Dimensional Modelling of Aviation Fuel Outgassing in Aircraft Fuel Tanks

Presented by

Adam Harris
EV Flight and Integration Test Centre, Airbus

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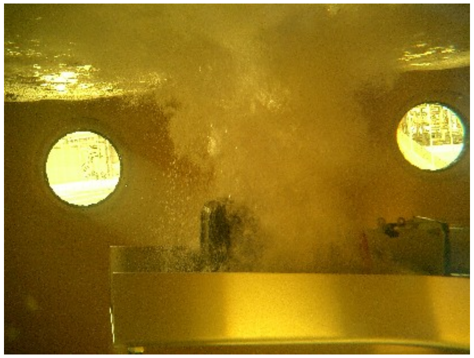
Background

- Fuel *outgassing* (oxygen release from fuel) increases the flammable envelope in aircraft fuel tanks
- Airworthiness authorities mandate flammability analyses take fuel outgassing into account[1]
- Performance of Fuel Tank Inerting system is impacted by outgassing
- Fuel outgassing phenomenon has been examined in the laboratory
- Previous fuel outgassing studies (laboratory) have failed to ensure ***dimensional similarity*** between physical models and aircraft[2]
- Difficult to apply existing laboratory results to aircraft analysis



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Effect on Flammability

- Fuel outgassing has a significant effect on fuel tank flammability
  - Flammable envelope is widened (Fig.1)
  - Air released from fuel is O_2 rich (up to 35% by vol.) – Gas Solubility coefficients O_2 > N_2 (Fig.2)

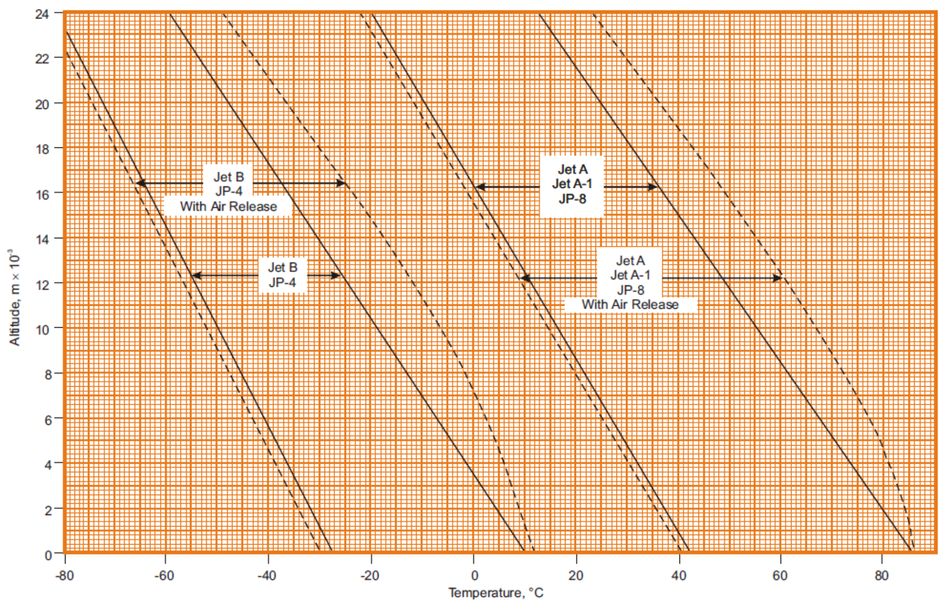

Figure 1. Flammability Limits[3]

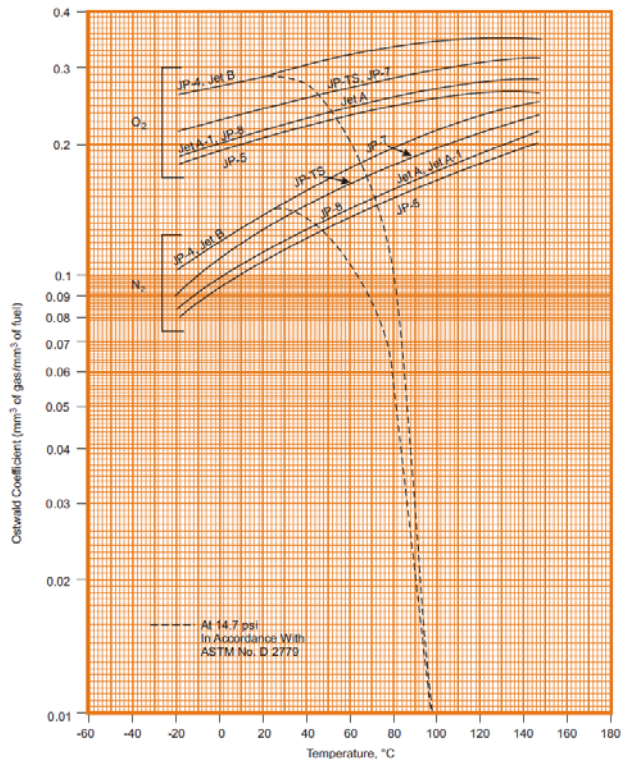

Figure 2. O_2/N_2 Gas Solubility in Aviation Turbine Fuels[4]

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Dimensional Modelling

- Behaviour of dimensionally similar systems **can** be closely correlated
- Results from measurement on either system can be projected to the other
- Dimensional Similarity – two systems having the same numerical values for defining dimensionless variables
- *A common misconception – Dimensional Similarity does not require Geometric Similarity!*

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Methodology

- Dimensional Modelling Method;
  1. Establish theoretical background (variables that affect O_2 release rate from aviation fuel)
  2. Develop the Model Law
  3. Design the Model
  4. Build the Model
  5. Execute experiments and tests
  6. Evaluate the data
  7. Draw conclusions

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Theoretical Background

- Variables and their fundamental dimensions using the SI (m, kg, s) mass based system relevant to rate of oxygen evolution from aviation fuel:

Variable	Symbol	Dimension	Remark
oxygen release rate	$\dot{m}O_2$	kg/s	Mass release rate
partial pressure of O_2 in Ullage	p_u	kg/(m.s^2)	Related to O_2 concentration in ullage
partial pressure of O_2 in fuel	p_f	kg/(m.s^2)	Related to O_2 concentration in fuel
fuel agitation factor	α	kg/s	Displacement of fuel per unit time
fuel surface tension	σ_f	kg/s^2	Energy barrier gas breaks for outgassing
rate of change of ullage pressure	$\dot{p}$	(kg/m.s^2)/s	Related to climb rate of aircraft
mass of fuel in tank	m_f	kg	Related to fuel load in aircraft tank

Table 1. Variables relevant to oxygen evolution rate from aviation fuel

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The Dimensional Set

[B] matrix

Physical variables

		$\dot{m}O_2$	p_u	σ_f	$\dot{p}$	α	p_f	m_f
Fundamental dimensions	m	0	-1	0	-1	0	-1	0
	kg	1	1	1	1	1	1	1
	s	-1	-2	-2	-3	-1	-2	0
Dimensionless Variables	π_1	1	0	0	0	-1	0	0
	π_2	0	1	0	0	0	-1	0
	π_3	0	0	1	0	-2	0	1
	π_4	0	0	0	1	-1	-1	1

[A] matrix

[C] matrix

[D] matrix (Identity Matrix)

- A & B matrices are formed from exponents of each variable's fundamental dimensions e.g. $\dot{m}O_2$ = kg/s
- A Matrix **<u>must</u>** be square and non-singular
- C matrix is determined from the *fundamental formula*[5]:

$$C = -\left(A^{-1} \cdot B\right)^T$$

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Dimensionless Variables and Scale Factors

- From Buckingham's theorem we have;

  N_v =7 variables N_d =3 dimensions

  $N_v – N_d$ = 4 dimensionless variables

- Dimensionless variables from *Dimensional Set* (pg. 7):

$$\pi_1 = \frac{\dot{m}O_2}{\alpha}\ ;\ \pi_2 = \frac{p_u}{p_f};\ \pi_3 = \frac{\sigma_f \cdot m_f}{\alpha^2};\ \pi_4 = \frac{\dot{p} \cdot m_f}{\alpha \cdot p_f}$$

- For dimensional complete similarity π_1, π_2, π_3 and π_4 must be identical for prototype and model where 1 and 2 designate prototype and model respectively:

$$\frac{\dot{m}O_{2(1)}}{\alpha_1} = \frac{\dot{m}O_{2(2)}}{\alpha_2}\ ;\ \frac{p_{u_1}}{p_{f_1}} = \frac{p_{u_2}}{p_{f_2}}\ ;\ \frac{\sigma_{f_1} \cdot m_{f_1}}{\alpha_1^2} = \frac{\sigma_{f_2} \cdot m_{f_2}}{\alpha_2^2}\ ;\ \frac{\dot{p}_1 \cdot m_{f_1}}{\alpha_1 \cdot p_{f_1}} = \frac{\dot{p}_2 \cdot m_{f_2}}{\alpha_2 \cdot p_{f_2}}$$

- These yield:

$$\frac{\dot{m}O_{2(2)}}{\dot{m}O_{2(1)}} = \frac{\alpha_2}{\alpha_1}\ ;\ \frac{p_{u_2}}{p_{u_1}} = \frac{p_{f_2}}{p_{f_1}}\ ;\ \frac{\sigma_{f_2}}{\sigma_{f_1}} \cdot \frac{m_{f_2}}{m_{f_1}} = \left[\frac{\alpha_2}{\alpha_1}\right]^2;\ \frac{\dot{p}_2}{\dot{p}_1} \cdot \frac{m_{f_2}}{m_{f_1}} = \frac{\alpha_2 \cdot p_{f_2}}{\alpha_1 \cdot p_{f_1}}$$

- The indicated ratios are called *Scale factors* and denoted by S. They are defined as:

$$S_{\dot{m}O_2} = S_\alpha\ ;\ S_{p_u} = S_{p_f}\ ;\ S_{\sigma_f} = \frac{S_\alpha^2}{S_{m_f}}\ ;\ S_{m_f} = \frac{S_\alpha^2}{S_{\sigma_f}};\ S_{\dot{p}} = \frac{S_\alpha \cdot S_{p_f}}{S_{m_f}}$$

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Model Law

- Model Law is the relation between Scale Factors in our oxygen evolution rate analysis
- From dimensionless variables $(\pi_{1\ldots4})$, the Model Law is:

$$S_{\dot{m}O_2} = S_\alpha \; ; \; S_{p_u} = S_{p_f} \; ; \; S_{\sigma_f} = \frac{S_\alpha^2}{S_{m_f}} \; ; \; S_{m_f} = \frac{S_\alpha^2}{S_{\sigma_f}} ; S_{\dot{p}} = \frac{S_\alpha \cdot S_{p_f}}{S_{m_f}}$$

- Surface tension of fuel in model and prototype is equal
- Assume partial pressure of dissolved O_2 in the fuel at equilibrium in model and prototype is equal due to Henry's Law:

$$S_{\dot{m}O_2} = S_\alpha \; ; \; S_{p_u} = S_{p_f} \; ; S_{m_f} = S_\alpha^2 ; S_{\dot{p}} = \frac{S_\alpha}{S_{m_f}}$$

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A320 Inner Wing Tank Analysis (Prototype)

- Model Law is used to design 'physical' laboratory model from **known** aircraft fuel tank conditions
- A320 collector cell – operating conditions:
  - Aircraft altitude = 38000 ft
  - 2 fuel pumps per engine
  - fuel temperature = 20 deg C
  - mass of fuel in CC =1038.4 kg

Engine Fuel System Parameter	Value (kg/s)
WSJP Motive Flow	0.125
Engine Feed Flow	0.333
Engine-Oil Fuel Cooling Flow	0.333
Individual Pump Performance @ 38 kft 20 deg C fuel	1.944
CC Fuel Agitation Factor (sequence valve discharge)	3.097

Table 2. A320 Fuel System Performance[6]

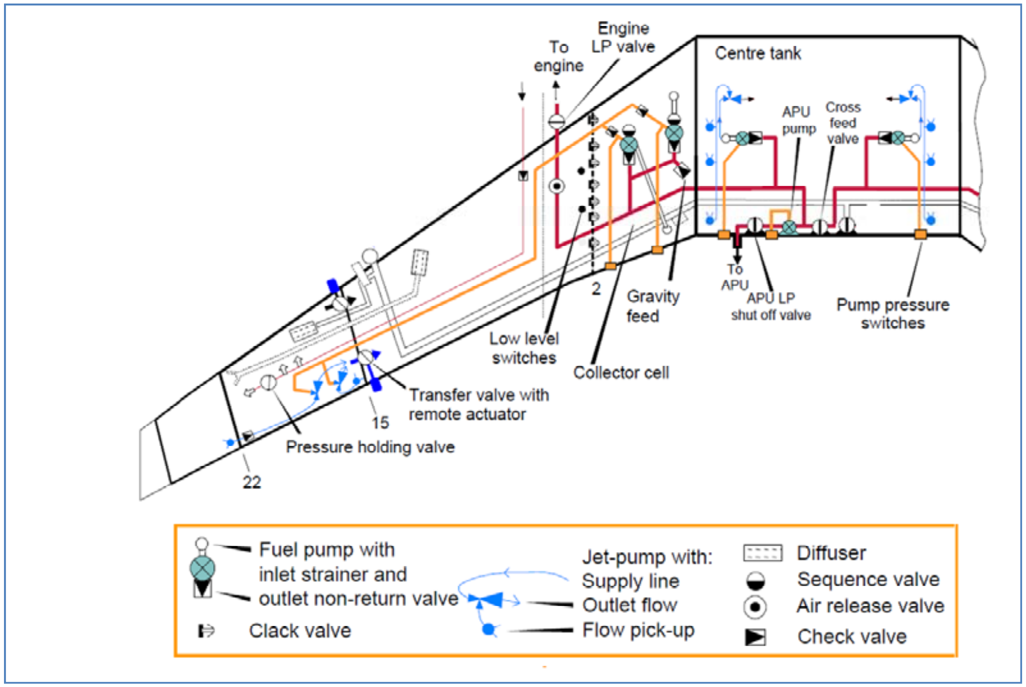

Figure 3 . A320 Engine Fuel Feed System

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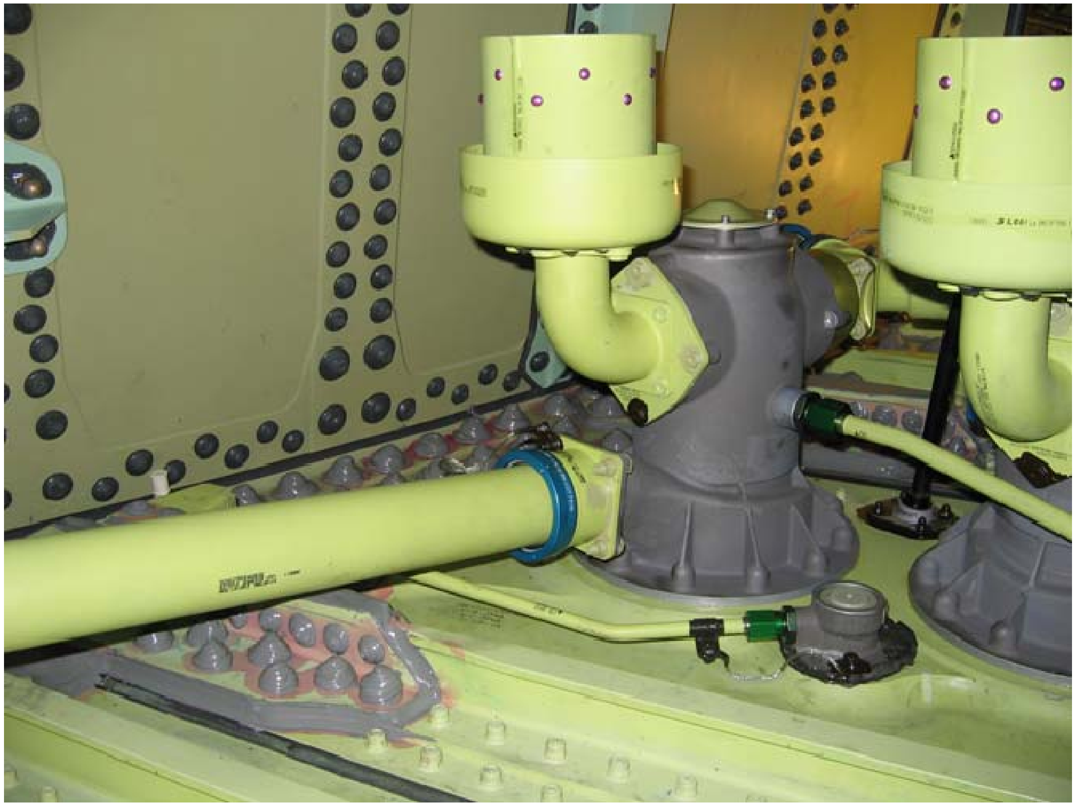
A320 Inner Wing CC

View looking aft towards RIB1 from RIB2 in A320 Collector Cell



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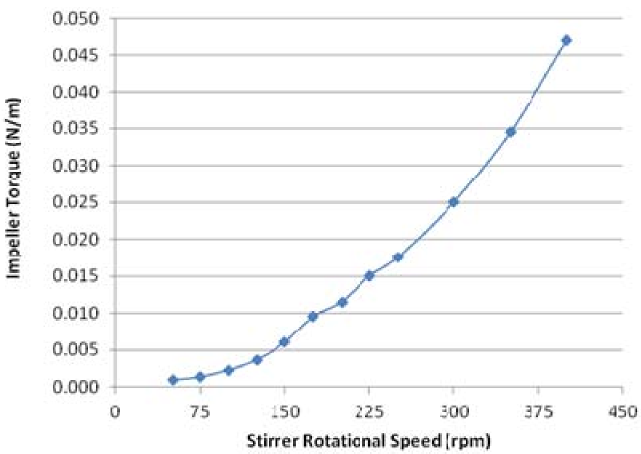
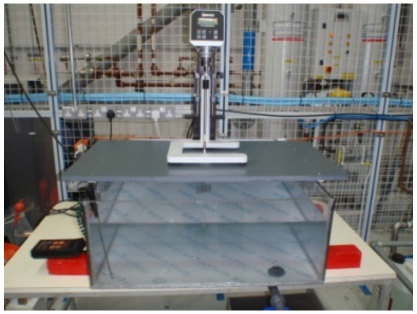
Model Design – Fuel Agitation (α_2)

- Radial flow mixing impeller (IKA1373) chosen to agitate fuel
  - Provides repeatable fuel agitation conditions in model fuel tank
  - Impeller Power and Flow numbers (Np & Nq) calculated from torque measurements in water using a Rheometer (0-50 mNm range)
  - Agitation factors (displacement of fuel mass per unit time) (kg/s) found from Np & Nq



Speed (rpm)	Torque (N/m)	Power (W)	Np	Nq	Q_{imp} (m^3/s)	Fuel Agitation Factor α_2 (kg/s)	Impeller Re No.
50	0.00090	0.0047	4.85	0.698	0.00020	0.16	4.08E+03
75	0.00130	0.0102	3.11	0.602	0.00026	0.208	6.13E+03
100	0.00225	0.0236	3.03	0.597	0.00034	0.272	8.17E+03
125	0.00365	0.0478	3.14	0.604	0.00043	0.344	1.02E+04
150	0.00600	0.0942	3.59	0.631	0.00054	0.432	1.23E+04
175	0.00950	0.1741	4.17	0.664	0.00066	0.528	1.43E+04
200	0.01150	0.2409	3.87	0.647	0.00074	0.592	1.63E+04
225	0.01500	0.3534	3.99	0.654	0.00084	0.672	1.84E+04
250	0.01750	0.4581	3.77	0.642	0.00092	0.736	2.04E+04
300	0.02500	0.7854	3.74	0.640	0.00110	0.88	2.45E+04
350	0.03450	1.2645	3.79	0.643	0.00129	1.032	2.86E+04
400	0.04693	1.9656	3.95	0.652	0.00149	1.192	3.27E+04

Table 3. Mixing Impeller Data



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Model Design – Fuel Agitation (α_2)

- From Model Law: $S_{m_f} = S_\alpha^2$
- Agitation factor needed in model:

$$\alpha_2 = \sqrt{S_{m_f}} \cdot \alpha_1$$

  - Choosing fuel mass (m_{f_2}) in model =100.31 kg (75% full at 20 deg C)
  - Using α_1 = 3.097 kg/s for A320 CC (from Table 2):

$$\alpha_2 = \sqrt{\frac{100.31}{1038.4}} \cdot 3.097 = 0.963\, kg/s$$

- Interpolation of fuel agitation factor vs. impeller rotational speed data gives a required impeller rotational speed of 330 rpm in the model

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Model Design – Rate of Pressure Change (p_2)

- From Model Law: $$S_{\dot{p}} = \frac{S_\alpha}{S_{m_f}}$$
- A320 ROC = 2111.11 ft/min = 154.58 Pa/s at t=0
- Rate of pressure change needed in model at t=0 is:

$$\dot{p}_2 = \frac{0.310946}{0.0966} \cdot 154.58 = 497.57 \ Pa/s$$

- 497.57 Pa/s at t=0 corresponds to a simulated ROC of 6753.94 ft/min from 0 to 38000ft in the model

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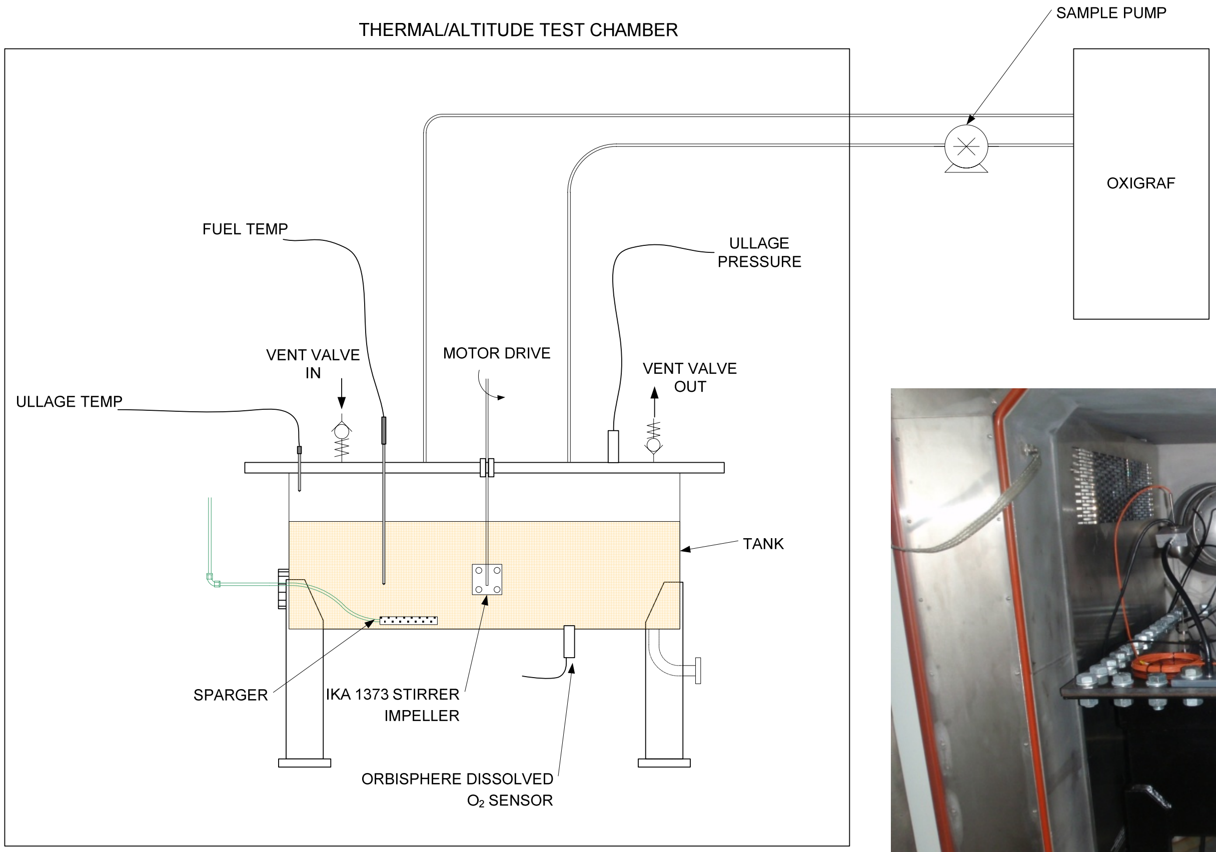
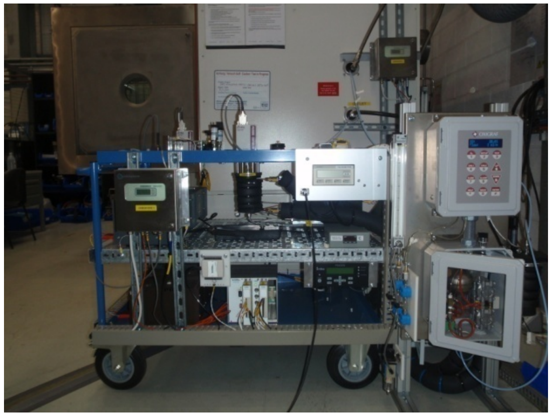
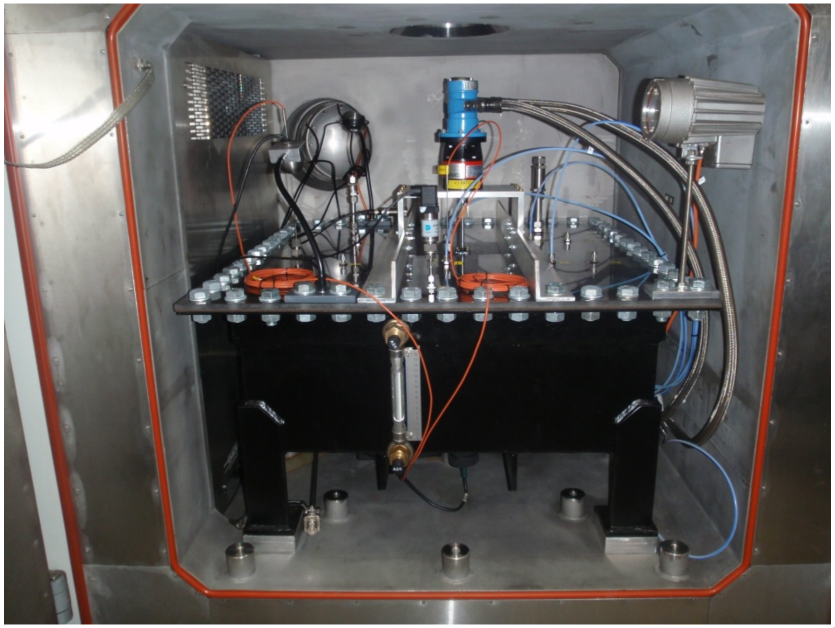
Physical Model

- Fuel Tank Model and measurement apparatus







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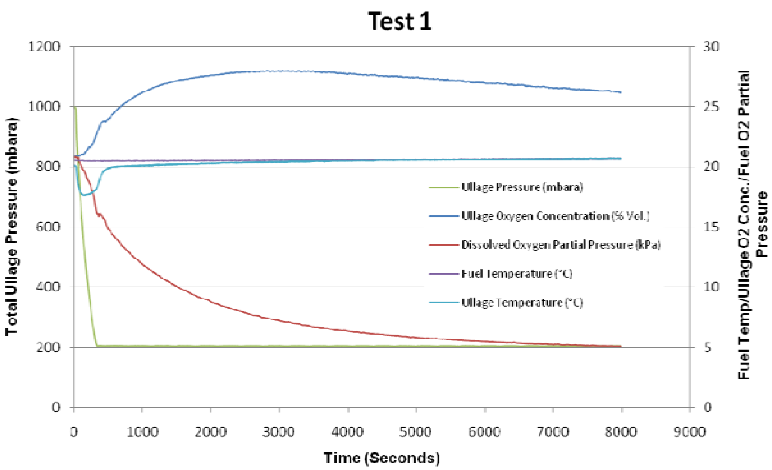
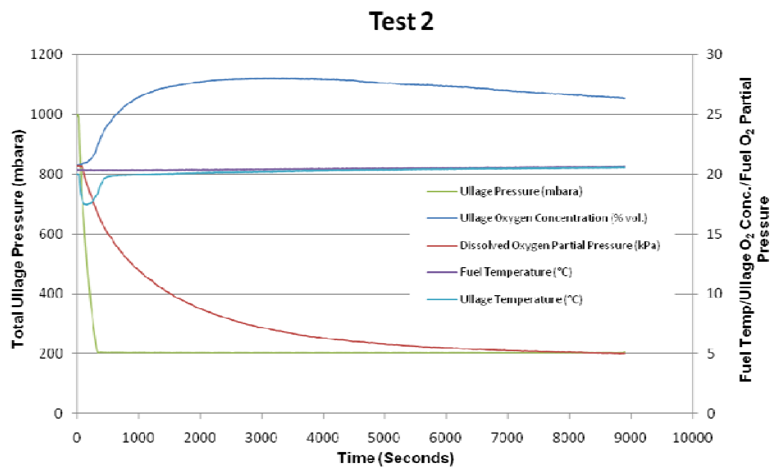
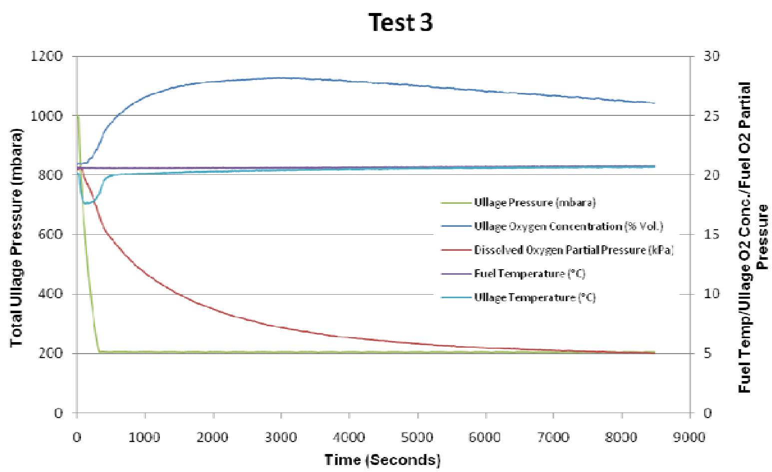
Raw Test Data (Model)







- 3 tests performed on model under identical test conditions
- Very good repeatability between individual tests
- 3 key observations made within data;
    - ➢ Ullage temperature drop due to pressure reduction (adiabatic cooling)
    - ➢ Exponential decay of dissolved oxygen partial pressures (due to gas release)
    - ➢ Ullage oxygen concentration drop after reaching equilibrium (possibly due to effects of fuel vapour, N_2 release and ullage mixing)

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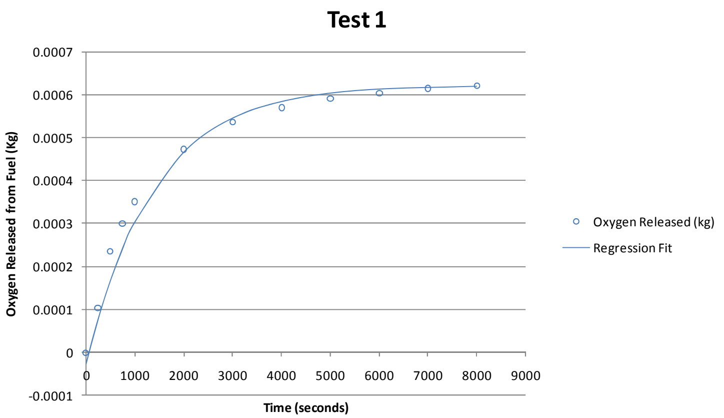
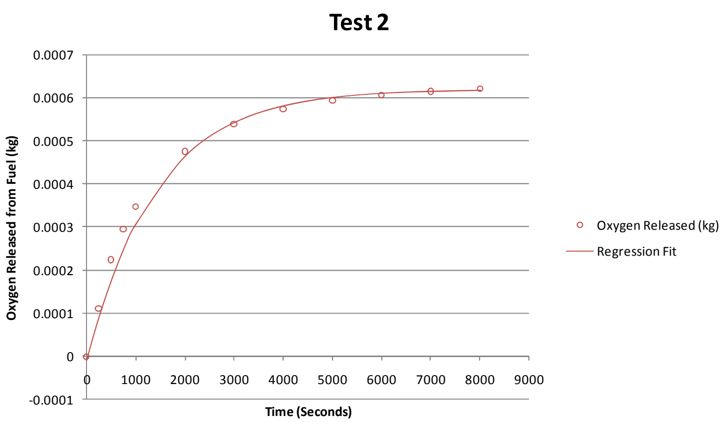
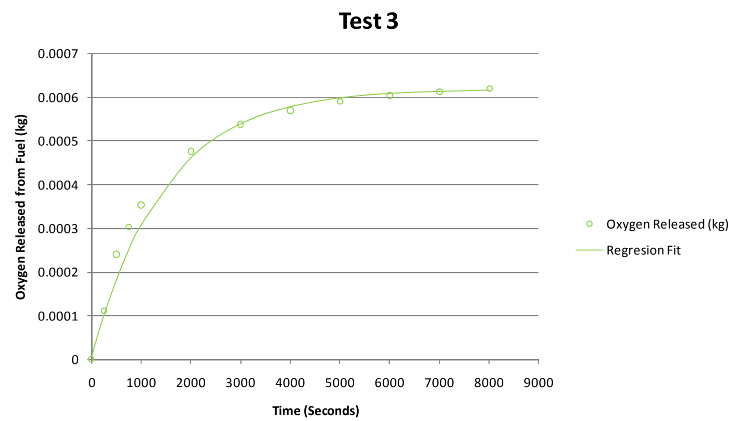
Results







Test No.	$\dot{m}O_2$ (kg/s)	Exponential Function	τ (sec)	RMSD
1	1.70391E-07	$mO_2 = 0.000622 \cdot \left(1 - 1.04 \cdot e^{-0.0007 \cdot t}\right)$	1401.3	3.20E-05
2	1.61878E-07	$mO_2 = 0.00062 \cdot \left(1 - 1.01 \cdot e^{-0.00069 \cdot t}\right)$	1429.8	2.37E-05
3	1.52775E-07	$mO_2 = 0.000619 \cdot \left(1 - 0.988 \cdot e^{-0.00067 \cdot t}\right)$	1472.9	2.58E-05

- Raw test data converted to mass of oxygen released from fuel (kg) using ASTM D2779[7] solubility calculation method
- Data fitted with regression equation:

$$mO_2 = A \cdot \left(1 - B \cdot e^{-kt}\right)$$

- Regression equation in terms of time constant (τ):

$$mO_2 = A \cdot \left(1 - B \cdot e^{-\frac{t}{\tau}}\right) \quad \tau = \frac{1}{k}$$

- Regression equations differentiated and release rates found at time, t = τ

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Modelling Results

- Projected O_2 release rate in A320 CC ullage is 222% > than measured model avg.
- Complete Dimensional Similarity achieved between model and prototype – only slight difference in π values due to rounding errors
- Model Law is satisfied!

Variable					Scale factor S	Category	
name	**symbol**	**dimension**	**prototype**	**model**	**model/prototype**	**prototype**	**model**
Mass release rate of O_2	$\dot{m}O_2$	kg/s	5.19964E-07	1.61681E-07	0.310946	2	3
Ullage O_2 partial pressure	p_u	kg/(m.s^2) = (Pa)	5718.46	5718.46	1	1	3
Fuel Surface Tension	σ_f	kg/s^2 = N/m	0.0281	0.0281	1	1	1
Rate of change of ullage pressure	$\dot{p}$	(kg/s^2.m)/s = (Pa/s)	154.58	497.57	3.218851	1	2
Fuel Agitation Factor	α	kg/s	3.097	0.963	0.310946	2	3
Fuel O_2 partial pressure	p_f	kg/(m.s^2) = (Pa)	5060.11	5060.11	1	1	3
Mass of Fuel	m_f	kg	1038.4	100.31	0.096	1	2
dimensionless	π_1	1	1.67892E-07	1.67893E-07	-	-	-
dimensionless	π_2	1	1.13	1.13	-	-	-
dimensionless	π_3	1	3.0422	3.0394	-	-	-
dimensionless	π_4	1	10.2427	10.2426	-	-	-
categories of variables	1	freely chosen, *a priori* given, or determined independently					
	2	determined by application of the model law					
	3	determined by measurement on the model					

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Conclusions

- Oxygen release rate from fuel has been measured in the laboratory using a physical model
- Results have been projected to an aircraft fuel tank operating case
- Dimensional similarity between laboratory model and aircraft has been achieved successfully
- Dimensional modelling can be applied to many more fuel tank conditions on different aircraft to quantify fuel outgassing
- Accuracy of fuel tank flammability studies can be improved with **significant benefit to the business**

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