Predictive Self-Healing for Pneumatic Actuated Systems

Project Number FE0031876

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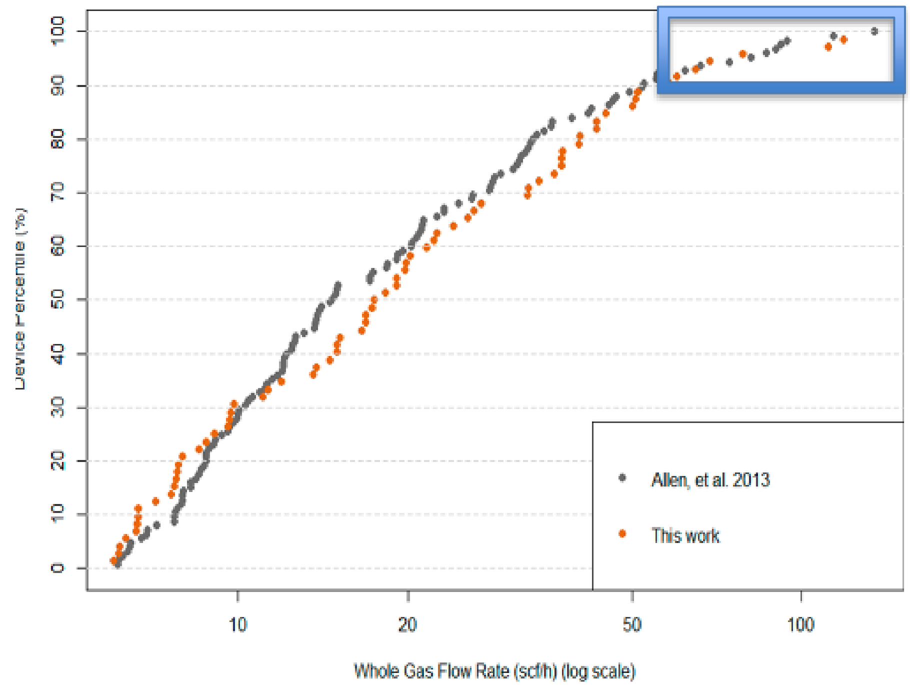
Methane Release from Damaged Systems

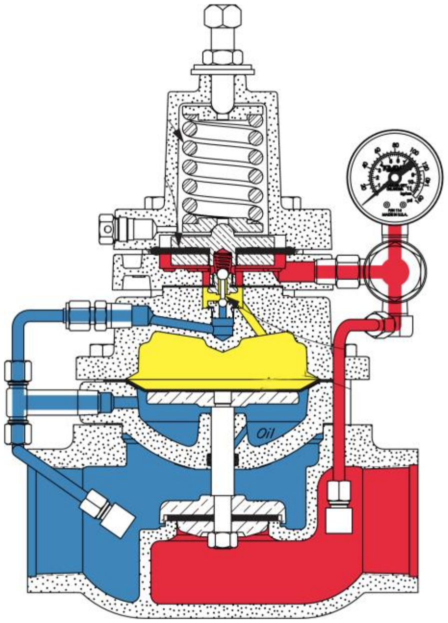
- Allen et al.* observed a significant number of anomalous methane releases in pneumatic actuators.
- This project targets 80% reduction of leak rate in those damaged systems.
- Release from damaged systems in the Allen study accounted for 14 million cubic feet of methane/year.
- Milestone goal would reflect a reduction in release by 11 million cubic feet/year for the systems in Allen paper.



* Allen, Pasci, Sullivan, et al. *Environ. Sci. Technol.* ***49*** *(2015)*

Pneumatic Controllers/Actuators

- Various models, but diaphragms are in large number of devices
- Damage can lead to direct venting of natural gas
- Proposed approach is intended to be direct retrofit
- Approach allows for “active” repair
  - Increases healing approach scope
  - Enables repair of large scale damage



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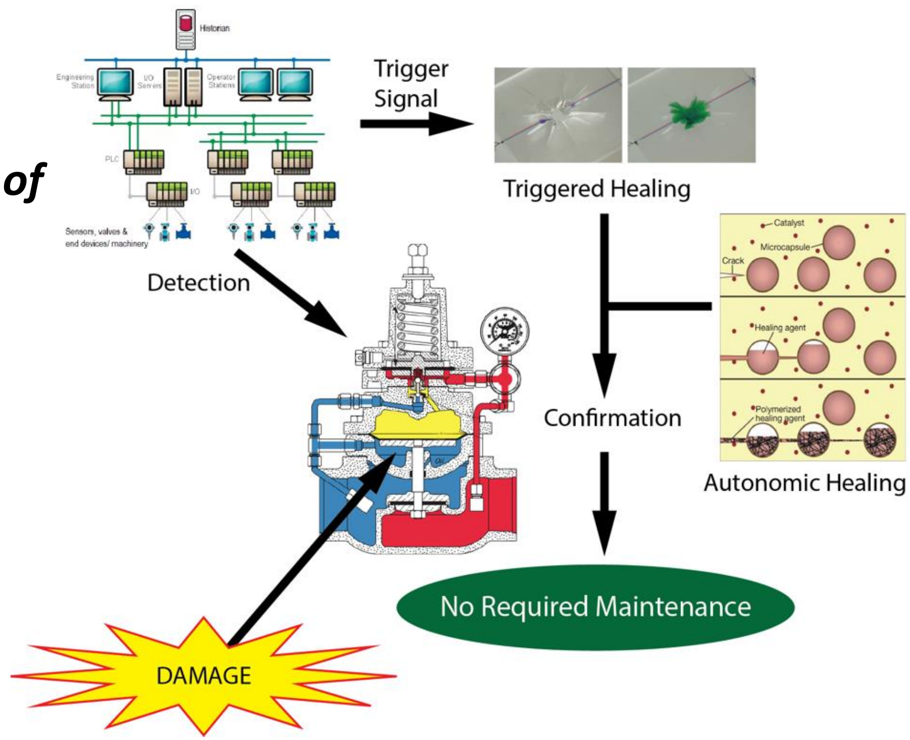
Self-Healing Diaphragm

Demonstrate automatic detection and repair of a pneumatic actuator in a pilot scale facility

- Synthesize self-healing system
- Develop detection model
- Build and validate pilot scale test stand



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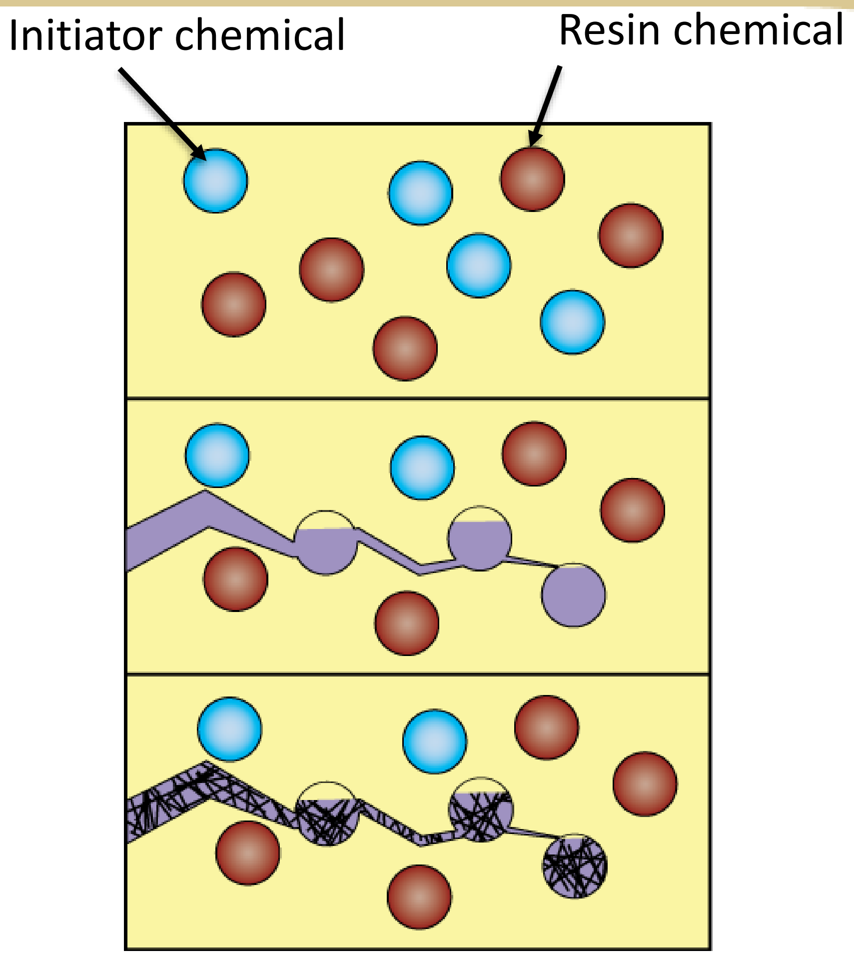
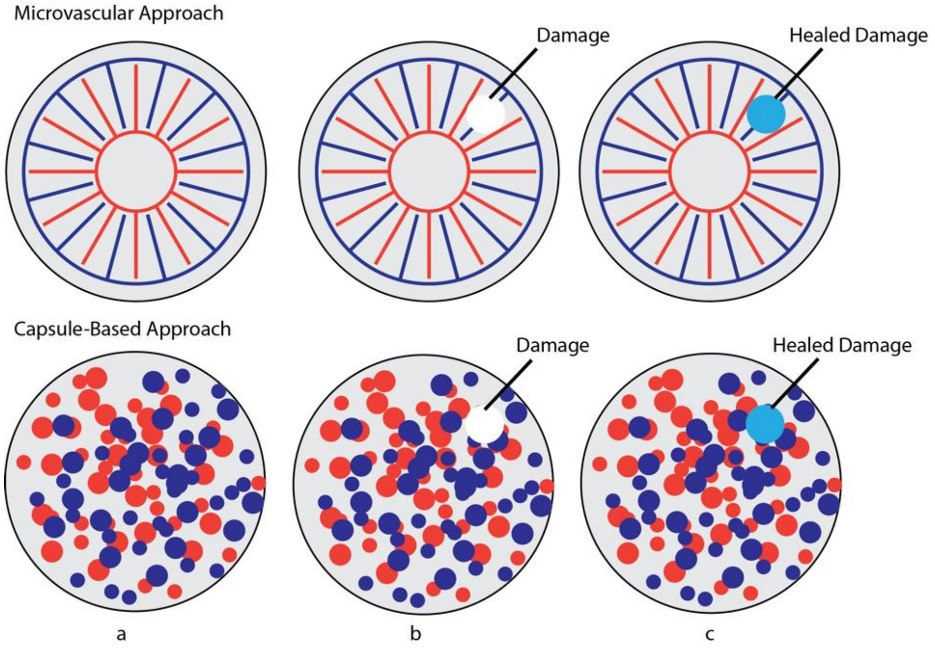
Synthesize Self-Healing Membrane

- Synthesize self-healing membrane material
- Confirm self-repair in laboratory setting
- Integrate system into commercial pneumatic actuator (PA)
- Confirm self-repair in commercial PA.



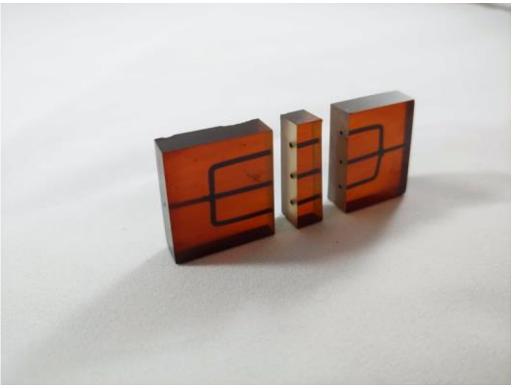
Membrane Processing/Synthesis

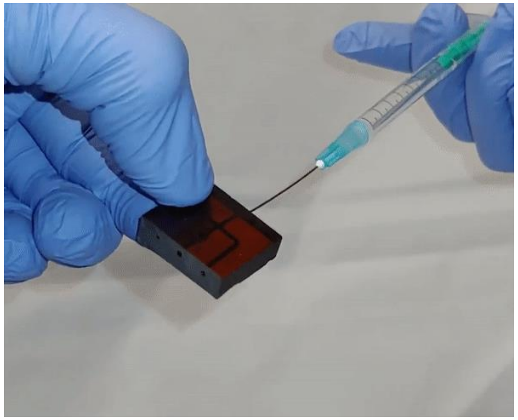
- Two approaches
  - Capsule-based repair
  - Microvascular networks
- Initial focus is polyurethane membrane systems
- Siloxane or acrylic-based healing chemistries are initial targets



Microvascular Systems

- Based on depolymerization of PLA or other lost-wax approaches
- Channel positive is printed via rapid prototype
- Membrane is cast around positive
- Channels are evacuated to provide circulatory system
- Healing chemistry is circulated in channels
- Monolithic and multilayered systems will be investigated





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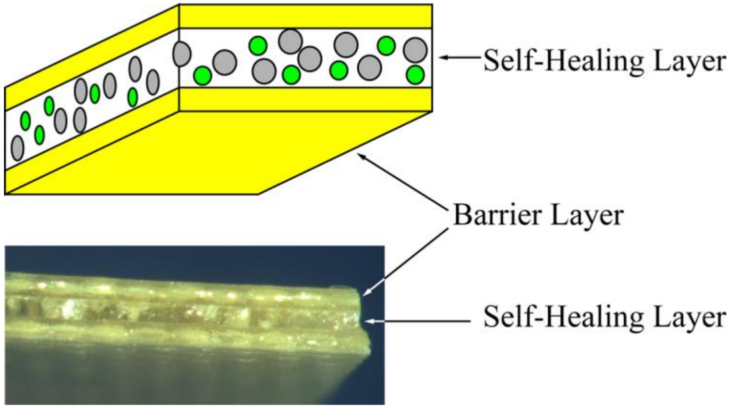
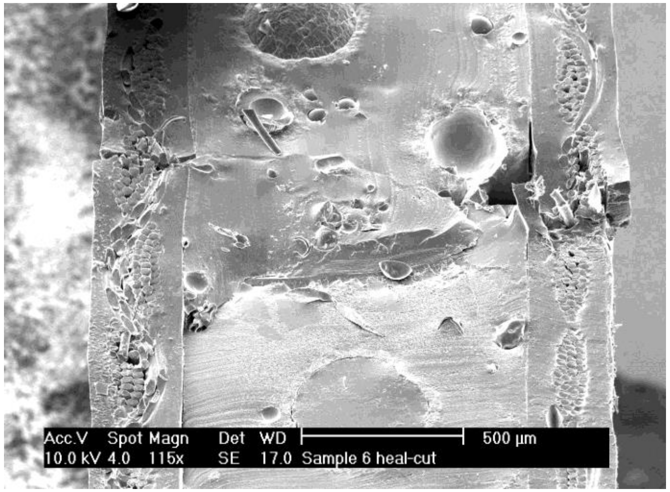
Capsule-based approaches

- Based on reactive monomer encapsulation
- Effective for small-scale damage
- Could be combined with microvascular approach for multi-scale repair
- Monolithic and multi-layer systems will be perused





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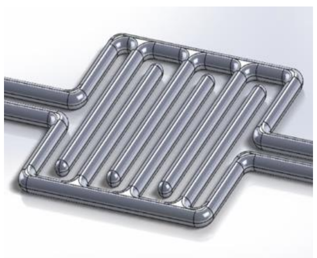
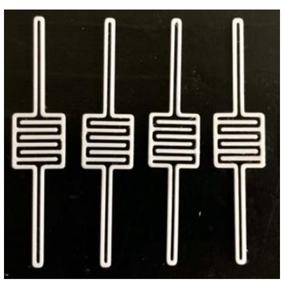
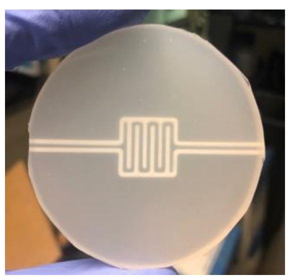
Microvascular Manufacturing

Design and print channels

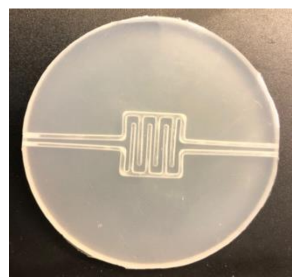




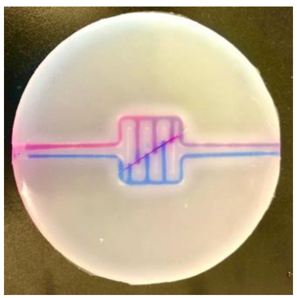
Mold samples

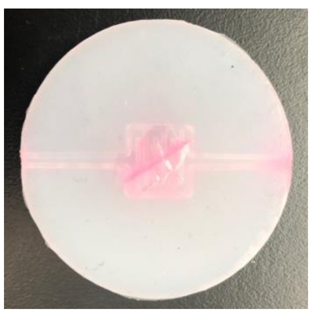


Create hollow channels



Inject with healing chemistries and damage





Test and collect data

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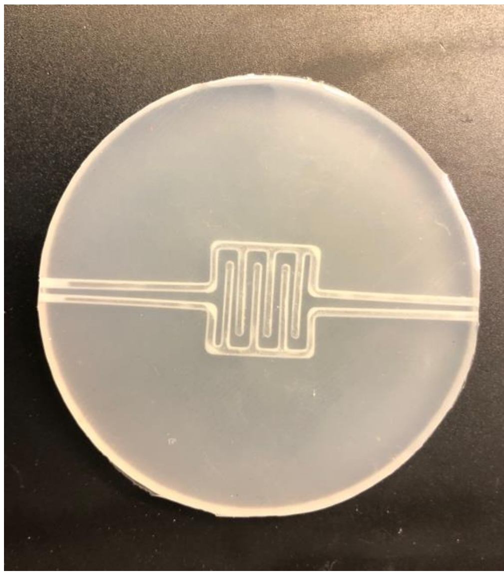
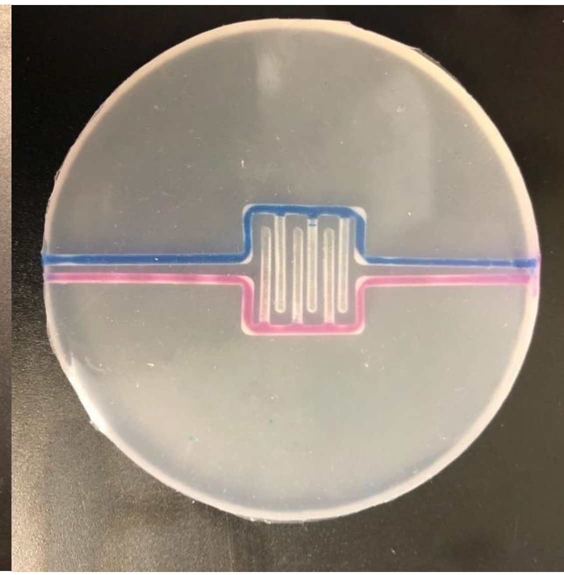
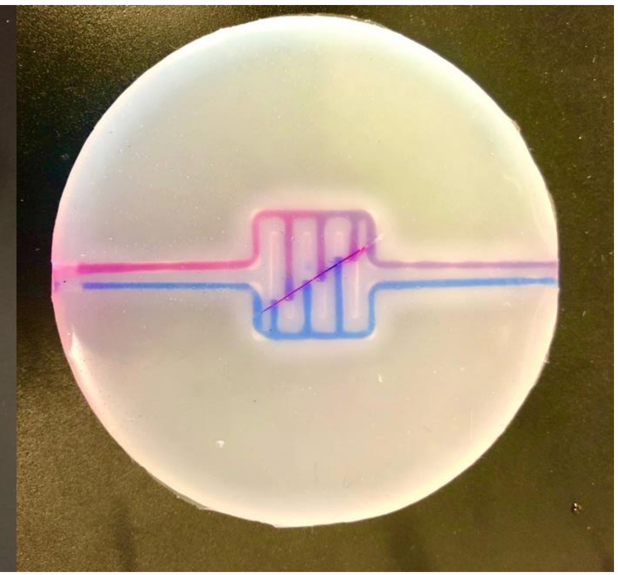
Initial Microvascular Material



Beginning Specimen

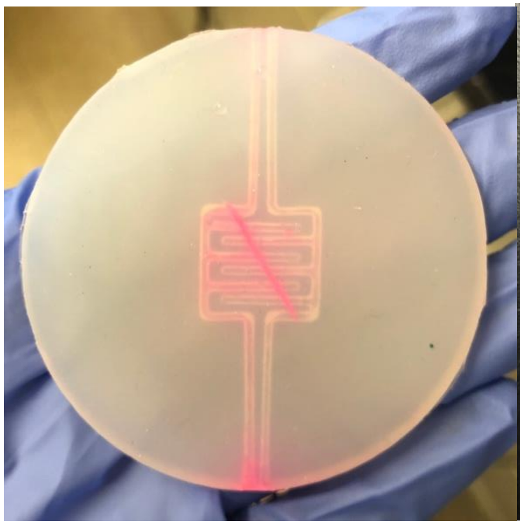


Injecting Dye (Air trapped)

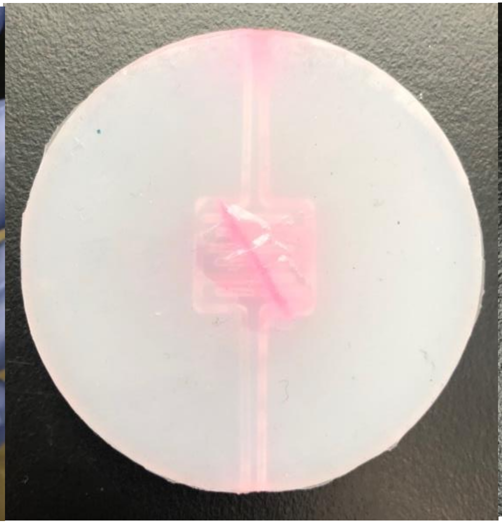


Cut on surface

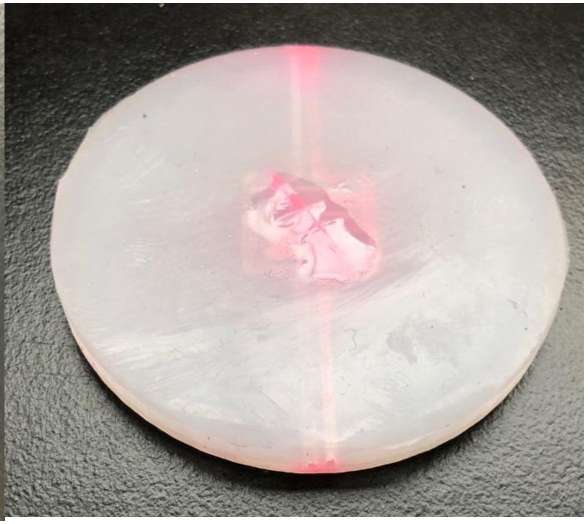
Preliminary healing demonstration



Cut on surface



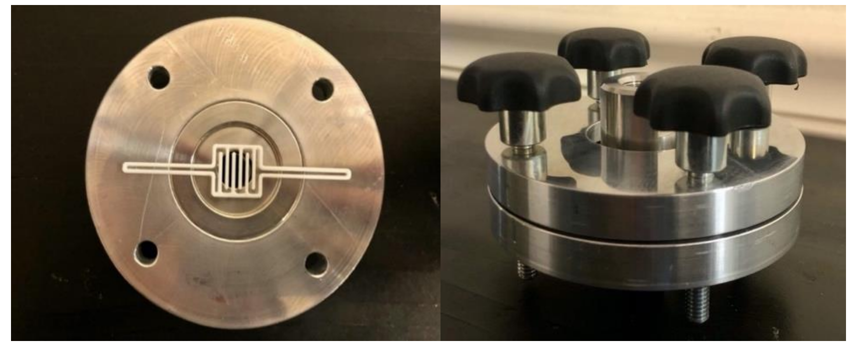
Injecting Healing chemistry

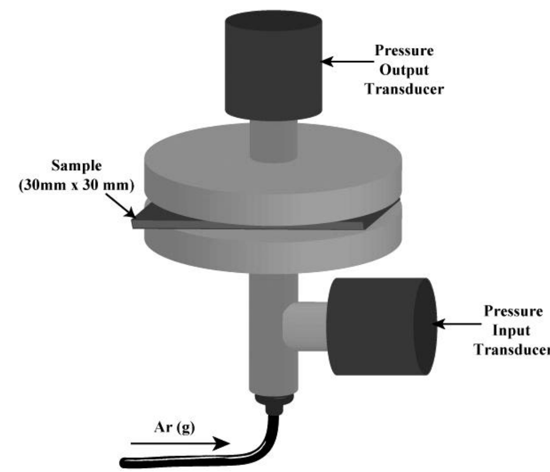


Healing completed

Healing Assessment

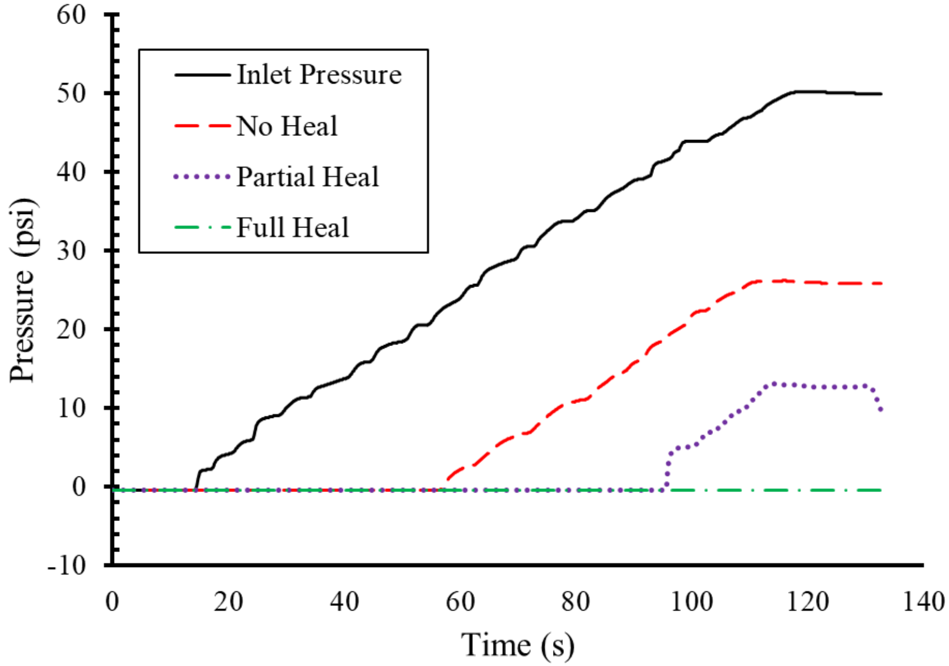
- Pressure test for leak
- Go/no-go healing determination
- Pre-damaged and pre-healed specimens





Test Results

- Leak initiation indicates failure of healed damage
- Healing effectiveness currently based on 100% repair



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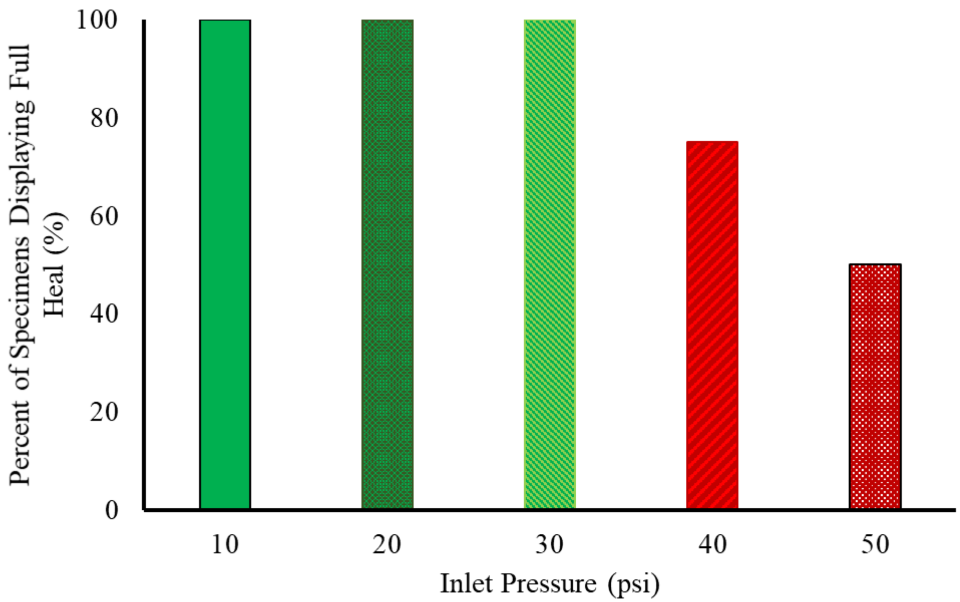
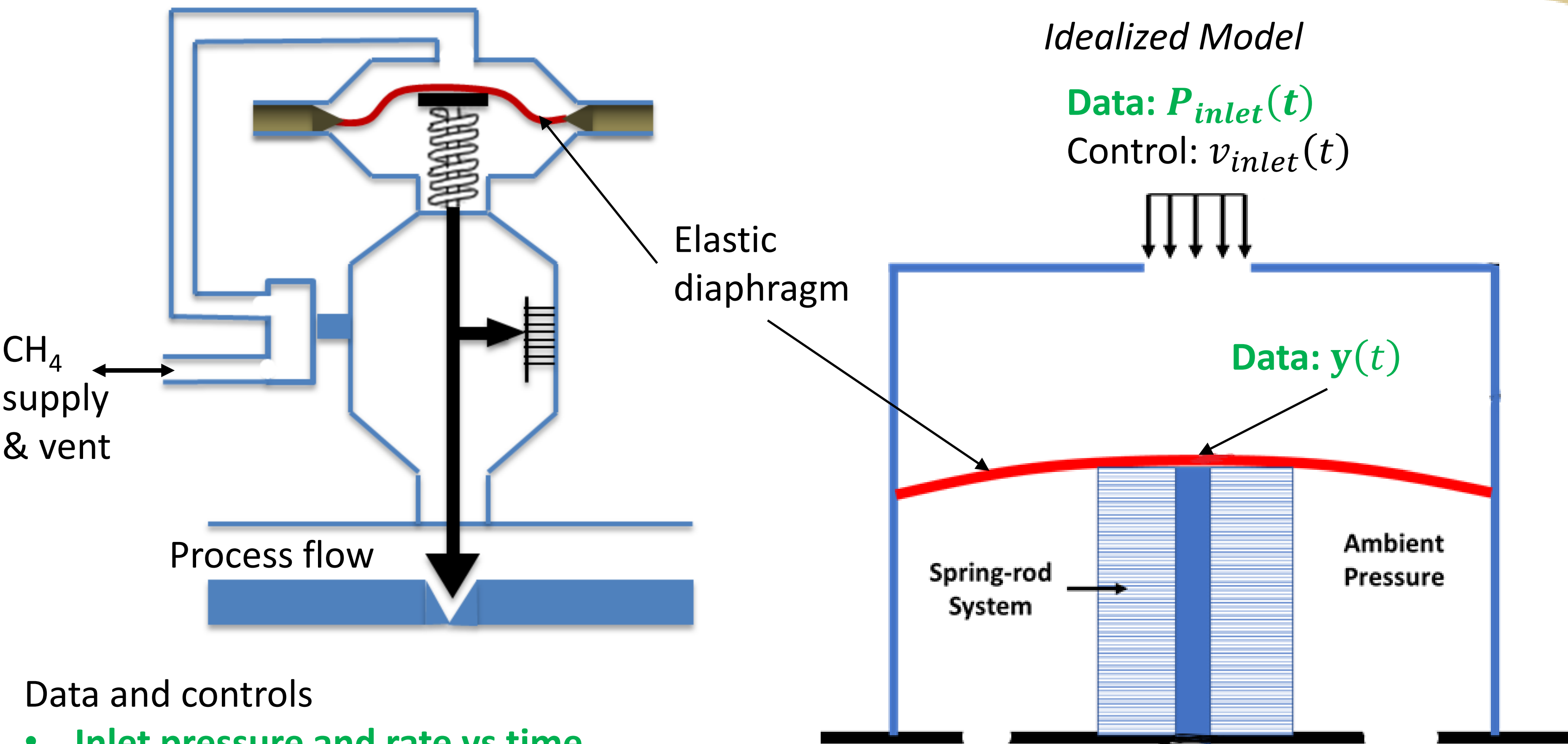
Inlet Pressure Effect on Healing

- Low inlet pressure improves healing
- 60% of specimens healed when exposed to max inlet pressure



Data & computation detection system



Data and controls

- **Inlet pressure and rate vs time**
- **Level meter setting**
- Process flow

Numerical simulation system

$$\rho \frac{\partial \boldsymbol{u}}{\partial t} - \nabla \cdot [-p\boldsymbol{I} + \mu(\nabla \boldsymbol{u} + \nabla^{\mathrm{T}} \boldsymbol{u})] + \rho(\boldsymbol{u} - \boldsymbol{u}_m) \cdot \nabla \boldsymbol{u} = \boldsymbol{F}$$

$$-\nabla \cdot \boldsymbol{u} = 0 \quad \text{in } \Omega^f \times (0,T)$$

$$\boldsymbol{u}(\boldsymbol{x},0) = \boldsymbol{u}_0 \quad \text{on } \Omega^f \times \{0\}$$

$$\boldsymbol{u}(\boldsymbol{x},t) = \boldsymbol{u}_D(\boldsymbol{x},t) \quad \text{on } \Gamma_D^f \times (0,T)$$

$$\boldsymbol{\sigma}^f \cdot \boldsymbol{n}^f = \boldsymbol{t}^f \quad \text{on } \Gamma_N^f \times (0,T)$$

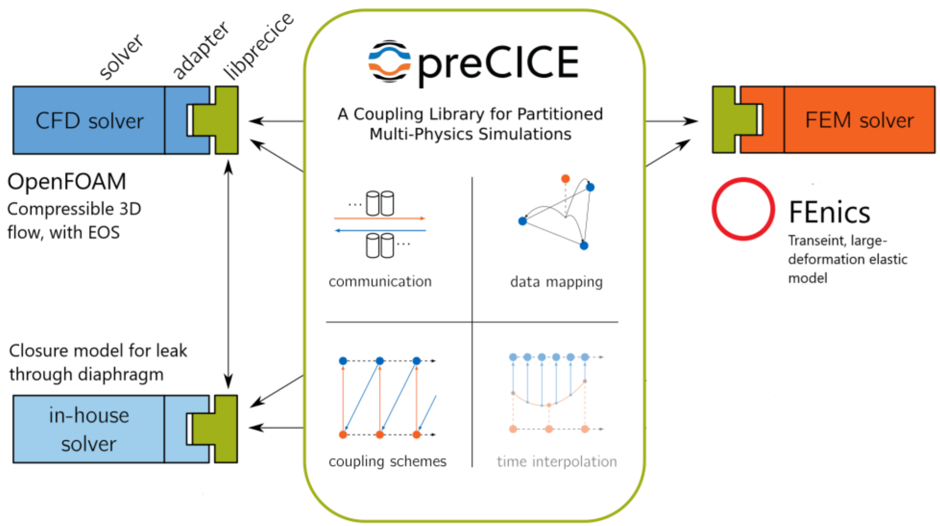
$$\rho_s \frac{\partial^2 \boldsymbol{v}}{\partial t^2} = \nabla \cdot (\boldsymbol{F}\boldsymbol{S}^s) + \rho_s \boldsymbol{b}^s \text{ in } \Omega^s \times (0,T)$$

$$\boldsymbol{v}(\boldsymbol{x},0) = \boldsymbol{v}_0 \text{ in } \Omega^s \times \{0\}$$

$$\frac{\partial \boldsymbol{v}}{\partial t} = \dot{\boldsymbol{v}}_0 \; in \;\; \Omega^s \times \{0\}$$

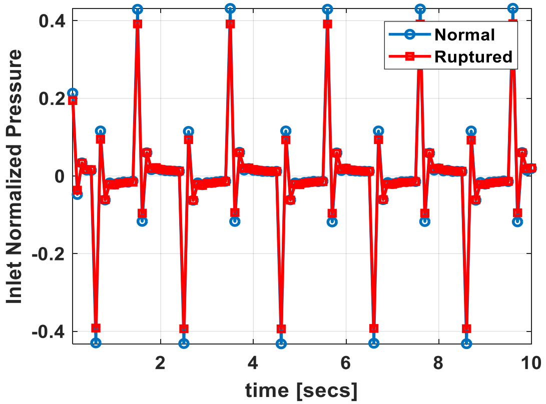
$$\boldsymbol{v} = \boldsymbol{v}_D \; in \; \Gamma_D^s \times (0,T)$$

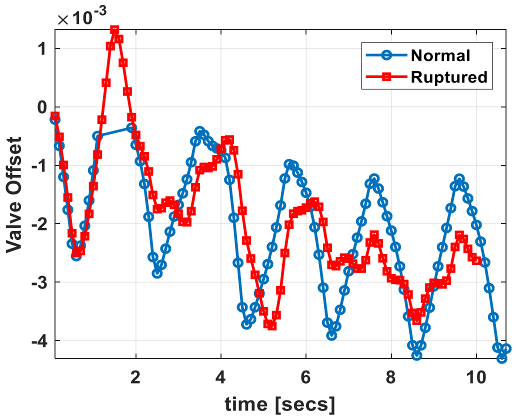
$$\boldsymbol{\sigma}^s \cdot \boldsymbol{n}^s = \boldsymbol{t}^s \; on \; \Gamma_N^s \times (0,T)$$

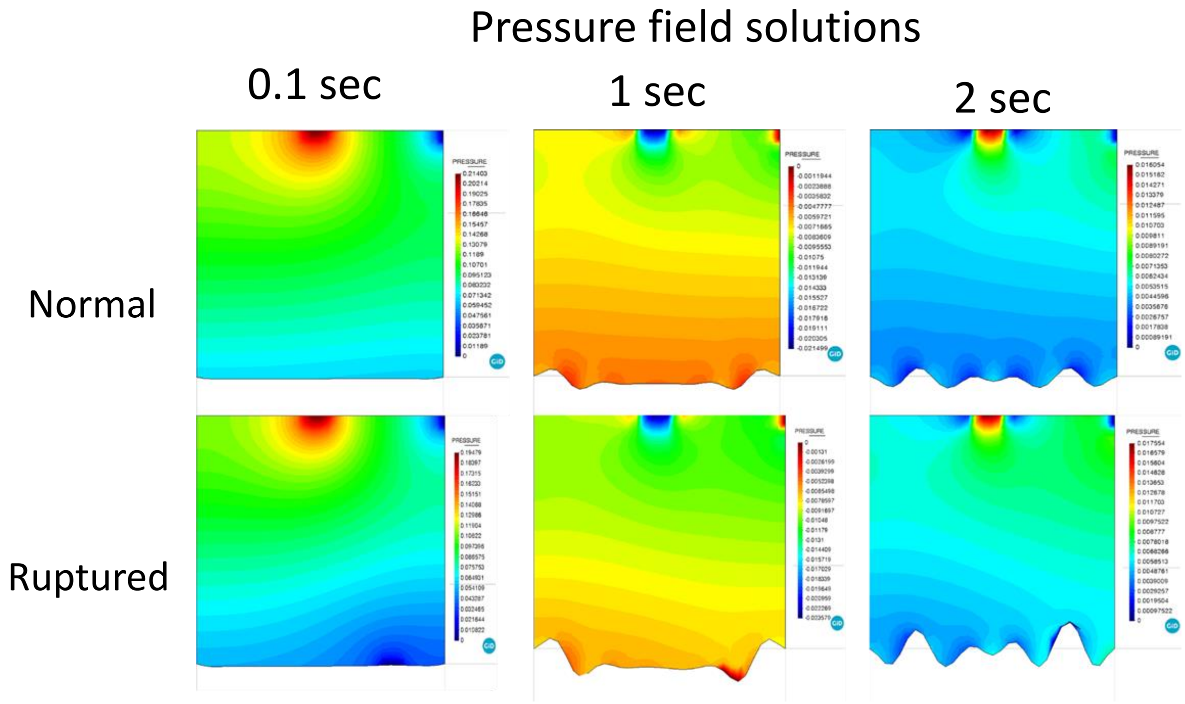


Validation & robustness

Applied extreme valve cycling to a prototypical case.
Introduced rupture at 1 sec.







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Simulated sampling of dimensionless parameter space

Scaling analysis produces:

- 3 dimensionless groups with design parameters
- 2 groups pertaining to controls and state variables

Ongoing work:

- Sample parameter space
- Identify statistically reliable correlation indicating damage
- Apply to test-stand
- Apply to flow-loop

Accomplisments/Summary

- Demonstrated the ability to heal diaphragm materials with microvascular networks
- Initial physical model developed to inform health monitoring
- Moving toward implementation in commercial system

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Lessons Learned

- Research gaps/Challenges
  - None at this time
- Unanticipated Research Difficulties
  - Removal of the PLA preform from elastomers was more complicated than in epoxies.
- Technical Disappointments
  - None at this time
- Changes that should be made next time
  - None at this time

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Appendix

Benefit to the Program

- Reduction of methane release by at least 80%.

- Currently there is no automated repair approach for that is available for pneumatically actuated valves. Additionally, the integrated leak detection approaches are also not well developed and represent a significant advancement in current SCADA technology in its own right. Furthermore, the large-volume self-healing approaches have not been demonstrated in a system that would allow for autonomous or automatic initiation of the healing. Successful demonstration of this integrated system would also represent a forward advancement in the general area of self-healing materials and structures. Finally, the successful demonstration of an integrated self-healing valve system would advance the goal of reduced methane emissions due to damaged or malfunctioning pneumatically actuated valve and control systems.

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Project Overview

Goals and Objectives

- Demonstrate the ability to automatically repair pneumatic controllers from a wide range of damage.
- Develop appropriate SCADA-based real-time monitoring tools to identify a damaged pneumatic controller
- Develop appropriate SCADA-based tools to determine if self-repair was effective.
- Provide technoeconomic analysis of the proposed system.
- Demonstrate the system in a pilot scale flow loop.

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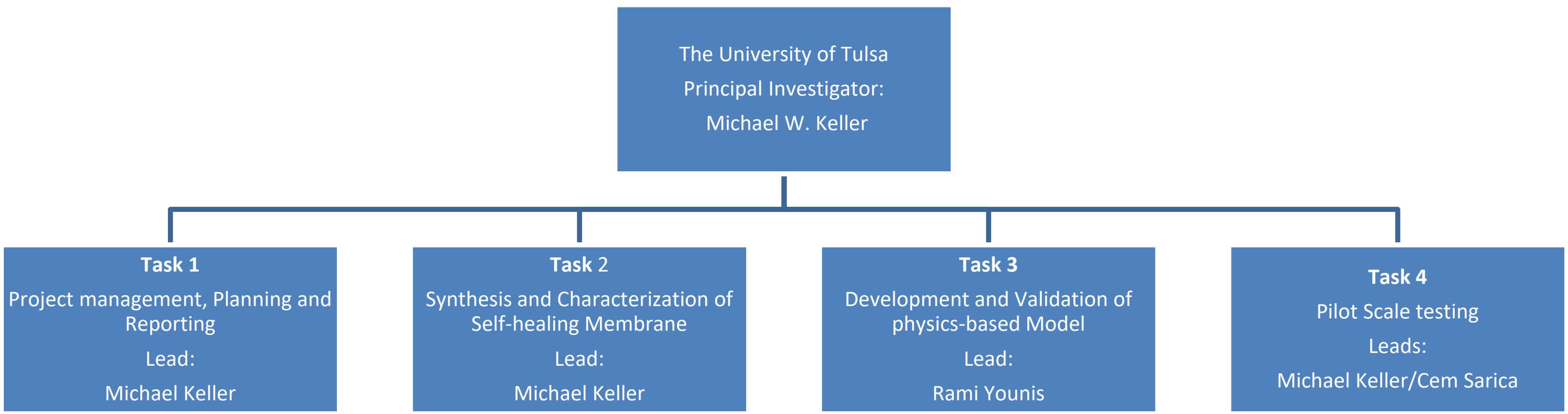
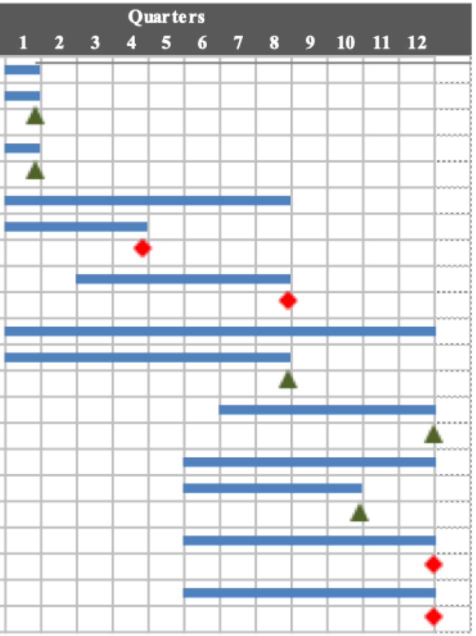
Project Organizational Chart



Gantt Chart

WBS	Task/Subtask/Milestone	G/N	Start	End
1	**Project management and Planning**		**0**	**1**
1.1	Revise PMP		0	1
M1.1.1	*Submit Revised PMP*		1	1
1.2	Technology Maturation Plan		0	1
M1.2.1	*Submit technology maturation plan*		1	1
2	**Demonstrate Self-healing of Diaphragm**		**0**	**8**
2.1	Assess self-healing using model system		0	4
M2.1	*Complete testing of self-healing diaphragm and controls for at least 1 self-healing system.*	G/N	4	4
2.2	Demonstrate self-healing in pneumatic controller		2	8
M2.2	*Demonstrate reduction of leak rate by at least 80% compared to a non-healing control*	G/N	8	8
3	**Demonstrate SCADA-based analytics**		**0**	**12**
3.1	Develop Physics-based model		0	8
M3.1	*Demonstrate physics model with sufficient fidelity to detect a 10 scf/h leak*		8	8
3.2	Demonstrate leak detection on test stand		6	12
M3.2	*Demonstrate the ability to detect a leak rate of at least 10 scf/h*		12	12
4	**Assess self-healing and SCADA detection in pilot loop**		**5**	**12**
4.1	Construct test stand in pilot loop		*5*	10
M4.1	*Construct and validate pilot scale test stand*		10	10
4.2	Demonstrate leak detection via SCADA in pilot plant		5	12
M4.2	*Demonstrate the ability to detect a leak rate of at least 10 scf/h*	G/N	12	12
4.3	Demonstrate self-healing in pilot plant		5	12
M4.3	*Demonstrate the ability to reduce the leak rate by 80% under simulated operating conditions.*	G/N	12	12



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Bibliography

– List peer reviewed publications generated from the project per the format of the examples below.

- None to report

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