



Hydrogen Fueling Infrastructure Research and Station Technology

## Dispenser Reliability 2020 DOE Annual Merit Review

Presenter: Mike Peters<sup>1</sup> (PI)  
Nalini Menon<sup>2</sup>, Matt Ruple<sup>1</sup>, Erin Winkler<sup>1</sup>, Kevin Hartmann<sup>1</sup>,  
Ethan Hecht<sup>2</sup>

<sup>1</sup> National Renewable Energy Laboratory

<sup>2</sup> Sandia National Laboratories

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Project ID # in008

This presentation does not contain  
any proprietary, confidential, or  
otherwise restricted information.

## T I M E L I N E

- Start date: 10/1/2016
- End date: 06/30/2020\*

\* Project continuation and direction determined annually by DOE

## B A R R I E R S

### **Multiyear RD&D Barriers**

#### ***Technology Validation Barriers***

- D. Lack of Hydrogen Refueling Infrastructure Performance and Availability Data
- E. Codes and Standards - Validation projects will be closely coordinated with Safety, Codes and Standards

## B U D G E T

### Project funding:

- **NREL**
  - FY20: \$200k
  - Project Total: \$1,940k
- **SNL\***
  - Project Total: \$677k

## P A R T N E R S

### **Funded**

NREL: Hardware testing and lifetime analysis  
SNL: Material testing\*

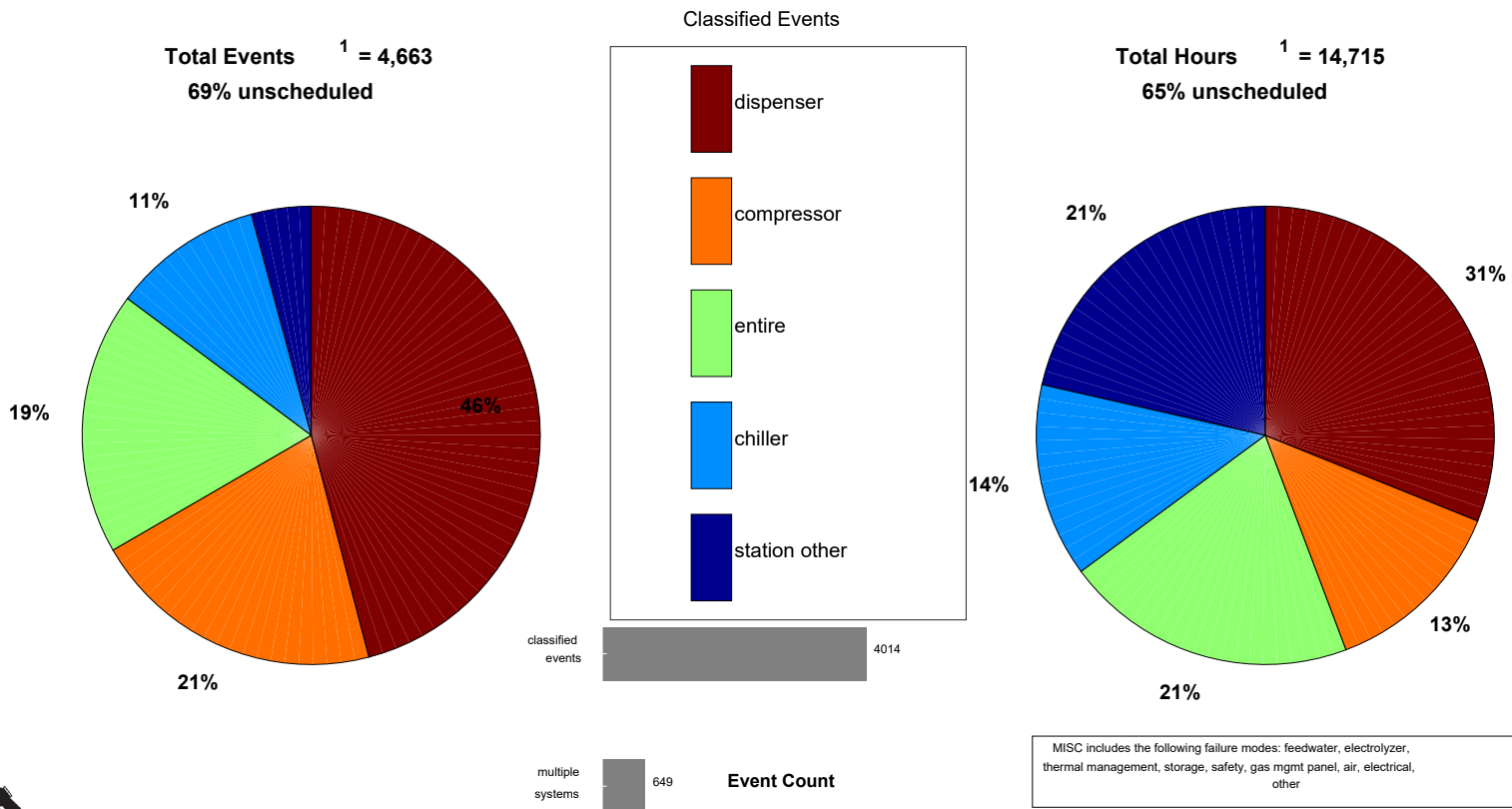
### **Close Collaboration**

Walther-Präzision GmbH & Weh GmbH:  
Material consulting and lifetime monitoring

\*SNL presenting their work as a separate AMR presentation – IN013

## Dispensers are the top cause of maintenance events and downtime at retail hydrogen stations

Maintenance by Equipment Type - Retail Stations



# Relevance: Background and History

## Focus on Accelerated Life Testing



- The NFCTEC data and interviews with station operators led to the conclusion that components in the chilled section of the dispenser were most likely to fail
- The team decided to test the components with the same flow rate, pressure profiles, and only vary the hydrogen gas temperature:
  - Originally -40°C (SAE J2601 standard), -20°C, 0°C, and ambient temperature filling were explored, however,
  - **Due to fueling practicality, budget, and schedule the team limited the testing to two temperature levels: -40°C and -20°C**

### SAE J2601 General Description

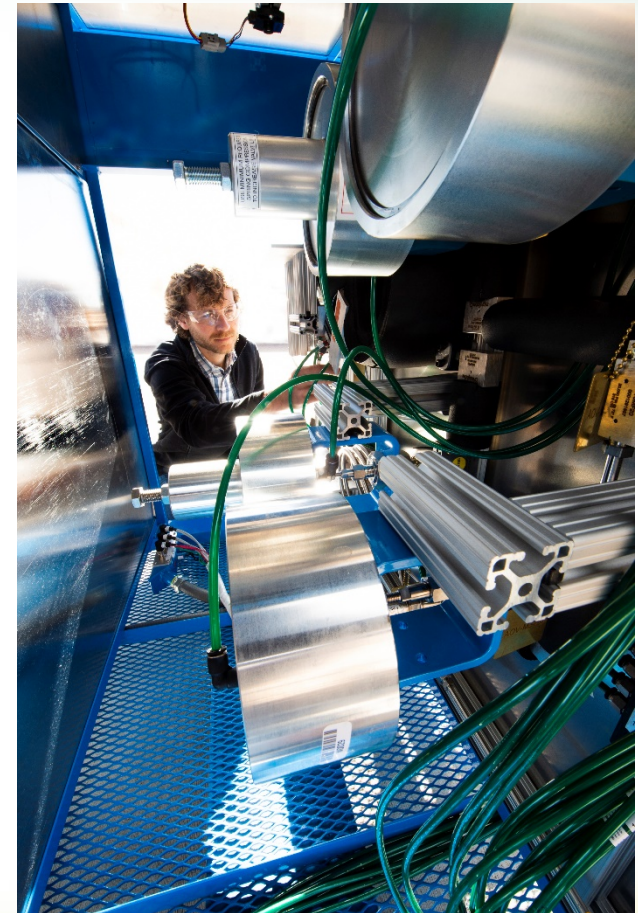
Light-duty fueling protocol  
(project aiming at 4 - 7 kg tables)

Set pressure ramp rate based on  
ambient temperature and vehicle start  
pressure

T40: Temperature window of -33 C to  
-40 C through duration of fill

Must reach temperature window within  
30 seconds of fill start

- There are some test campaigns on performance of piping components at the pressures and temperature in a fueling dispenser, but:
  - Available information is qualitative only, or
  - Results of specific qualification tests do not assess effects other than pass/fail
- SNL adds another level of detail with material characterization pre and post exposure to hydrogen



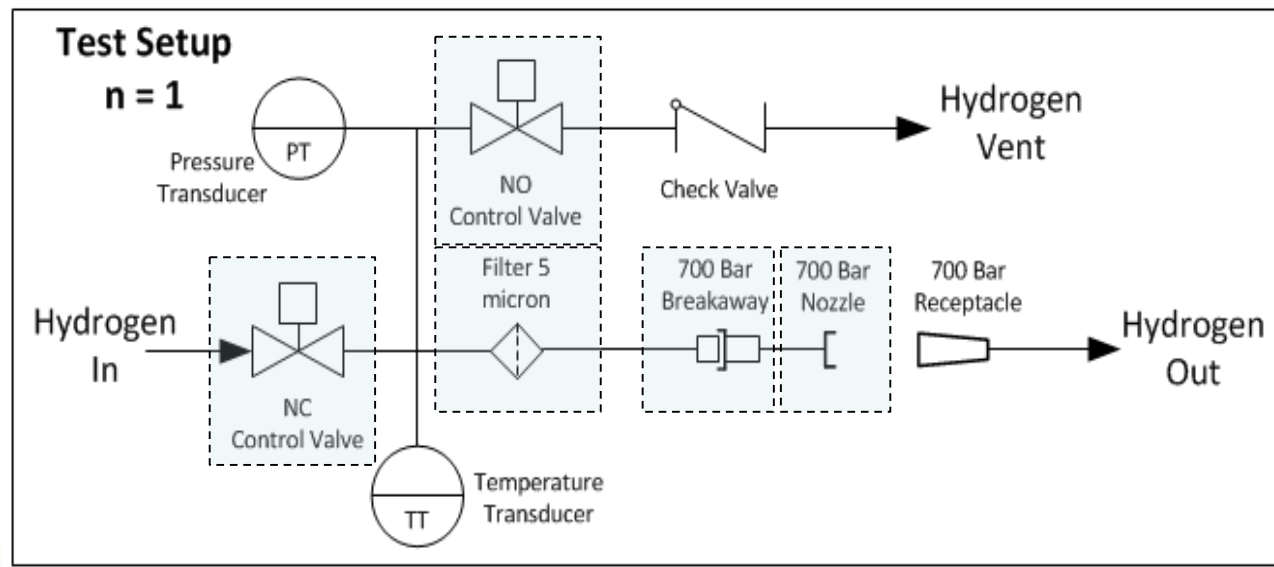
# Approach: Accelerated Reliability Testing



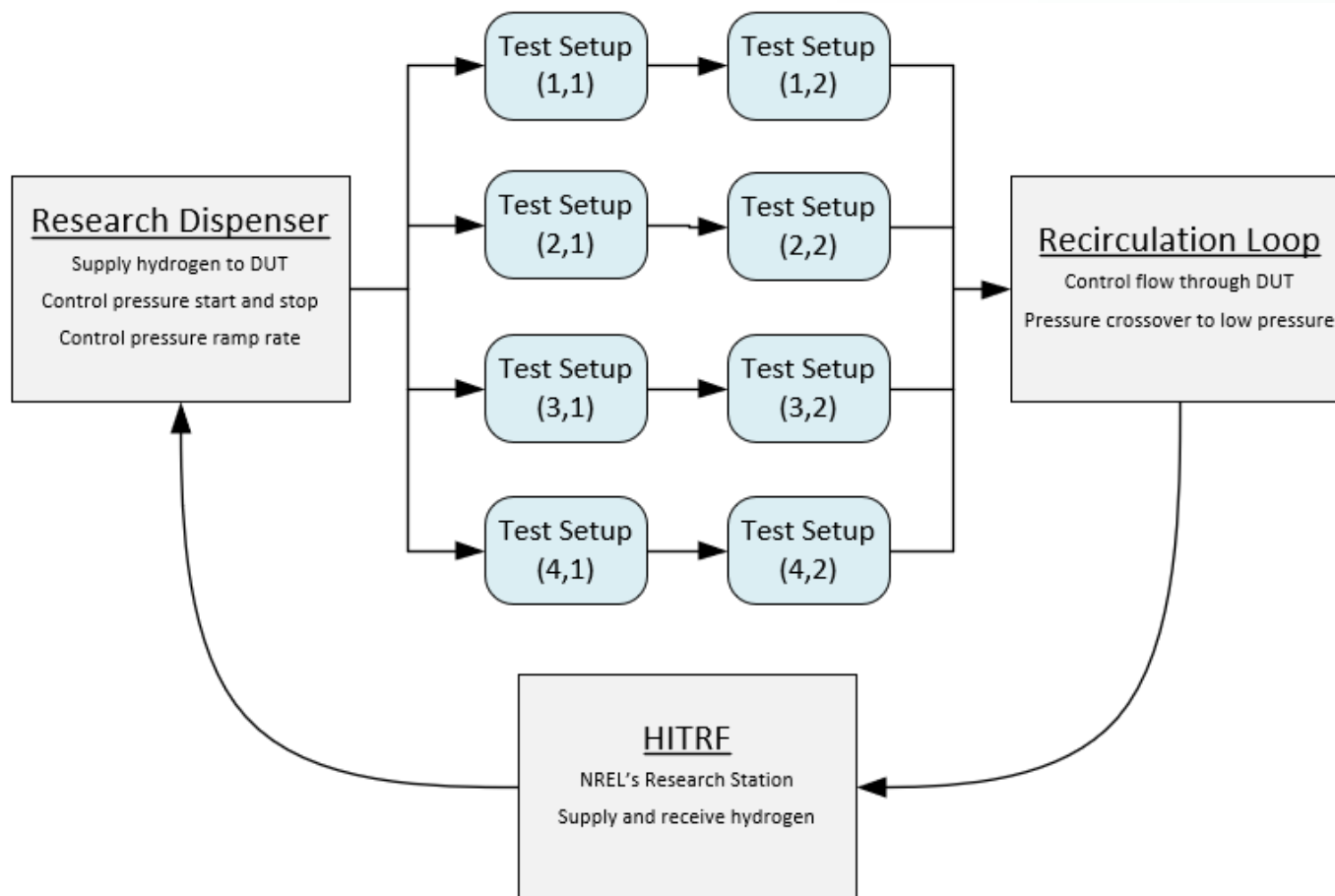
*Measure the mean fills between failures (MFBF) and mean kilograms between failures (MKBF) of hydrogen components subjected to pressures, ramp rates, and flow rates similar to light duty fuel cell electric vehicle fueling at -40°C and -20°C*

Devices Under Test (DUTs):

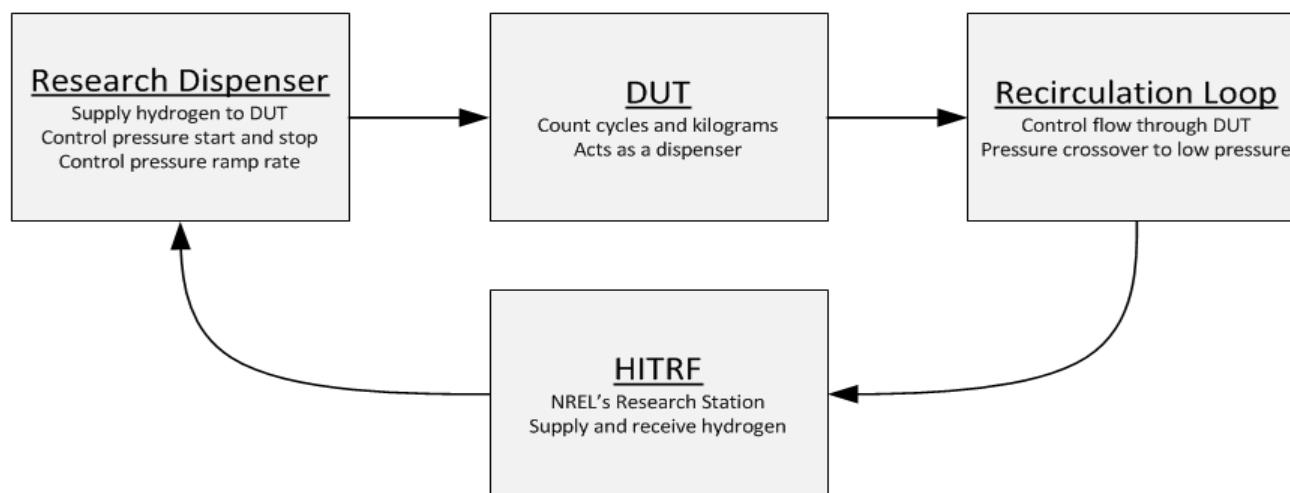
- Nozzles, breakaways, normally closed valve, normally open valve, filter



# Approach: Recirculation System

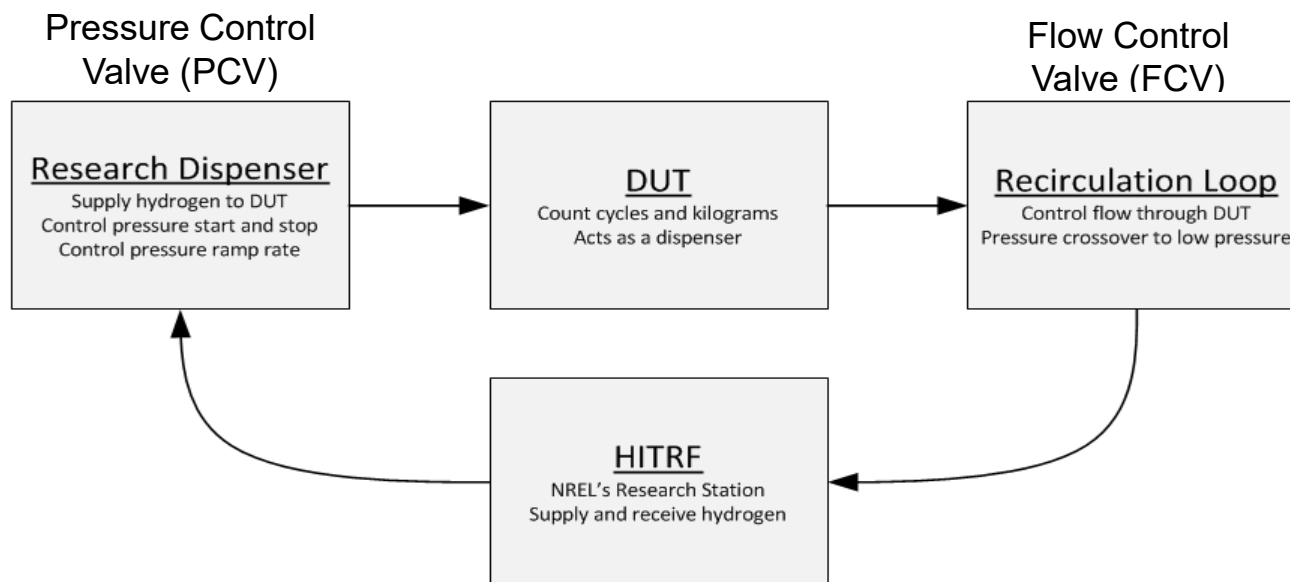


*How is a continuous hydrogen flow at a specific ramp rate achieved?*

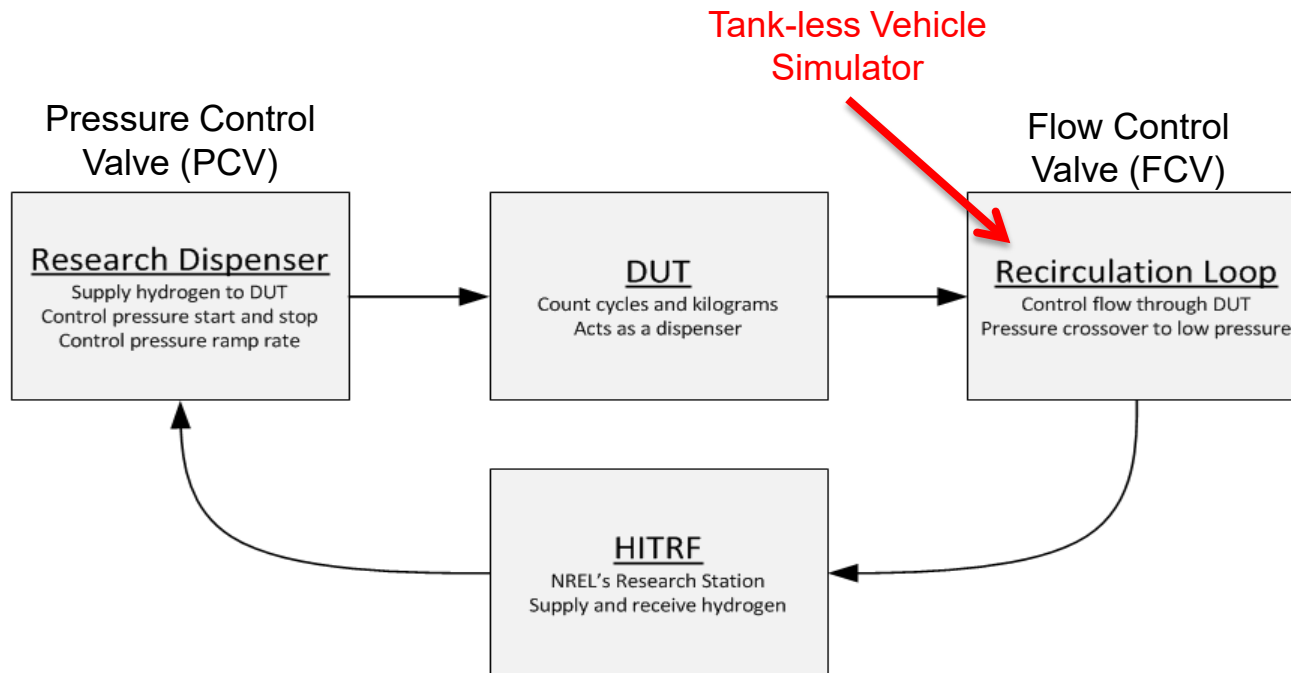




# Approach: Recirculation System



# Approach: Recirculation System



- Added capability at NREL's Hydrogen Infrastructure Testing and Research Facility (HITRF)
  - Addition high pressure hydrogen gas storage
    - 2 Tanks = 32 kg at 90 MPa
  - Increased distribution line size from high pressure storage to the Research Dispenser
    - 3/8" tubing changed to 9/16"
  - Chiller and heat exchanger shared capability
    - Upgrade to triple block heat exchanger, also required for Consolidation Testing
  - Build and install of the Research Dispenser and Recirculation Loop gas management panel and control cabinet
    - Forklift placement of the electrical and gas management panel enclosure on the pad
    - Electrical connections to control cabinets
- Upgrades needed to meet pressure ramp and flow rate requirements of the Dispenser Reliability Project

# Site Layout, Build of the Test Pad



Pre-Dispenser Reliability Test System

Operational Dispenser Reliability Test System



Accelerated Life Testing Apparatus

Research Dispenser/ Recirculation Loop

# Accomplishment: Test Campaign and Results Overview



**The accelerated test campaign was able to achieve an equivalent of over 16,000 light-duty vehicle fills**

- During the test campaign there were over 2,000 cycles on the accelerated life testing apparatus
  - Approximately a 50/50 split between T20 and T40 test conditions
  - 2,000 cycles x 8 dispenser systems active = 16,000 equivalent vehicle fills

<b>Test Overview</b>	<b>T20</b>	<b>T40</b>
Cycles per component	1063	1017
Kilograms throughput per component	983	1023
Number of leaks*	19	30
Number of component failures**	11***	20

\* Leak indicates that a component failed a leak check, or a leak was picked up on H2 detector

\*\* Component failure indicates that the component needs to be replaced, repaired, or retorqued

\*\*\* 3 of the 11 failures on T20 were from manufacturing debris in the NO AOV. If those are excluded, there would only be 8 failures and 16 leaks at T20 (see slide 15)

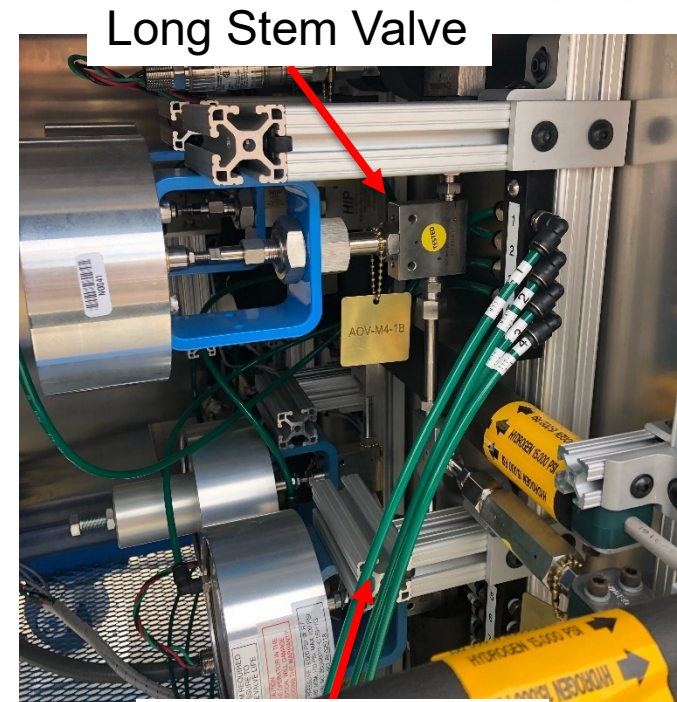
# Accomplishment: Test Campaign and Results

## Individual Components



### Valves

- Out of the 31 component failures, 26 of them (84%) were attributed to valves
- Campaign explored short stem design versus long stem design and found that the short stem valve was much more reliable
  - only 2 out of the 26 failures
  - Opposite from what the team original theorized would happen in the test campaign – other factors may be more important (next slide)



Short Stem Valve

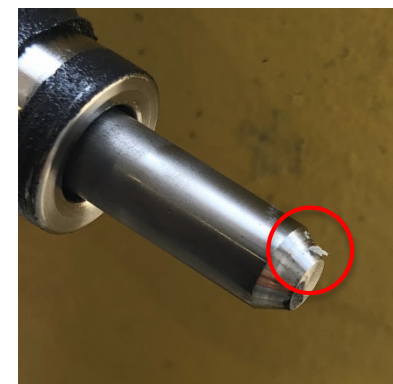
# Accomplishment: Test Campaign and Results

## Individual Components



### Valves

- ~2/3 of all the valves came in out of specification on their stem torque setting
- The long-stem valve manufacturer was found to have sub-par manufacturing and QA processes
  - Pictures show metal debris found inside the valve stem of one of the valves (before use)



# Accomplishment: Test Campaign and Results

## Individual Components



### Nozzles

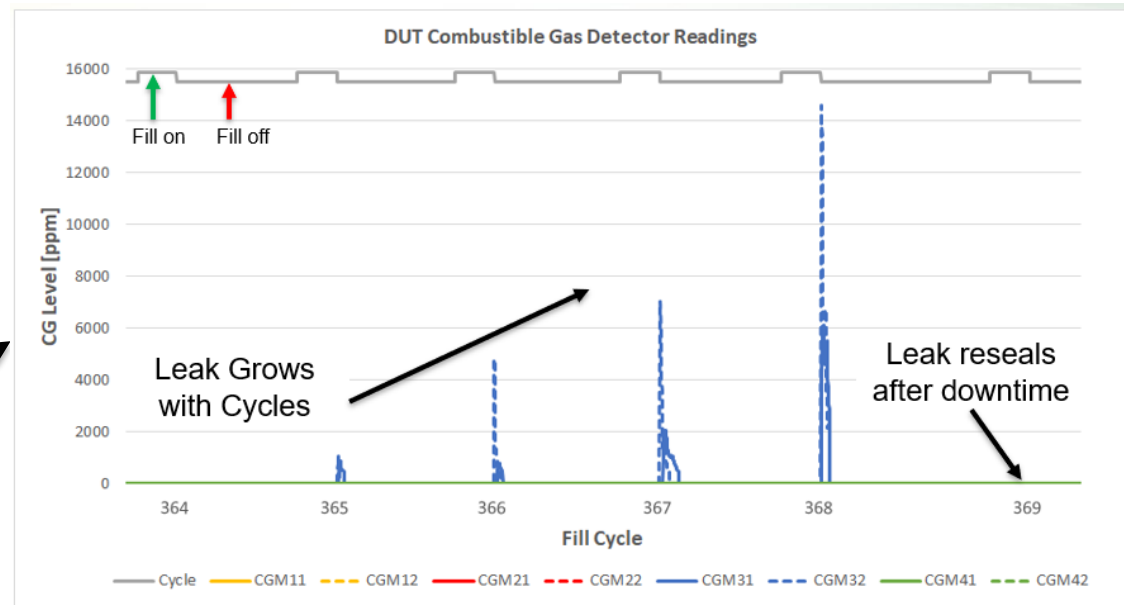
- The test campaign saw 2 nozzle failures: 1 failure at T20 and 1 failure at T40

### Breakaways

- There were 3 breakaway failures and all of them were in the T40 temperature range
- Breakaways were suspected to leak & reseal once the component warmed up

### Filters

- Not a single filter failed or leaked during the test campaign





# Accomplishment: Test Campaign and Results

## T20 versus T40



**The components that were tested at T40 experienced more leaks (30 versus 19) and more component failures (20 versus 11) than the components that were tested at T20.**

- Breakaways showed the biggest difference in performance between the two temperature levels with 3 failures in T40 and 0 failures at T20
  - Breakaways leaking and resealing was a common complaint from field interviews and the team experienced this quite a bit in the test program
- The team noted that nozzle freeze-lock occurs more at T40 than T20
- Some of the valve leaks and failures in both temperature categories can be attributed to poor manufacturing and QA processes

# Accomplishment: Test Campaign and Results

## T20 versus T40 – System Performance



Comparing T20 and T40 Test Conditions	Category	Average (all cycles)	Standard Deviation
Ambient Temperature [C]	T20	29.1	4.1
	T40	12.0	2.2
Ambient Relative Humidity [%]	T20	27.1	4.2
	T40	29.9	1.3
Fill Time [min]	T20	4.5	0.1
	T40	4.2	0.0
Mass Through per Fill [kg]	T20	0.9	0.1
	T40	1.0	0.1
Average Pressure Ramp Rate [MPa/min]	T20	17.6	1.3
	T40	19.1	1.2
Start Pressure [MPa]	T20	17.0	4.1
	T40	15.7	3.8
End Pressure [MPa]	T20	76.7	1.1
	T40	77.2	0.4

### Main Takeaways

- T20 testing had warmer ambient conditions
  - Fall vs. Winter Testing
- T20 and T40 had roughly equivalent test conditions in:
  - Relative humidity
  - Fill time
  - Mass through per fill
  - Start pressure
  - End pressure
- T40 had a slightly higher APPR

# Accomplishment: Test Campaign and Results

## T20 versus T40 – System Performance



Comparing T20 and T40 Test Conditions	Category	Average (all cycles)	Standard Deviation
Start of Fill Gas Temperature [C]	T20	2.8	2.5
	T40	-13.0	1.4
End of Fill Gas Temperature [C]	T20	-17.7	3.5
	T40	-34.8	2.5
Maximum Gas Temperature During Duration [C]	T20	2.6	2.6
	T40	-12.2	1.3
Minimum Gas Temperature During Duration [C]	T20	-20.2	3.1
	T40	-36.1	2.3
Average Gas Temperature During Duration [C]	T20	-15.2	3.5
	T40	-31.4	3.3
Average Gas Temperature After Thermal Shock [C]	T20	-16.9	3.4
	T40	-33.4	3.1
Average Gas Differential Temperature - Thermal Shock [C]	T20	12.8	7.9
	T40	13.0	8.6

### Main Takeaways

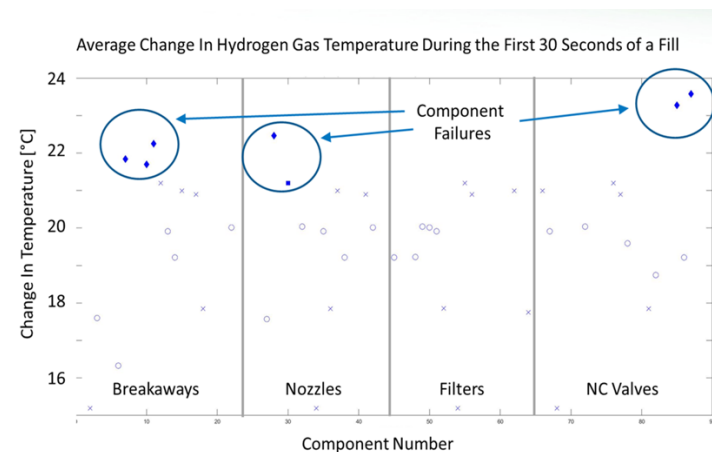
- T20 and T40 did not warm up to ambient temperature between fills
  - Back-to-back fills kept the system cool
- System performed well in terms of hitting target temperatures: end gas temp, average gas temp, etc. all in line with expectation
- **Average thermal shock between T20 and T40 was almost equal**

# Accomplishment: Test Campaign and Results

## T20 versus T40 – Thermal Shock



- Thermal shock was defined as the change in temperature over the first 30 seconds of the fill
- **The average thermal shock to the components for all the fills was 12.8°C for T20 and 13.0°C for T40**
- **Although the expectation is to see greater thermal shock at T40, due to the back-to-back nature of the testing and the seasonal conditions of when tests were run, T20 and T40 have similar outcomes**
- The data showed a relationship between component failures and thermal shock, however, more can be done in this space



*X's and diamonds are -40 deg C components, O's and squares are -20 deg C, Solid color components are failures*

### Literature Review: “Dispenser Reliability Q1 Milestone Report”

*Statistical analysis took advantage of a literature review in lieu of low sample sizes and non-extensive testing - some important quotes:*

- “During the hardware review, it was noted that component failures occur with much higher frequency when precooling below  $-20^{\circ}\text{C}$ . ...The failure rate of automatic valves also increases by more than an order of magnitude when using  $-40^{\circ}\text{C}$  precooling as opposed to  $-20^{\circ}\text{C}$  precooling, whereas the failure rate with  $-20^{\circ}\text{C}$  precooling is only slightly higher than with non-precooled hydrogen. A similar failure rate was observed with manual valves and check valves.”
- Nozzle: “The nozzles appear to be capable of functioning properly with  $-40^{\circ}\text{C}$  pre-cooled hydrogen, but durability may be reduced”
- Breakaway: “The 700 bar breakaways currently on the market have been tested with hydrogen pre-cooled to  $-40^{\circ}\text{C}$ . The original Walther design exhibited leakage issues that have since been resolved. The Weh design showed no issues with pre-cooled gas. The breakaway force was higher with “cold” breakaways, but the value was within the acceptable range.”

# Accomplishment: Statistical Analysis



## Assumptions

### Assumptions made based on literature review:

- We chose betas (failure modes) for all components that saw failures
- We would expect lifetimes to be extended for  $-20^{\circ}\text{C}$  over  $-40^{\circ}\text{C}$ 
  - Assumption matches material analysis from SNL on this project – IN013
- The relationship between beta and eta (the Weibull distribution parameters to parametrically approximate failures) is that mean-time-to-failure (MTTF) and eta (life characteristic) are related by a gamma function of beta
- We chose a random normal distribution ranging from  $1 \leq \beta \leq 2.5$  for  $-20^{\circ}\text{C}$ , since it appears that components exposed to colder conditions fail at a higher frequency and are less durable
- Therefore, components are likely expressing infant mortality which implies  $0.1 \leq \beta < 1$  would better fit for components at  $-40^{\circ}\text{C}$
- We choose to implement a random sample of 1000 from a normal distribution to choose prior beta parameters for each component by temperature, and by temperature and manufacturer
- Weibayes analysis then was used to approximate useful life thus, the following results are based on Weibayes analysis with the literature review assumptions

# Accomplishment: Statistical Analysis



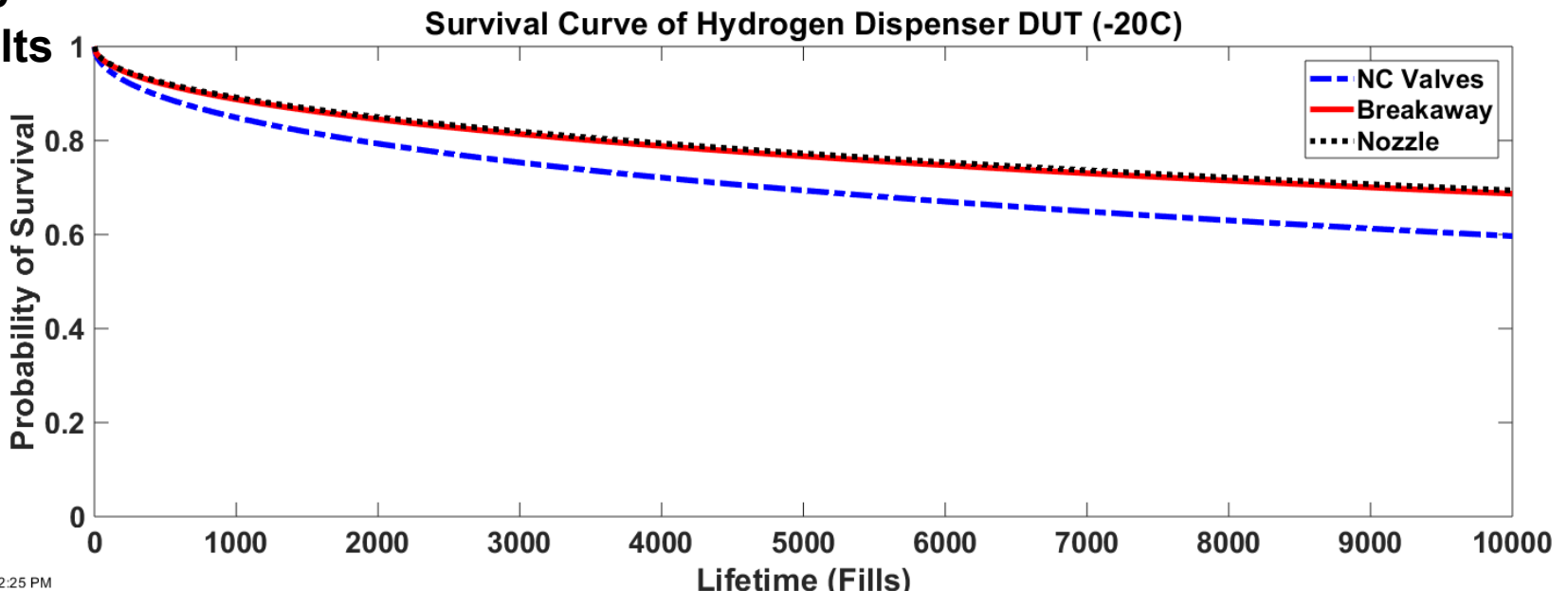
## T20 Results

Based on the test data and statistical analysis the T20 results showed:

- Some components failed early in the testing, however, very few components failed after the first few cycles
- T20 showed significantly better performance than T40
- More cycles are needed at T20 to better understand the shape of the T20 survival curve

### T20

### Results



# Accomplishment: Statistical Analysis

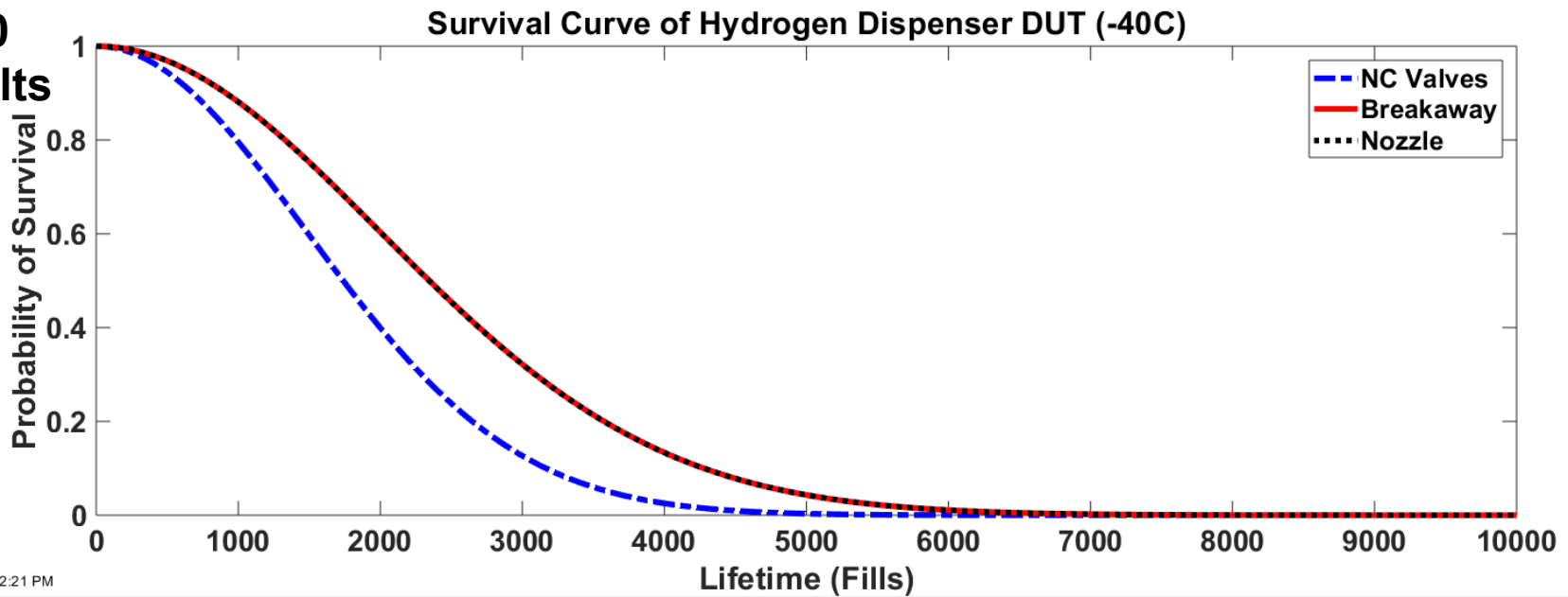


## T40 Results

Based on the test data and statistical analysis the T40 results showed:

- Most T40 components have about a 50% probability of survival at around 2,000 fills
- Stations won't see dispenser components last much longer than ~6,000 fills before needing to be repaired or replaced
- More cycles at T40 would be useful to refine results

### T40 Results





**Reviewer:** The quantity of data is low, mostly owing to the extended time that is required by the testing, rather than to any lack of effort on the team's part. Perhaps it would be possible to add additional test bays or to create duplicate test stands to increase the rate of data generation. This is probably outside of the project budget, but it is worth considering for future testing.

**Response:** The team agrees with this comment. It is difficult to create test campaigns that cover a range of components, conditions, and cycles within a reasonable budget and timeframe. Simulating 8 dispensers at once pushed our hydrogen infrastructure to its maximum capacity but there were a lot of lessons learned in the process. Additional test bays, different manufacturers, more cycles, etc. are all part of what the team wants to pursue in future work.

**Reviewer:** Although there seems to be good collaboration with certain manufacturers, there should be an opportunity to bring more component manufacturers into the mix as the industry grows. There may be an opportunity to bring third-party testing organizations into the project to help develop certification standards for critical components.

**Response:** Managing multiple manufacturer relationships can be an expensive and time-consuming pursuit. The team has a close collaboration with the breakaway/nozzle manufactures because there are only a handful of them in the world and those are specialized components dedicated to hydrogen systems. When we start diving into valves and fittings the number of manufacturers increases significantly which is why we choose to compare technologies (short stem vs. long stem) instead of manufacturers in the valve space. We are always open to collaborations with third-party testing organizations.

## Component Manufacturers

- Team maintained an open communication with the breakaway/nozzle manufacturers as results became available
- NREL and SNL secured NDAs with both manufacturers and allowed them to review failure results + material analysis



# Technology Transfer

## Summary of Main Project Takeaways



- Proper material selection can lead to higher reliability at stations
  - See SNL AMR presentation as part of this project – DOE AMR 2020 #IN013
- Poor manufacturing processes and QA at the plant cause significant issues at stations
  - Station operators could benefit from taking time to inspect and check components before putting them in operation
- Material damage in components is physical
  - Design of fixture is important (i.e., o-ring to metal interface) -> especially with thermal shock aspect
  - Build process and cleaning of debris at station can help keep metal fragments from flowing through the system

# Technology Transfer

## Summary of Main Project Takeaways



- T20 and T40 components were tested with over 1,000 equivalents light-duty fills each
- T20 fills experienced 11 failures and 19 leaks
- T40 fills experienced 20 failures and 30 leaks
- **The statistical analysis showed that T20 components were significantly more reliable than the same components exposed to T40 conditions**

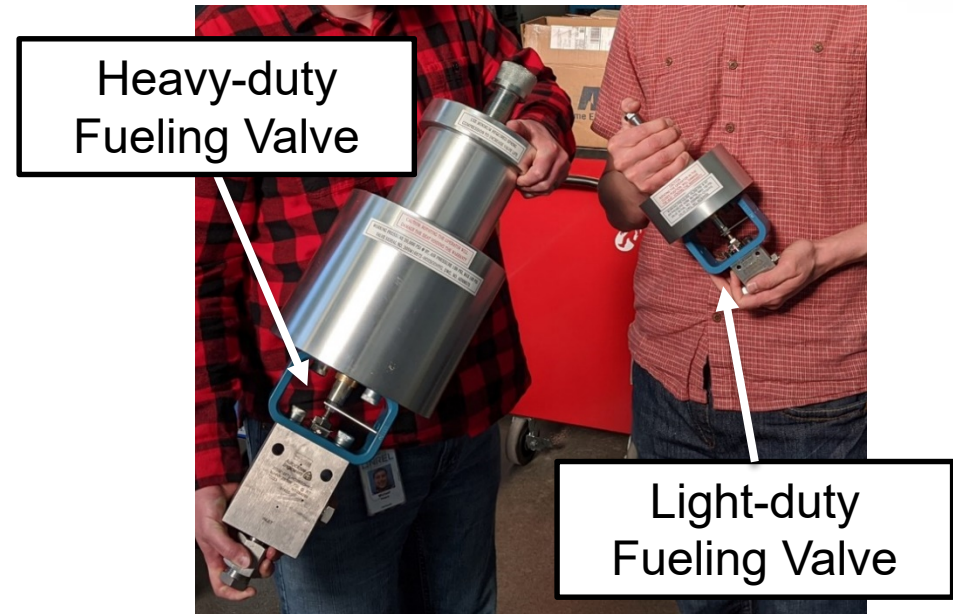
## Closeout this Test Campaign

- Publish the final report and findings alongside SNL

## Move Towards the Future

*Consider additional testing with:*

- Heavy-duty components
- New designs
- To obtain more cycles
- Leverage different materials



*Any proposed future work is subject to change based on funding levels.*

Michael Peters – NREL – [Michael.Peters@NREL.gov](mailto:Michael.Peters@NREL.gov)

Nalini Menon – SNL – [ncmenon@sandia.gov](mailto:ncmenon@sandia.gov)

**THANK YOU**

# TECHNICAL BACKUP SLIDES

## Weibayes Analysis:

- Uses failure data and past failure data or experience to make predictions
- Weibayes is a Weibull Bayesian analysis, thus, there is a prior and a posterure distributions
- The prior distribution comes from, in this case, Type B data (or expert/field observation data)
- Bayesian inference is performed with the prior distribution and produces a new posterior distribution with updated parameters based on the Type B data
- Since our testing was not as extensive as we had hoped and the material analysis was inconclusive for measurable degradation, we relied on the literature review to yield better results



## Weibayes Analysis Assumptions:

- Assumptions are based on the literature review
- Experts heavily implied that components exposed to temperatures below -20C failed prematurely
- Premature failures, or infant mortality, have a failure mode (beta parameter) between 0 and less than 1
  - For T40, a random infant mortality rate was chosen from a randomly generated normal distribution
  - The mean of the sample was chosen to act as an estimated prior beta to be used in the analysis
- Experts also implied that components not exposed to more extreme temperatures were more durable
- The failure mode categorized as “early wear out” was chosen to fit the expert’s notes
  - For T20, a random failure mode was chosen from a random normal sample ranging from 1 to 2.5 (where a 2 would represent a Rayleigh distribution and maximize the life characteristic)
  - The mean of the sample was chosen to act as an estimate prior beta for T20