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A NEW METHOD TO QUANTIFY THE LEAKAGE SCENARIOS (FREQUENCIES AND FLOWRATES) ON HYDROGEN HIGH PRESSURE COMPONENTS

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ICHS2023-Quebec City_september 19-21

Hydrogen in the public domain ?

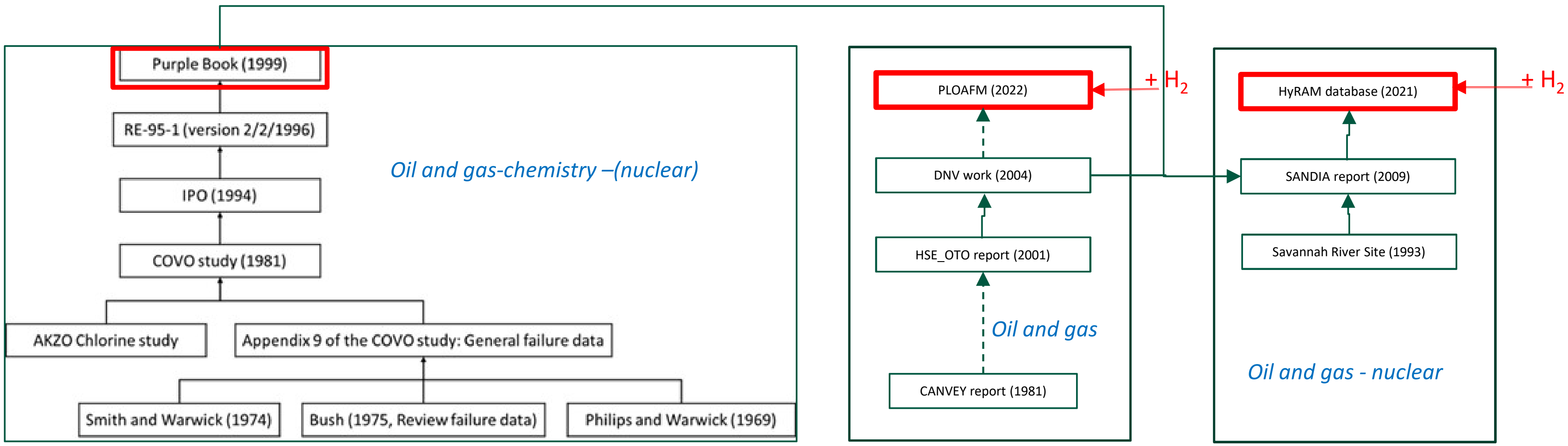
https://www.aria.developpement-durable.gouv.fr/accident/53772/

MultHyfuel targets :

- Evaluate the risk for the public
- Produce **missing data**
- Evaluate safety barriers peformances
- Best practise guidance (stake holders)

https://multhyfuel.eu/

Leakage databases (F&Q) : genealogy



Pasman, H.J., J. of Loss Prevention in the Process Industries, 24, 2011, 208–213
Spouge, J., Process Safety Progress, 25, 2004, 249-257
Lachance, J. et al., Sandia Report, SAND2009-0874 , 2009

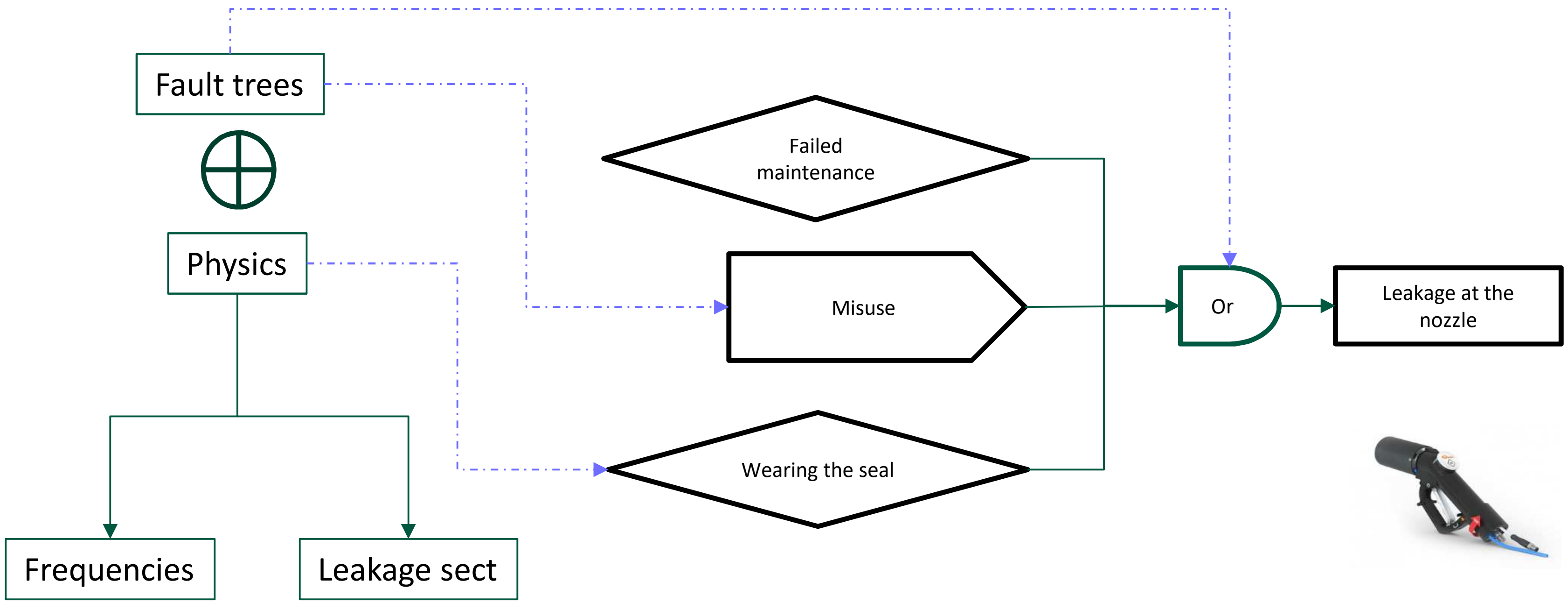
Leakage databases (F&Q) : practice

Multhyfuel – deliverable 3.4

Config.	CFE	Pressure	DATABASE (leak/year) BEVI (purple book)	Sandia (HyRAM)	Norskeolje&gas PLOAFM	PhD
1	Loss of H2 containment (medium leak 10%) on hose	350 bar	10^{-3}	10^{-4}	10^{-5}	(U)VCE Flashfire Jet fire
2			10^{-3}	10^{-4}	10^{-5}	
3			10^{-3}	10^{-3}	10^{-4}	
1		700 bar	10^{-3}	10^{-4}	10^{-5}	
2			10^{-3}	10^{-4}	10^{-4}	
3			10^{-3}	10^{-3}	10^{-4}	
1		1000 bar	10^{-3}	10^{-4}	10^{-4}	
2			10^{-3}	10^{-4}	10^{-4}	
3			10^{-3}	10^{-3}	10^{-4}	
1	Full bore rupture (1'' = 2.54 mm) on hose	350 bar	10^{-3}	10^{-4}	10^{-5}	
2			10^{-3}	10^{-4}	10^{-5}	
3			10^{-3}	10^{-3}	10^{-4}	
1		700 bar	10^{-3}	10^{-4}	10^{-4}	
2			10^{-3}	10^{-4}	10^{-5}	
3			10^{-3}	10^{-3}	10^{-5}	
1		1000 bar	10^{-3}	10^{-4}	10^{-5}	
2			10^{-3}	10^{-4}	10^{-5}	
3			10^{-3}	10^{-3}	10^{-5}	

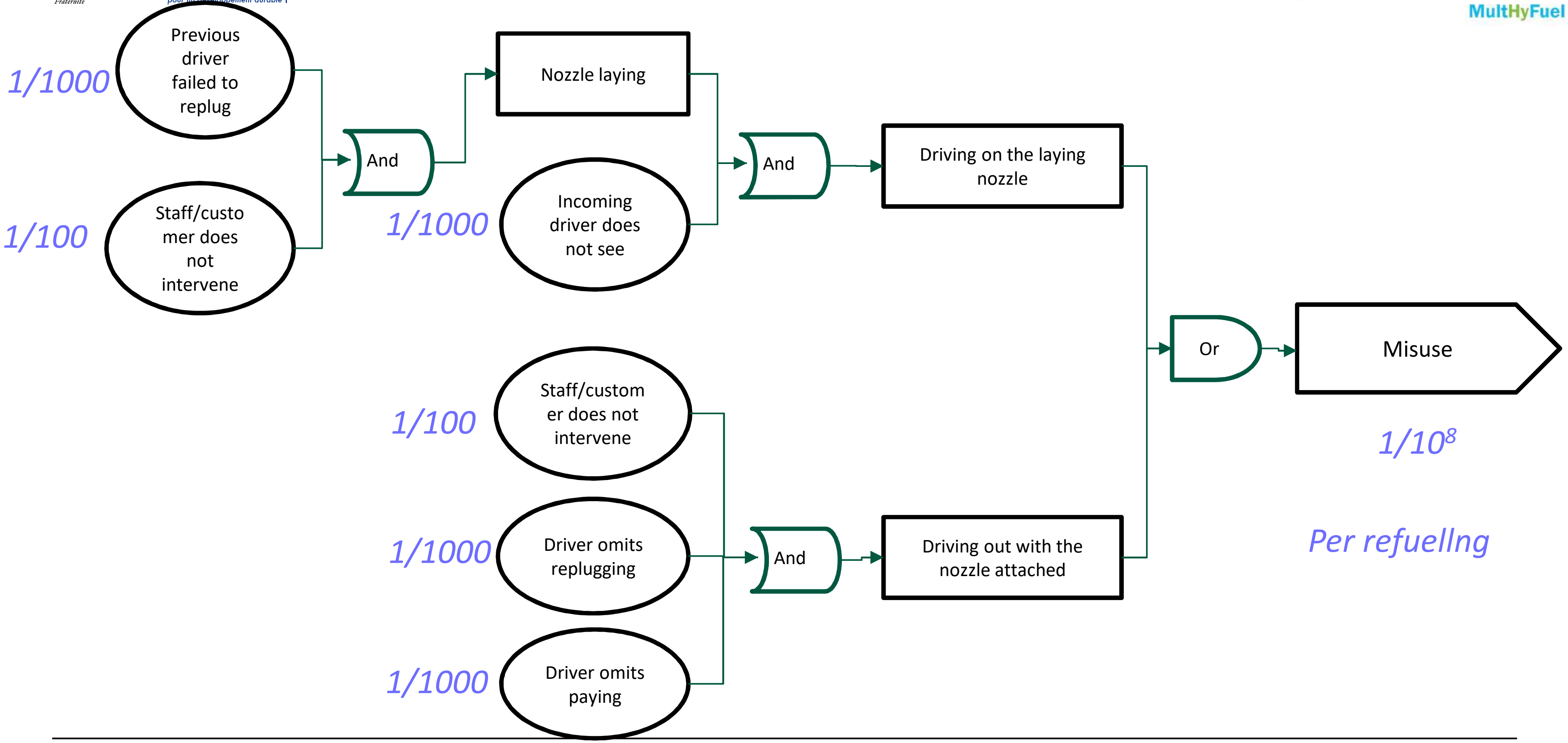
?

A tentative « new » approach



A. Duclos, Développement de modèles phénoménologiques et de maitrise des risques d'explosion pour la filière émergente hydrogène-énergie, Thèse de doctorat de l'Université de Technologie de Compiègne, soutenue le 29 octobre 2019

J.R. Taylor, Hazardous Materials Release and Accident Frequencies for Process Plant, Volume II Process Unit Release Frequencies, Taylor Associates APS, 2006



1/1000
Previous driver failed to replug
1/100
Staff/customer does not intervene
And
Nozzle laying
1/1000
Incoming driver does not see
And
Driving on the laying nozzle
1/100
Staff/customer does not intervene
1/1000
Driver omits replugging
1/1000
Driver omits paying
And
Driving out with the nozzle attached
Or
Misuse
1/10^8
Per refuellng

Physical modeling => wear :

- Moving part like valve stems and the closing part of a check valve (in the breakaway and in the nozzle) are concerned. Steel dry rubbing over steel is assumed.
- The steel/steel wear rate is between 10^8 and 10^9 $\mu m^3/(km.N)$. In km the length of the sliding zone and in N the normal force.
- The steel/polymer wear rate is between 10^9 and 10^{10} $\mu m^3/(km.N)$
- It is assumed that the tightness is lost after having abraded 10% of the thickness of the sealing piece

Component name	nozzle
comment	abrasion of the O ring
diameter of the O ring (m)	0,012
thickness (m)	0,002
sliding ditance at each cycle (m)	0,01
wearing rate (micro m^3/kmN)	10000000000
sliding force (N) assumed 10 kgf max	100
reduction of thickness at each cycle (mm)	2,65258E-10
leaking criterion abrasion of x% thickness	10
number of cycles before leakage	**753982,2369**
Maximum feeding diameter (m)	0,004
outer leakage diameter m	0,0102
inner leakage diameter m	0,01
leakage path length m	0,02
Hydraulic diameter m	0,0002
Physical leakage cross section m2	3,17301E-06
Area reduction due to head losses	0,377964473
% of feeding area	**9**

Application 1st STEP : equipement and use

Mounting mishaps

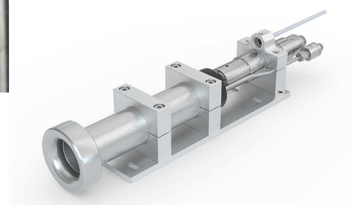
Fatigue

Misuse

Wear

Corrosion

Untightening



Application 2nd STEP calculating

Components
- 1000 b Nozzle ID4mm (3/8'')

Solicitations
- Deficient mounting procedure
- Misuse
- Wear (seals, seats)

For one manipulation

Component name	nozzle
comment	leakage through sealing system
nber of critical operations to assemble the component	10
nber of assembly/disassembly of the component/year	1
nber of such component in the dispenser	1
Leakage frequency nber/year	**0,01**
Maximum feeding diameter (m)	0,004
outer leakage diameter m	0,0102
inner leakage diameter m	0,01
leakage path length m	0,02
Hydraulic diameter m	0,0002
Physical leakage cross section m2	3,17301E-06
Area reduction due to head losses	0,377964473
% of feeding area	**9**

- Conclusions :
  - Deficient mounting :
    - Failed maintenance procedure of the nozzle (fault tree : 10^{-2}/proc)
    - Bad plugging by the user (damaged or dirty receptacle : not properly maintained) => as above
    - 9% of full bore cross section
  - Wear :
    - Failure of the compression seal after 10^5 cycles or refuelling ($N_{end\text{-}cycles}$)
    - Note : abrasion of the seal of the vehicle after 7 10^5 cycles whereas only about 10^3 refuelling during vehicle lifetime
    - 9% of full bore cross section
  - Misuse : tearing off the nozzle:
    - slide 8 : 10^{-8}/refuelling
    - Full bore rupturing (ID 4 mm)
- Comments :
  - Breakaway assumed not functional
  - Fatigue of the clamping system ?

Component name	nozzle
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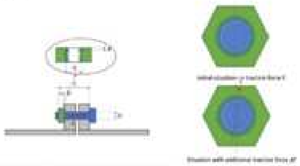
Verification & Validation



Appendix 2 : Loosening by cyclic loading of screwed items

To illustrate the method, the situation addressed is that of flat flanges assembled and tightened by screws as shown below.

Usually, screws are stressed up to 80% of their yield limit (600 MPa for 316L stainless steel). There are several ways to describe loosening. A rather "natural" one is to consider that loosening occurs when the energy stored in tightening the pieces has been dissipated by the frictional movement along the threads. But since both energies are proportional to the forces (tightening force and sliding force respectively) times the products of the nominal diameter and of the angles (tightening angle and sliding angle respectively), it is simpler and equivalent to consider the cinematics: untightening would occur once the tightening angle would have been absorbed but the sum of the small deformation angles produced by the cycles.

Loosening occurs when the surfaces in contact start moving relative to each other. The movement may occur whenever the additional force overcomes the frictional forces or when submitted to the same additional stress the subsequent deformations of the two contact surfaces are different. The first mechanism would require an additional force on the same order of magnitude than the tightening force which is not, by far, the situations under investigation. The second mechanism is modelled below.

A simplified approach is proposed below.

Tightening angle

If σ is the stress applied on the screw at the end of the tightening, L_m, the length of the threaded zone engaged in the nut and p the thread size, then the variation of L_m, ΔL_m is given by the Hooke's law (E is the Young modulus) :

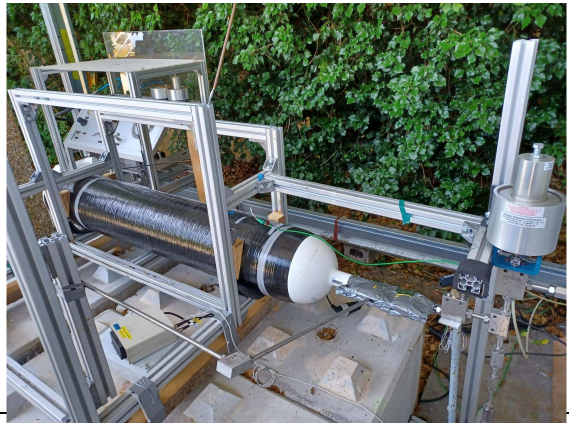
$$\sigma = E \cdot \frac{\Delta L_m}{L_m} = E \cdot \frac{n \cdot p}{L_m} \quad \text{(A2-1)}$$

Where n is the fraction of thread engaged in the nut to produce ΔL_m. In one turn (2. Π Rad) a screw progresses a distance p. So the crewing angle corresponding to n is β=2.π.n. thus :

$$\beta = 2 \cdot \pi \cdot \frac{\sigma L_m}{E p} = E \cdot \frac{n p}{L_m} \quad \text{(A2-2)}$$

Loosening due to axial loading [31, 32]

Let G_i be the shear modulus of the screw and nut materials (i=1 or 2), D the nominal diameter of the screw/nut system, ΔF the additional force due to the variations of the pressure/temperature, α_i the average angles of deformation in material i and M the momentum of friction. Then the equilibrium of forces (torsion) reads :



VALIDATION : frequencies

Component name	flow valve 3/8 -KIWA stem
comment	blockage of the stem in the screw
inner diameter of the screws (m)	0,005
thickness of the thread (cross section m)	0,0005
sliding distance at each cycle (m)	0,157079633
sliding force (N)	137,4446786
wearing rate (micro m^3/kmN)	1000000000
abraded thickness at each cycle	1,37445E-09
blockage criterion by accumulation in % Din (0,0002 mm)	4
number of cycles before blockage	**14551,30908**

Component name	ckeck valve 3/8
comment	internal leakage
inner diameter of the seal (m)	0,005
thickness of the seal (m)	0,001
sliding distance at each cycle (m)	0,001
sliding force (N) assumed 10 kgf	1374,446786
wearing rate (micro m^3/kmN)	10000000000
abraded thickness at each cycle	8,75E-10
leackage criterion by decreasing in % Din	10
number of cycles before blockage	**114285,7143**

situation	size	failure (cycles)
manual valve rotation 0-360°	3/8''	10 000 - 60 000
check valve cycling 0->70b	3/8''	order 100 000
hose pressure cycling 0->70b	3/8''	75 000
fittings pressure cycling 0->70b	9/16''	above 250 000

Component	POM hose
3 mm POM thick (75 Mpa) + 0.5 mm steel wires (800 MPa)	
Temperature amplitude (int/ext)	0
mean working pressure (Mpa)	70
Thermal dilatation coef (1/°C)	0,00008
Poisson coefficient	0,35
Young modulus (MPa axial)	3000
Radial Ultimate strength (MPa axial 100 MPa)	192,481203
Radial yield stress (MPa axial 100 MPa)	141,3533835
Pipe outer diameter (m)	0,013
Pipe inner diameter (m) -feeding	0,006
length (m)	1
min bend (m)	0,18
Sollicitation mode	***radial stress***
Maximum internal temp gradient (°C)	0
Maximum stress due to temperature cycles (M	0
Maximum stress due to pressure cycles (Mpa)	95
number of cycles to rupture	**111418,1718**

Component	fitting 9/16
Pressure amplitude (Mpa)	70
Temperature amplitude	0
nber of identical fittings	1
nber of Pcycles/y	1
unscrewing by axial loading	
Friction coefficient x dissipation factor	0,001
Thermal dilatation coef (1/°C)	0,000017
Poisson coefficient	0,3
Young modulus (Mpa)	200000
Yield stress (Mpa)	600
screw core diameter (m)	0,022
inner diameter of the screw (m)	0,014
thread size (m)	0,001
screwing force (% of yield)	80
length of the stressed zone	0,011
Tightening stress (Mpa)	480
Tightening angle (rad)	0,165876092
extra stress due to pressure cycle (Mpa)	14,7875
maximum internal temperature difference °C	0
extra stress due to temperature cycle (Mpa)	0
Sliding angle due to extra stress by overpressure	3,84475E-07
nber of pressure cycles to unscrewing	**431435,3134**

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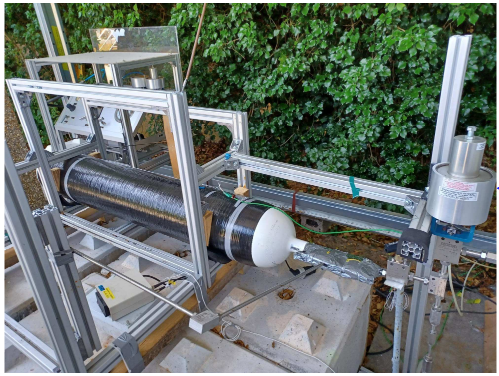
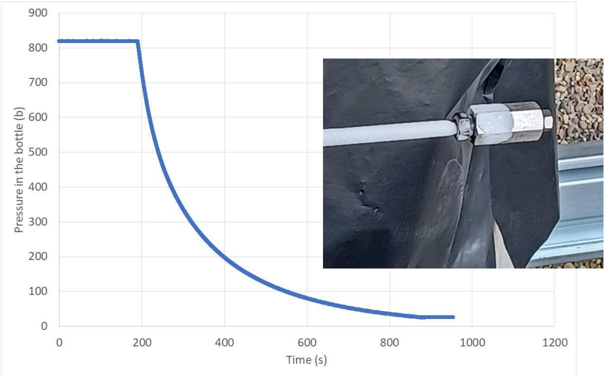
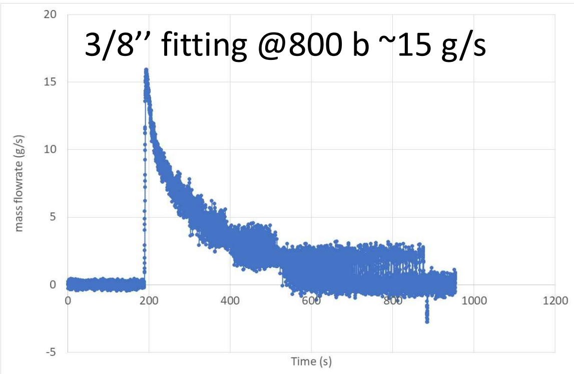
Validation : leak cross section



Validation : leak cross section





P (b)	component	event	mass flowrate (g/s)	meas % full cross section	Predicted %
800	full bore 0.5 mm	reference	10	100	
800	full bore 2 mm	reference	160	100	
800	full bore 2.6 mm (1/4'')	estimated	270	100	
800	full bore 5 mm (3/8'')	estimated	1000	100	
800	full bore 7.8 mm (9/16"")	estimated	2434	100	
800	Maximator U fitting 9/16''	Unscrewing/bad mounting	30-50	1,6	**5**
800	Maximator U fitting 3/8''	Unscrewing/bad mounting	15-30	2,0	**8**
800	Maximator U fitting 1/4''	Unscrewing/bad mounting	10	3,7	**19**
800	Maximator valve 9/16''	Bad mounting	1-3	0	**4**
800	Maximator valve 3/8''	Bad mounting	20-30	3	**9**
800	Maximator valve 1/4''	Bad mounting	10-12	4	**24**

Note :

1. *Elastomer seals can compensate for a loss of volume of more than 20%*
2. *Overestimation of the leak cross section possibly due to an underestimation of the head losses*

Conclusions

- No « medium » leaks…
- Full bore from databases 10^{-5} to 10^{-3}/y)

Equipement	sollicitation	nbre/cycle or year to failure	%fullbore	nber/components	nber/cycle/year	unit failure rate /year	failure rate /year
pipe 9/16 (ID=7.8 mm)	Fatigue due to P and T cycling (elongation mode)	2E+11	100	10	10000	0,00000005	5,00E-07
pipe 9/16 (ID=7.8 mm)	Corrosion	5000	100	1	1	0,0002	2,00E-04
pipe 3/8 (ID=5 mm)	Fatigue due to P and T cycling (elongation mode)	3000000000	100	10	10000	3,33333E-06	3,33E-05
pipe 3/8 (ID=5 mm)	Corrosion	3000	100	1	1	0,000333333	3,33E-04
Hose (3/8)	Fatigue due to P and T cycling (radial mode)	100000	100	1	10000	0,1	1,00E-01
Hose (3/8)	Misuse (tearing off, driving on)	100000000	100	1	10000	0,0001	1,00E-04
Nozzle (3/8)	Deficient mounting (plugging, maintenance)	100	9	1	10000	100	1,00E+02
Nozzle (3/8)	Wear (seals)	100000	9	1	10000	0,1	1,00E-01
Nozzle (3/8)	Misuse (tearing off, driving on)	100000000	100	1	10000	0,0001	1,00E-04
Breakaway (3/8)	Fatigue due to P and T cycling (elongation mode)	10000000	9	1	10000	0,001	1,00E-03
Breakaway (3/8)	Deficient mounting (plugging, maintenance)	100	9	1	1	0,01	1,00E-02
Flow valves (9/16)	Deficient mounting (maintenance)	100	4	5	1	0,01	5,00E-02
Flow valves (9/16)	Wear (seals)	20000000	2	5	10000	0,0005	2,50E-03
Flow valves (1/4)	Deficient mounting (maintenance)	100	24	1	1	0,01	1,00E-02
Flow valves (1/4)	Wear (seals)	20000000	15	1	10000	0,0005	5,00E-04
Pressure control valve (9/16)	Deficient mounting (maintenance)	100	1	1	1	0,01	1,00E-02
Pressure control valve (9/16)	Wear (seals)	1000000000	1	1	10000	0,00001	1,00E-05
Pressure safety valve (3/8)	Deficient mounting (maintenance)	100	1	1	1	0,01	1,00E-02
9/16'' union couplings	Deficient mounting (maintenance)	100	5	20	1	0,01	2,00E-01
9/16'' union couplings	Untightening due to pressure cycling	400000	5	20	10000	0,025	5,00E-01
3/8'' union couplings	Deficient mounting (maintenance)	100	8	20	1	0,01	2,00E-01
3/8'' union couplings	Untightening due to pressure cycling	300000	8	20	10000	0,033333333	6,67E-01
1/4'' union couplings	Deficient mounting (maintenance)	100	19	20	1	0,01	2,00E-01
1/4'' union couplings	Untightening due to pressure cycling	200000	19	20	10000	0,05	1,00E+00

Eq typically 1-2 mm

Conclusions

1. Classical methods used to derive leakage frequencies from incident databases for new technologies (ex : HP H2) do not seem to provide reliable results,
2. A sort of « ab initio » method is proposed based on the reality of each [item/condition of use] described by physical and logical models of the solicitations. For each couple [item/condition of use] a leakage frequency and a leakage flowrate (% of the full cross section) can be obtained,
3. Experiments were performed to attempt validating both the leakage frequency and the flowrate,
4. Only limited data is available sofar but the results seem to support the modeling approach,
5. The method seems applicable to many components and should be confronted to further data. But the latter need to be very accurate (constitution of the component, solicitation,..),
6. It was applied to the high pressure components of a H2 dispenser →