Reliability in scaling of flow batteries

Detlef Jannes, Ming-Jyh Chern
Department of mechanical engineering, NTUST, Taipei, Taiwan

IOYOI
CONSULTING

TAIWAN
TECH
NATIONAL TAIWAN UNIVERSITY OF
SCIENCE AND TECHNOLOGY

Flow battery celebrations

1975 -The first Redox Flow Battery (RFB) - Iron-Chromium

1986 - First patented Vanadium RFB - Maria Skyllas-Kazacos

2016 - my first steps into flow batteries

Question

What mechanical reliability risks emerge when redox flow batteries scale from laboratory systems to commercial installations?

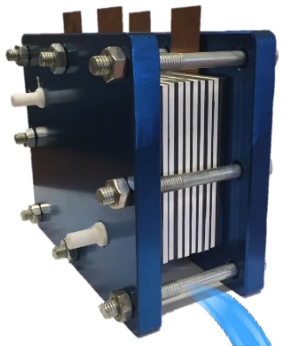
Investigation of various Flow Battery

17 operational systems were monitored in 2021-2025

9 Small systems (S) represents lab prototypes (<100 W)

5 Large systems (L) represents pilot projects (100 W – 100kW)

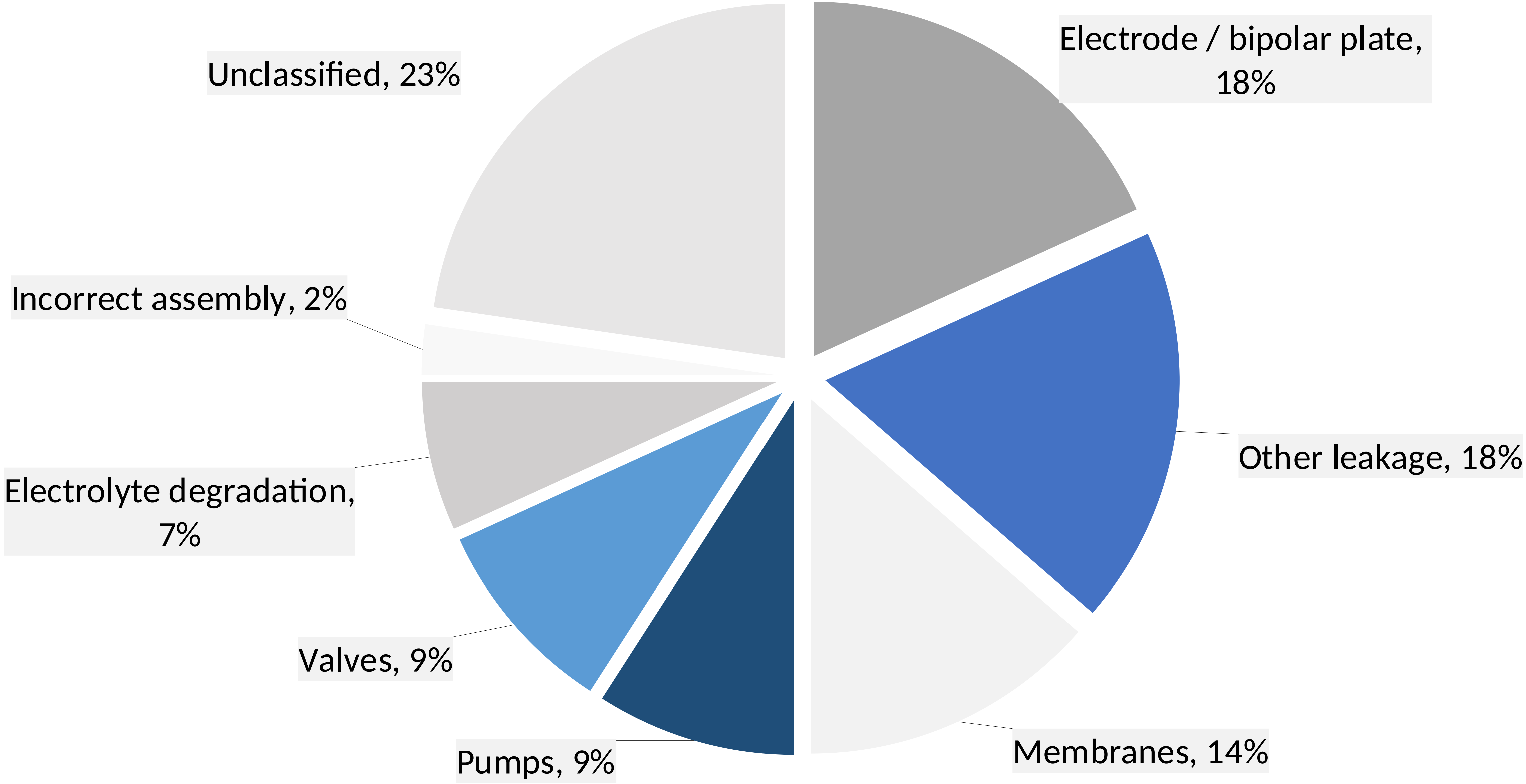
3 Extra Large systems (XL) are commercial systems (>100kW)



Scale-based failure results

Measure	S	L	XL
Failures	22	15	7
Share of total failures	50,0%	34,1%	15,9%
Failures per system	3	7	2.33
95% Poisson CI	1.53–3.70	1.68–4.95	0.94–4.81

OVERALL FAILURE-CATEGORY DISTRIBUTION %



Mechanical sealing related issues account for +35%

Failure Mode	Small (S)	Large (L)	Extra Large (XL)
Pumps	1	3	0
Membranes	5	1	0
Electrode/BPP	2	4	2
Valves	2	1	1
Leakage	5	2	1
Electrolyte	1	1	1
Assembly	1	0	0

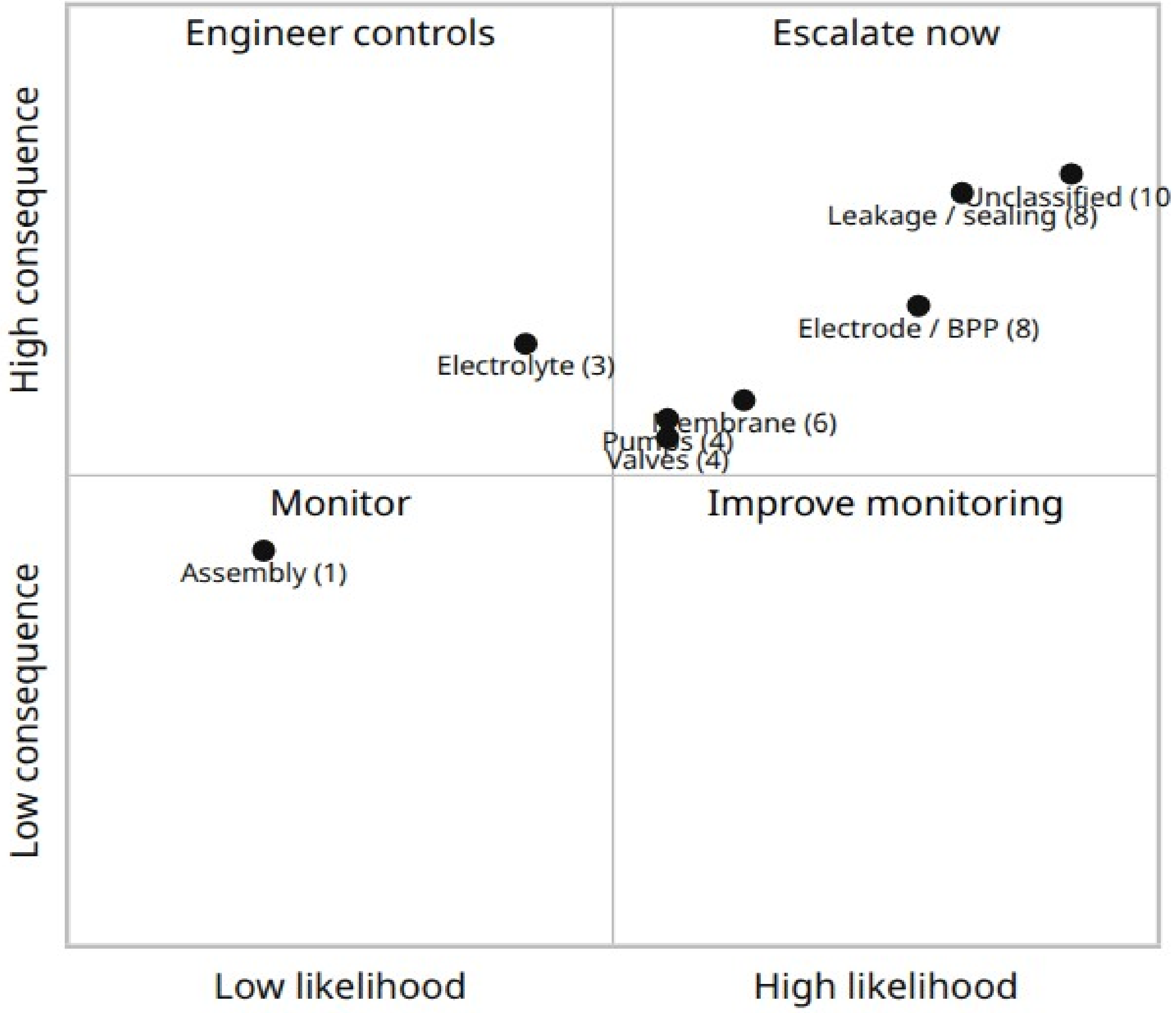
Sealing failure analysis per system

Failure Mode	S - Lab Scale	L - Pilot Scale	XL - Commercial Scale
Tolerance Stacking	High (manual builds, no formal QA)	Medium (some CNC parts; inconsistent stack tolerances)	Low (tight tolerance control; verified by metrology)
Flange Surface Roughness	Often unpolished polymer; surface waviness common	Improved via CNC or basic casting; moderate roughness	Surface finish optimized; often ground or coated
CSR & Compression Loss	Low preload, significant early compression loss	Relaxation seen over weeks/months; design still evolving	Actively monitored via pressure/load sensors; pre-load modelling used
Elastomer Swelling	Often detected visually; test data from swelling models	Can vary with electrolyte concentration; swelling tests done occasionally	Documented cause of flange failures in some XL stacks
Startup Blow-by	Frequent in first cycles; uneven pressure leads to bypass	Managed with controlled pressurization and venting	Avoided through pre-conditioning and controlled ramp-up
Transient Thermal Effects	Rarely accounted for; negligible heating in most cases	Occasional failure in open racks or poor thermal design	Critical: Outdoor systems require modelling & temperature stress analysis
Human Error	High (lack of assembly guidance or torque specs)	Medium; partial SOP use, but no formal RAMS discipline	Low (automated procedures, operator training, digital QA)
Component Quality Variability	Prototype components; limited supplier traceability	Procurement improving; mix of qualified and unqualified suppliers	Vendor-certified components with full QA traceability

Example of risk management

Observed failure	Frequency signal	Main consequence	Relevant standard	Proposed control
Leakage / sealing	High	Electrolyte release, downtime, corrosion	IEC 62932-2-2, IEC 62933-5-1, IEC 62933-4-2	leak detection, secondary containment, pressure monitoring, torque QA
Pump / valve failures	Medium	Loss of flow, imbalance, overheating	IEC 62933-5-1, IEC 60812	FMEA, redundancy review, predictive monitoring
Membrane failure	Medium	crossover, capacity loss, contamination	IEC 62932-2-1, IEC 62933-3-1	performance monitoring, acceptance tests
Electrode/BPP failure	High	resistance increase, cracking, flow maldistribution	IEC 62933-3-1, IEC 60812	design review, compression control, FAT
Electrolyte degradation	Low-medium	performance loss, chemical hazard	IEC 62933-4-2	electrolyte quality monitoring, sampling plan
Incorrect assembly	Low count but high preventability	early failure	IEC 60812, IEC 62933-5-1	QA checklist, torque record, assembly validation

SEMI-QUANTITATIVE PRIORITIZATION GRAPHIC



Better quantitative risk management with: Weibull Cumulative Failure Distribution (CDF)

$$F(t) = 1 - \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right]$$

F(t)= cumulative probability of failure
t= time
η= characteristic life (scale parameter)
β= shape parameter

Interpretation of β:
$\beta < 1$: Infant mortality/early failures
$\beta = 1$: Random failures (equivalent to exponential distribution)
$\beta > 1$: Wear-out failures

We need more data to determine system's:
Mean Time To Failure (MTTF)
Hazard rate (failure rate)

Expecting distribution values…

Scale	β [/]	η [hours]	MTTF [hours]
S	0,8 - 1,0	2000	2250
L	1,4 - 1,8	9000	7700
XL	2,1 -5,0	22000	19500

Scale		η [hours]	MTTF [hours]
S	0,8 - 1,0	2000	2250
L	1,4 - 1,8	9000	7700
XL	2,1 -5,0	22000	19500

…Satisfying for improvement tactics

Interpretation of β:

$\beta < 1$: Infant mortality/early failures

$\beta = 1$: Random failures (equivalent to exponential distribution)

$\beta > 1$: Wear – out failures

TAIWAN TECH
NATIONAL TAIWAN UNIVERSITY OF SCIENCE AND TECHNOLOGY

Detlef Jannes

LinkedIn

IOYOI
CONSULTING