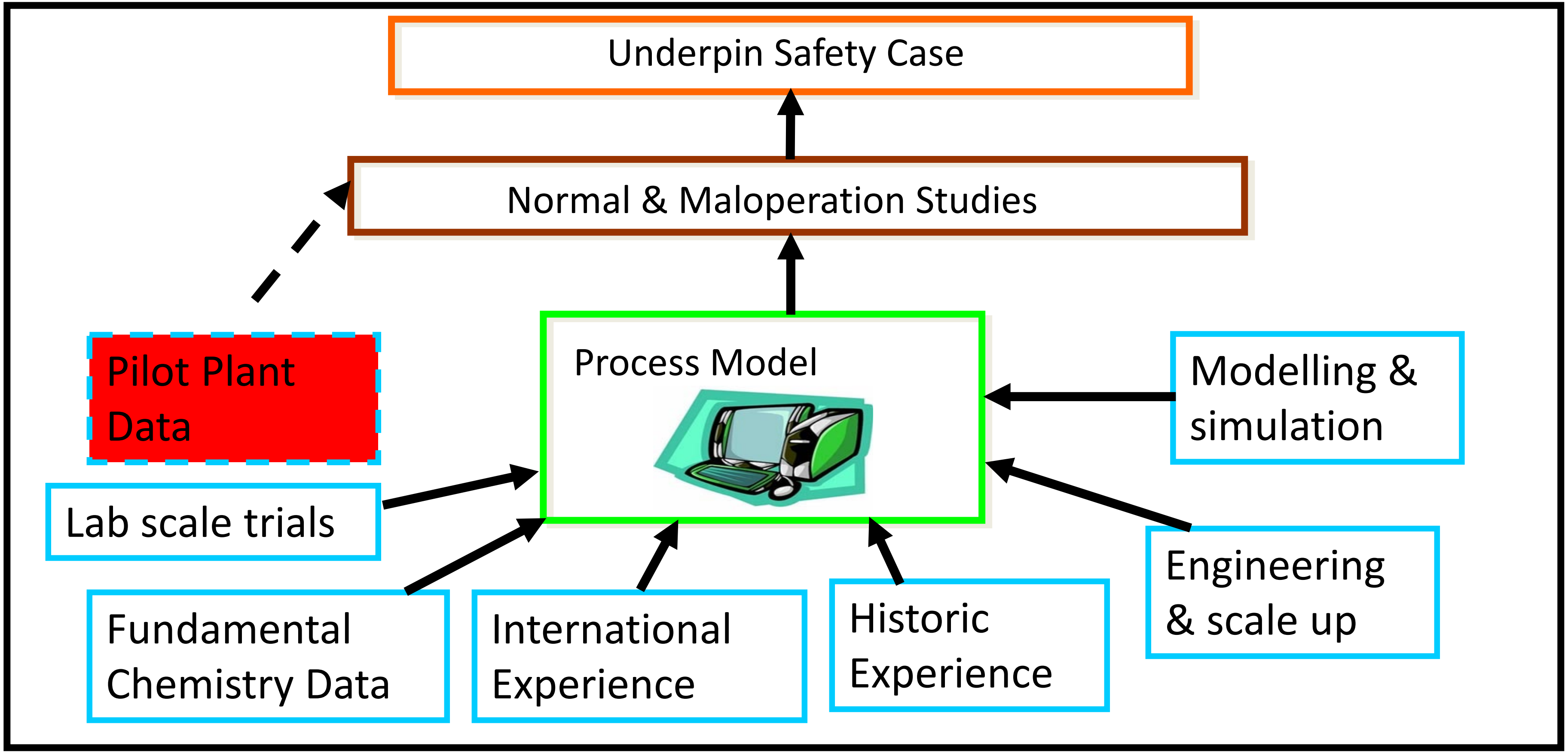
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Stage
Eu Aq
Sm Aq
Nd Aq
Pr Aq
Ce Aq
La Aq
Y Aq
Am Aq

Underpinning the flowsheet & safety case

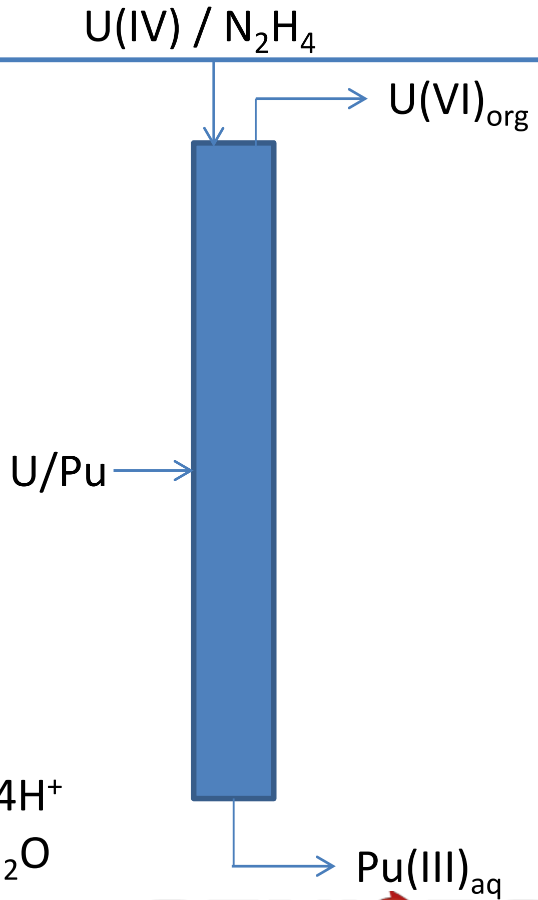


Dealing with the unexpected

- Flowsheet testing (alpha active and hot tests) is essential to:
  - Demonstrate flowsheet performance
  - Validate process models
  - Investigate impact of malop conditions
  - Identify potential issues not highlighted by fundamental studies
- Despite extensive testing and modelling of the flowsheet operational issues may still arise during commissioning
- An early issue for the development of Thorp flowsheet:
  - Tc behaviour in 1BX column (identified by alpha active / pilot plant trials)

Trouble with Technetium (Tc)

- Separation of U/Pu achieved using U(IV) stabilised with hydrazine.
- Alpha active testing and pilot plant trials identified excessive consumption of hydrazine occurring in the process
- Tc is co-extracted with U and Pu in HA/HS contactor.
- Excessive consumption attributed to Tc catalysed oxidation of hydrazine by nitric acid.



$$U^{4+} + 2Pu^{4+} \rightarrow 2Pu^{3+} + UO_2^{2+} + 4H^+$$

$$HNO_2 + N_2H_5^+ \rightarrow HN_3 + H_3O^+ + H_2O$$

Consequences for U/Pu separation

- Excess hydrazine added to process to ensure stability of U(IV) and Pu(III)
- Operation of U/Pu separation column modified from aqueous continuous to solvent continuous (validated by additional trials using pulsed column test rig).

A Hazard not identified cannot be protected against

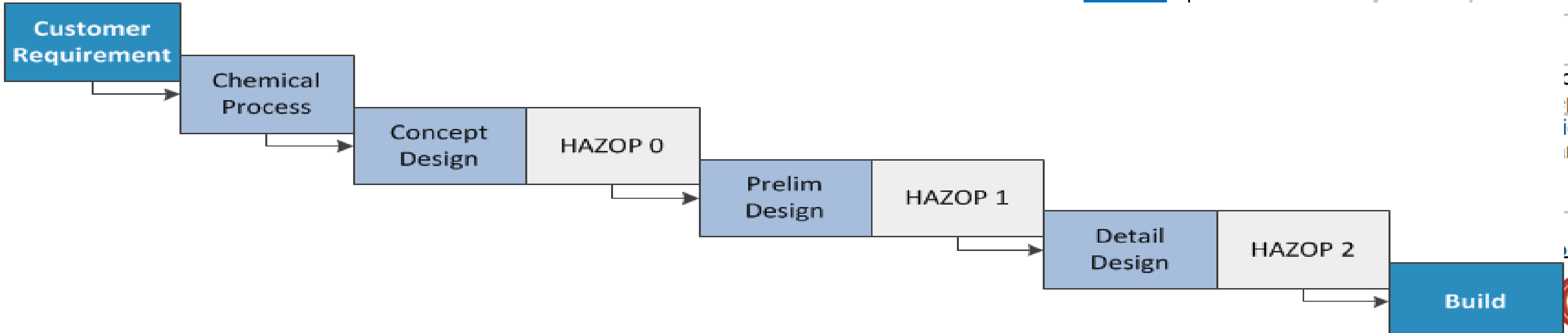
Piper Alpha

- Explosion and subsequent fire
- Fatalities – 167

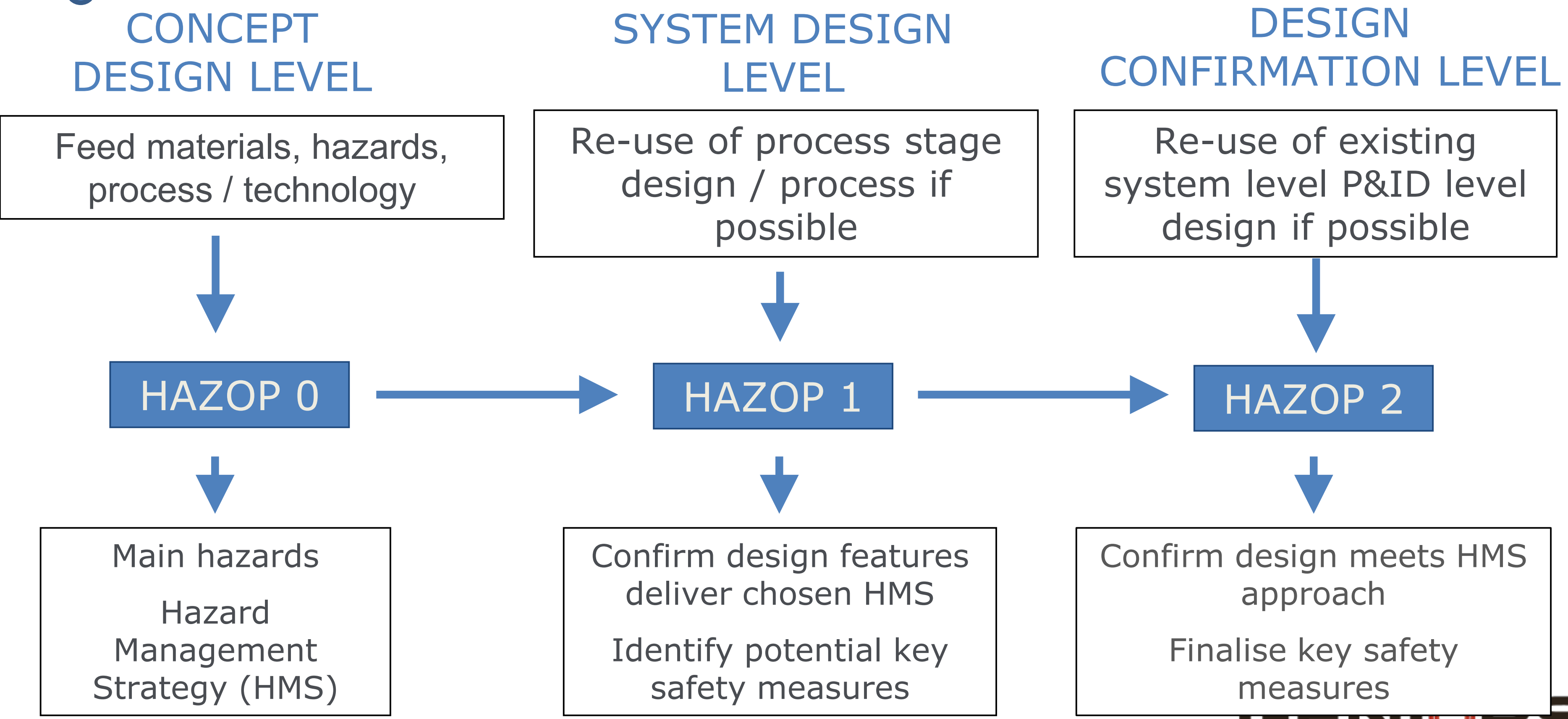
Process Safety

- It is important to consider safety at each stage of development.
  - Changes and improvements to the process.
  - New designs at different scales.
- HAZOP study developed for use in industry.

Phase	TRL	Stage
Operations	TRL9	Operations
Deployment	TRL8	Active Commissioning
	TRL7	Inactive Commissioning
Development	TRL6	Large Scale
	TRL5	Pilot Scale
		Scale
		of pt
		ion and rch
		les



HAZOP Approach



HAZOP Study – Hazard and Operability Study

Node	Guide words	Possible Cause	Consequence	Indications/ Safeguards	Safety Assessment Required	Additional Notes
1. Dissolver	Flow None					
	Flow Less					
	Flow More					
	Flow As Well As					
	Flow Reverse					
	Temperature None					
	Temperature Less					
	Pressure None					
	Pressure Less					

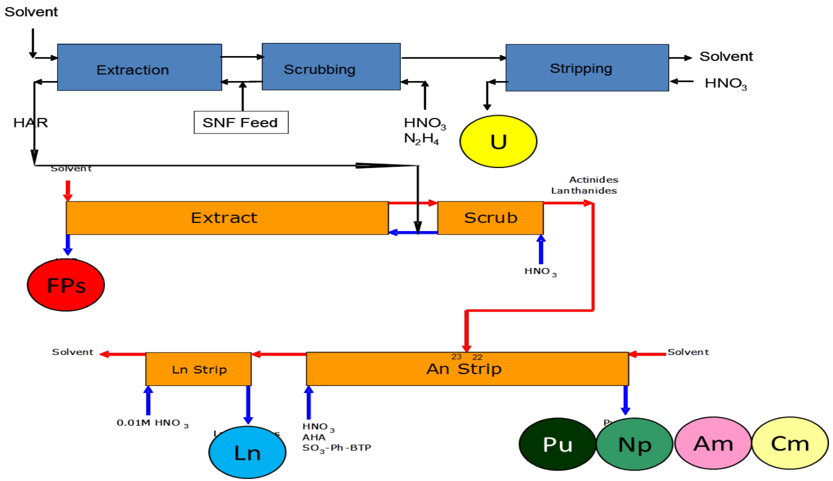
Property Words	Guide Words
Basic Property Words	Basic Guide Words
Flow	None
Temperature	More of
Pressure	Less of
Level	Part of
Concentration	As well as
Radiation	Other
Other	Reverse
Additional Property Words	Additional Guide Words
Oxygen	Early
Viscosity	Late
Density	
Acidity	
Settle	
Dissolve	

xt

- Different key words depending upon stage in design process.

SACSESS & GENIORS

- HAZOP style safety reviews performed for Euro GANEX under SACSESS & GENIORS Programmes
- Key words specific to EU flowsheet projects developed under SACSESS
- Think Tank adopted HAZOP style process – output will be used in GENIORS safety review deliverable

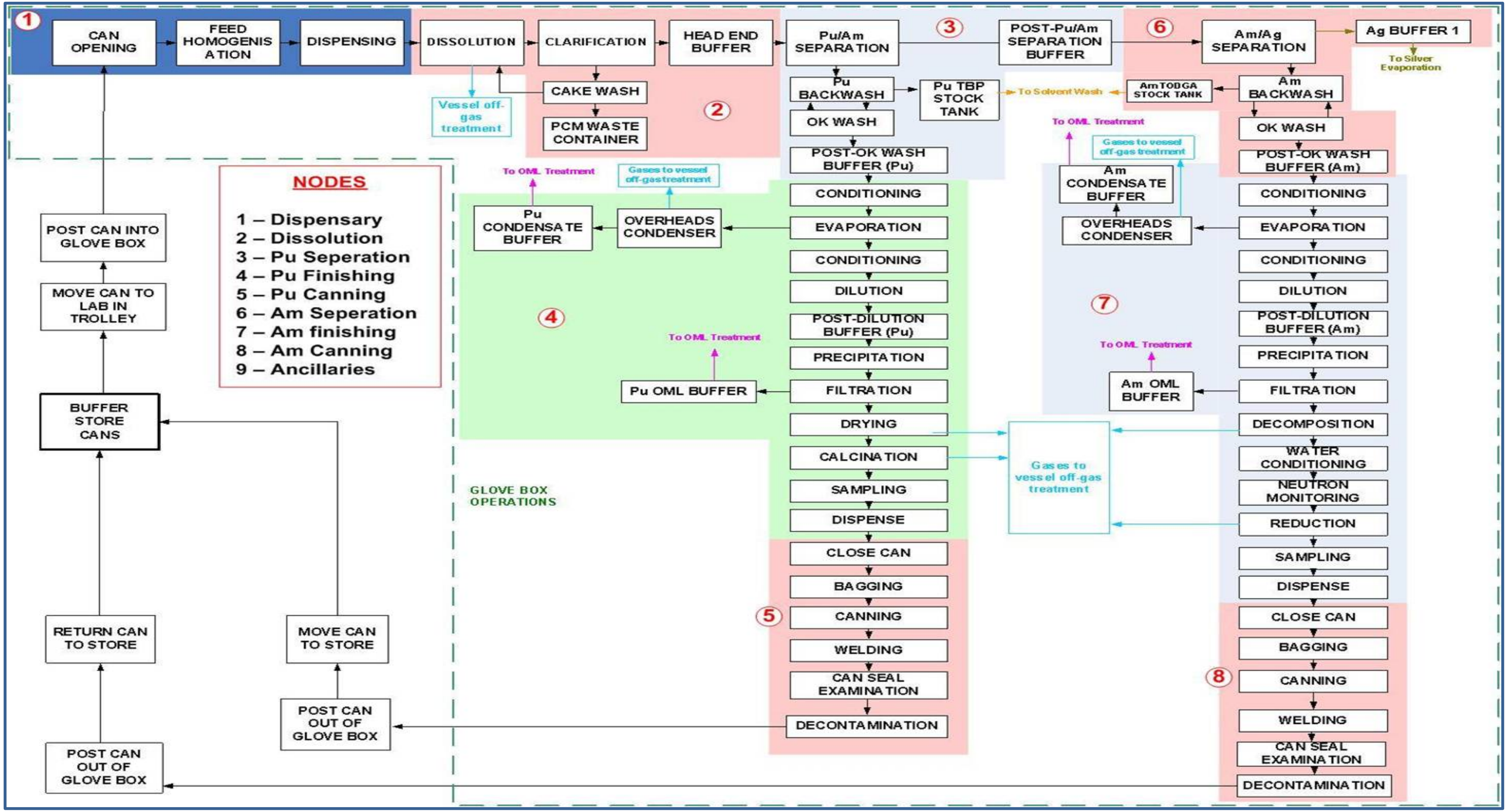


^{241}Am Space Battery Project

- Project Initiates from a requirement

$$ {}^{241}_{94}Pu \xrightarrow{\beta \quad 14.4y} {}^{241}_{95}Am $$

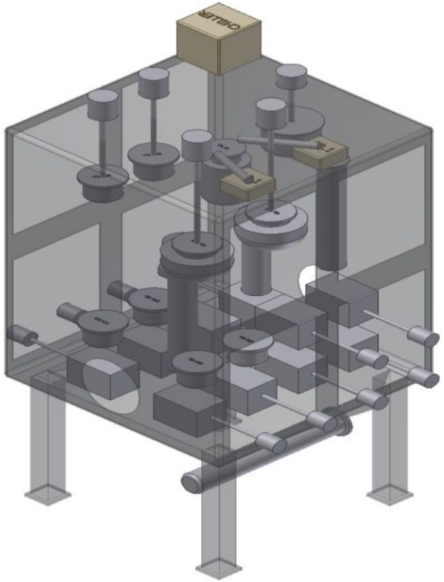
- Chem. Sep Flowsheet produced which can achieve the required separation.
- This then requires expansion to include all the process ‘blocks’ required. i.e. the job doesn’t start with Pu nitrate and end with Am nitrate
- Assign and scale equipment to each operation

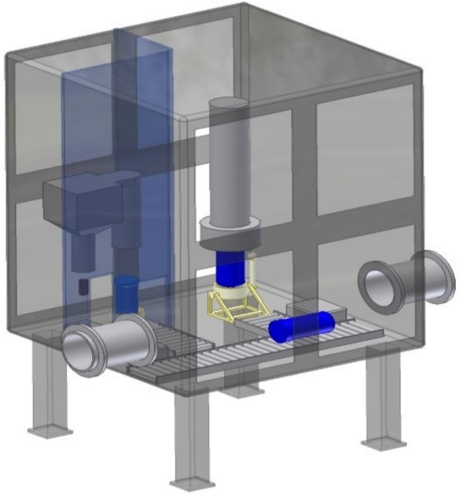


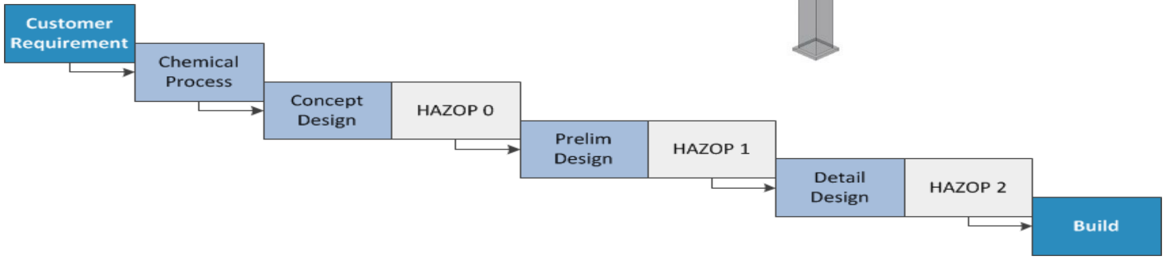
GENIORS
GEN IV integrated oxide fuels recycling strategies

Layout the Process

- Layout process flow
- Add mechanical movement equipment
- Build containment around this
- Understand faults / hazards & iterate

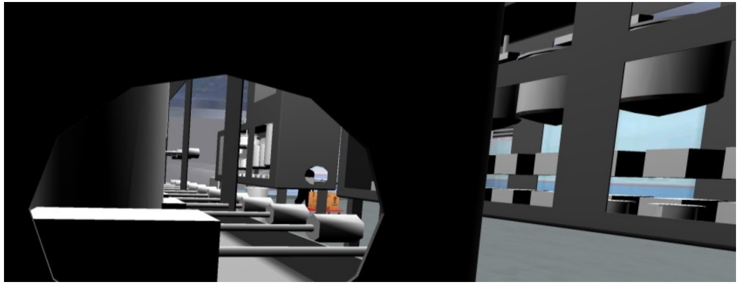


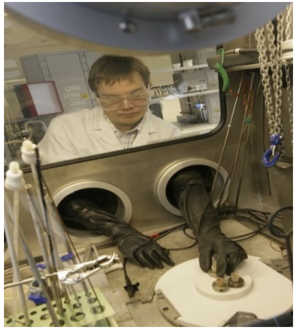


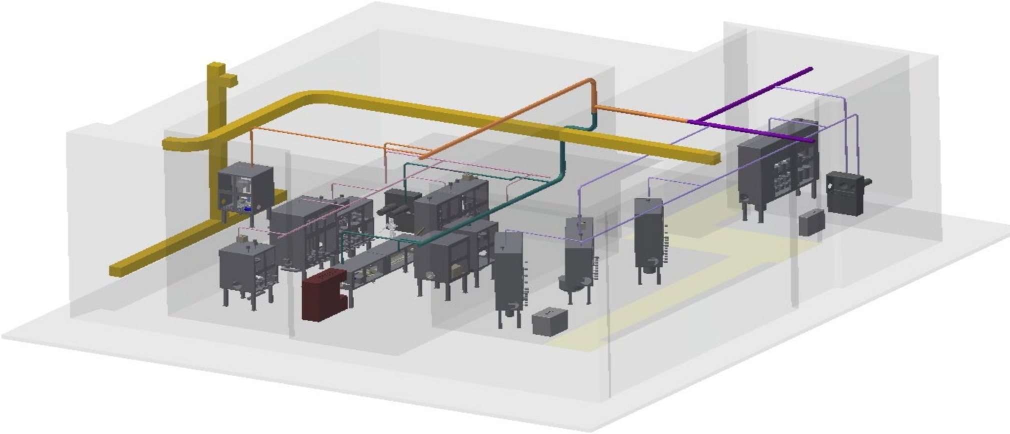


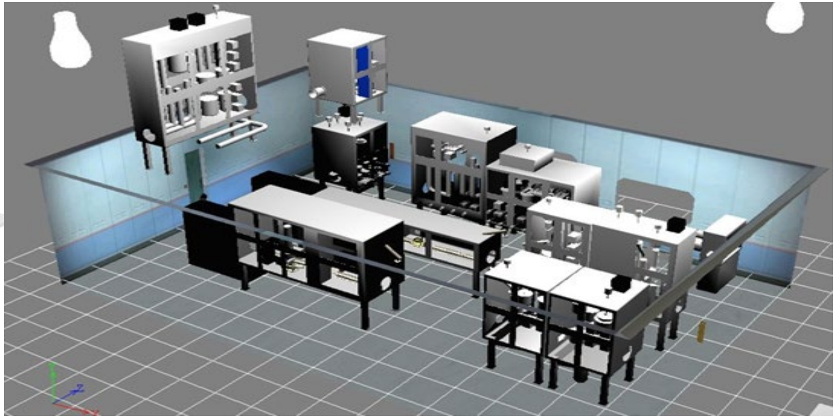
GENIORS
GEN IV integrated oxide fuels recycling strategies

Layout the Plant









GENIORS
GEN IV integrated oxide fuels recycling strategies

Summary – steps in moving from lab to plant scales

- Stick with reference processes => flowsheet optimisation
- Greater use of modelling & simulation => process models
- Underpin process safety => maloperations
- Address interfaces between head end, SX & conversion stages
- Process monitoring & control needed
- Understand S&T gaps => basic research needed
- What are the plans for demonstration tests to reach TRL 6?
- Increase communications with designers & engineers => layout the plant
- Integration with fuels & transmutation => feeds & products