Institution: University of Leeds

Unit of Assessment: 12

Title of case study 3: Energy saving from improved fuels, engine combustion, and reduced hazards.

1. Summary of the impact (indicative maximum 100 words)

Experimental research and computer modelling in the School of Mechanical Engineering have been applied by engine and oil companies to reduce fuel consumption and noxious emissions. Studies into high pressure explosions and burn rates have helped industry improve engine efficiencies by up to 30% and contributed to the development of much improved fuels. These new products perform better, are less environmentally damaging and have generated new company revenues. Research into burn rates, detonations, and large jet-flames has also informed health and safety investigations, particularly the UK Government Inquiry into the Buncefield explosion, providing calculations and explanations of the blast, and recommendations on future safety controls.

2. Underpinning research (indicative maximum 500 words)

The team's research has centred on theoretical, experimental and computer modelling studies [1;i] directed at: (a) burn rate control, (b) high pressure, 'knock-free' combustion, and (c) reduction of explosion risk, and control of jet-flames. These have resulted in better understanding of the dynamics and mechanisms of controlled combustion (and uncontrolled explosions). New insights have been widely accepted and applied, resulting in improved fuels and better control of combustion in engines and turbines, with safety features to prevent explosions and detonations.

Burn rates

Between 1993 and 2012, **Sheppard**, **Bradley**, **Gaskell**, **Lawes** and **Burluka** conducted rigorous mathematical modelling and experimentation on flame front propagation and auto-ignition, under different conditions, in a number of collaborations, with Alstom [iii], British Gas [i], Jaguar Land-Rover [iii,iv,vi], Lotus [iii], Mahle [vii], VW [ii], Ricardo [ii], Rolls-Royce [i,iii], Sasol [viii] and Shell [i,iii,iv,vi,viii]. They discovered new correlations between the parameters which influence the velocity of turbulent burning, enabling the Team to model high pressure combustion scenarios and predict the onset of knocking with greater accuracy [2-4, 6]. The studies employed a unique facility, designed and developed by the Team: a fan-stirred explosion bomb incorporating laser diagnostics, pressure transducers, and high speed photography [2]. **Burluka** and **Lawes** improved understanding of two-phase mixing and burning of liquid sprays and **Lawes** found fuel-rich aerosols burned much faster than had been suggested previously, indicative of an additional instability [4].

High pressure combustion

Although more fuel-efficient, a high burn rate in spark-ignition engines can lead to high pressure engine 'knock' – caused by auto-ignition at reactant 'hot spots'. The consequent over-pressures are highly detrimental and can even destroy an engine. The generation of hot spots in engine auto-ignition and the propagation of the reaction fronts were studied throughout the period by **Sheppard** and **Burluka** [3]. Parallel direct numerical simulations embodying detailed chemical kinetics were initiated by **Bradley** with Morley, of Shell, and Gu, of the Daresbury Laboratory. These simulations, combined with extensive engine research, revealed that increased pressure can create particularly damaging and spasmodic 'super-knock' [6]. Since 2008, collaborations with both Shell and Aramco, revealed "super-knock" to be associated with an unexpected gas-phase pre-ignition, an important discovery which has led to studies on the auto-ignition characteristics of lubricating oil [6].

The Leeds/Shell collaboration demonstrated fundamental limitations in the international criterion for engine knock – the octane number – for the higher temperatures and pressures in modern engines. The simulations showed that the complex relationships between the different physico-chemical parameters can be combined into a single dimensionless group, indicative of the severity of hot spot pressure pulses. **Sharpe** [5:v], showed the group was also indicative of the stability of detonation fronts. This gave rise to a new universal parameter, the Chi-number, now being adopted rapidly by the wider community.

Jet-flames and explosion risk

The stretched turbulent premixed flame model of **Bradley** and **Gaskell** [1] was further developed, to explore the structural detail of large jet-flames. These range from burning pools of fuel to supersonic jets. The model revealed the correlating parameters for the height of jet-flames and their thermal powers. In explosions in ducts, premixed flame modelling and fan-stirred bomb research showed that, as turbulence increases, because of increasing localised flame extinctions the turbulent burning velocity, after increasing to a maximum value, subsequently declines. This determines whether the shock wave generated by the accelerating flame is strong enough to promote auto-ignition and a possible detonation, characterised by the Chi-number.

Research Team

D **Bradley** (Research Professor 1992-present)
PH **Gaskell** (Senior Lecturer 1991-96, Professor of Fluid Mechanics 1996-2013)
CGW **Sheppard** (Professor of Applied Thermodynamics 1993-retired 2012)
AA **Burluka** (Lecturer 1998-2009, Senior Lecturer 2009-present)
M **Lawes** (Lecturer 1992-2000, Senior Lecturer 2000-present)
GJ **Sharpe** (Principal Research Fellow 2005-2008, Reader 2008-2013).

3. References to the research (indicative maximum of six references)

1. D **Bradley**, PH **Gaskell**, XJ Gu, (1994). Application of a Reynolds stress, stretched flamelet, mathematical model to computations of turbulent burning velocities and comparison with experiments. *Combust. Flame*, **96**, 221-248.http://dx.doi.org/10.1016/0010-2180(94)90011-6
2. D **Bradley**, MZ Haq, RA Hicks, T Kitagawa, M **Lawes**, CGW **Sheppard**, R **Woolley**, (2003). Turbulent burning velocity, burned gas distribution and associated flame surface definition. *Combust. Flame*, **133**, 415-430. http://dx.doi.org/10.1016/S0010-2180(03)00039-7
3. AA **Burluka**, K Liu, CGW **Sheppard**, AJ Smallbone, R Woolley, (2004). "The influence of simulated residual and NO concentrations on knock onset for PRFs and gasolines.*SAE Trans. Jour. Fuels and Lubricants,* 113(4), 873-1889.http://dx.doi.org/10.4271/2004-01-2998
4. M **Lawes**, Y Lee, N Marquez, (2006). Comparison of iso-octane burning rates between single-phase and two-phase combustion for small droplets. *Combust.Flame* 144, 513–525. http://dx.doi.org/10.1016/j.combustflame.2005.07.015
5. MI Radulescu, GJ **Sharpe**, Chung K Law, JHS Lee, (2007). The hydrodynamic structure of unstable cellular detonations. *J. Fluid Mech*., 580, 31-81. http://dx.doi.org/10.1017/S0022112007005046
6. GT Kalghatgi and D **Bradley,** (2012). Pre-ignition and 'super-knock' in turbo-charged spark-ignition engines. *International J. of Engine Research*, 13(4) 399–414. http://dx.doi.org/10.1177/1468087411431890

Note: All Leeds researchers in **bold**. All of the above publications are internationally recognised, with rigorous peer review processes and international editorial boards, The quality of the underpinning research being at least 2* is demonstrated by references 2, 4 and 5. Other relevant publications comprise 3 books and upwards of 98 papers, 9 of which received prizes or awards.

Key research grants

i. D **Bradley**, PH **Gaskell.** Advanced Turbulent Combustion Modelling. EPSRC grant GR/K96212, April 96 - March 99. Liaisons with British Gas, Ishikawajima-Narima Heavy Industries, National Power, Rolls-Royce, Shell, Computational Combustion for Engineering Applications Consortium, £154,158.
ii. CGW **Sheppard**, (PI), M **Lawes**, AA **Burluka**, R Woolley. Gasoline Engine Turbo-charging: Advanced Gasoline Powertrain for reduced fuel consumption. EU contracts G3RD-CT-2000-00364 (GET-CO2), £595,200, and G3RD-CT-2002-00789 (GET-DRIVE), Jan 01 – Dec 05. In collaboration with Ricardo Consulting Engineers, UK and VW, Germany, £80,925.
iii. M **Lawes**, (PI), D **Bradley**, R Woolley. Fundamental engine fuel studies at intermediate and high pressures & temperatures. EPSRC grant GR/S70203/01, July 04 – Jun 07. In collaboration with Alstom Power UK, Jaguar Cars, Lotus Engineering, Rolls-Royce and Shell Global Solutions, £291,206.
iv. CGW **Sheppard**, (PI), M **Lawes**, AA **Burluka**, D **Bradley**, R Woolley. Combustion Concepts For Sustainable Premium Vehicles. EPSRC grant GR/S58843/01, Oct 03-Sept 07. In collaboration with Jaguar Cars and Shell Global Solutions, £299,314.
v. GJ **Sharpe**, (PI). Ignition, propagation and failure of detonations and deflagration-to-detonation transition. Oct 2005– Dec 2009. EPSRC Advanced Fellowship GR/S49513/02, £160,408.
vi. AA **Burluka**, (PI), CGW **Sheppard**. UltraBoost for Economy. TSB grant BN008E, Aug 2010 – Aug 2013. In collaboration with JLR, Shell, GE Precision, Univ. of Bath, Imperial College,

£142,676.

vii. AA **Burluka**, (PI). Autoignition in strongly boosted engines. DHPA award with Mahle Powertrain UK, Oct 2010 – Oct 2013, £92,000.

viii. GJ **Sharpe**, (PI), CGW **Sheppard** M **Lawes**, D **Bradley**, J Griffiths. Collaborative Research in Energy with South Africa: Fundamental Characterisation of Autoignition and Flame Propagation of Synthetic Fuels. EPSRC grant EP/G068933/1, Apr 2009. In collaboration with SASOL Technology, South Africa, and Shell Global Solutions, UK, £396,550.

All Engineering and Physical Sciences Research Council (EPSRC), Technology Strategy Board (TSB) and European project grants are peer-reviewed and evaluated on stringent quality criteria.

4. Details of the impact (indicative maximum 750 words)

Much progress has been made in developing high pressure, knock-resistant, engines through a range of industrial collaborations with high value returns. In parallel, the Team's fundamental studies have made major contributions to reductions in fire and explosion hazards throughout the automotive, aviation, and energy sectors.

Energy efficient engines.

Engines with high burn rates are generally cleaner and more efficient, provided knock is avoided. As a result of extensive collaborations with Jaguar Land-Rover (JLR), Lotus, Rolls-Royce (R-R), and VW, the Leeds experimental and modelling insights into burning rates have had a widespread influence on reciprocating engine and gas turbine design. The R-R collaboration led to improved igniters and prevention of high-altitude flame-out in aero-turbines, as well as the prevention of auto-ignition and flash-back in land-based turbines. A long term collaboration with JLR [A] and, latterly, GE Precision Engineering [B] has led to improved control of fuel/air mixing, ignition, burn rates, and knock suppression, together with reductions in the uncontrolled variations in working cycles. The Leeds computer modelling code was incorporated by JLR into its internal engine system modelling packages [A]. These fundamental improvements in the design and engineering of the companies' engines [A,B] have contributed to their development, in the UK, of commercially very successful, high pressure, knock-free, turbo-charged, engines. These are characterised by their reduced size, yet with higher power, combined with consequent impressive improvements in efficiency and reductions in emissions. Both of these savings amount to up to approximately 30% of previous values [A]. Since 2010, collaborations to this end were consolidated in the UltraBoost project [vi], which included JLR, GE Precision, Shell, the Universities of Bath and Imperial College, with Leeds making its major contributions in the key area of carefully-controlled high pressure combustion, just short of the knock limit. JLR has invested £355M to manufacture the engines into production [C] and has created 10,700 new jobs in UK since 2008. Data in [D] indicate the huge savings from even a 1% improvement in efficiency.

Energy efficient fuels

The detailed observations and modelling of high-pressure combustion and auto-ignition, not only showed the widely used Octane Number criteria to be misleading for modern engines, but it also led to the development of alternative design approaches [E]. These, combined with fuel tests in the Leeds bomb, supported Shell's development of a new vehicle fuel formula with increased burn rate and minimised auto-ignition [F]. This world-wide FuelSave range, launched in 2010, improved engine efficiency by up to 2%, with consequent reduction in carbon emissions. Specialist support was given also to the development of Shell's Formula One fuels and fuel-blending laws with Sasol.

Fuel explosions – contributions to inquiries and safety recommendations

Following the vapour cloud explosion at Buncefield oil storage terminal in 2005, **Bradley** was asked to advise the late Lord Newton's Major Incident Investigation Board [G] into the Buncefield disaster, through membership of its Explosion Mechanism Group. Findings from the Leeds Team, along with input from others members of the expert group, were used to explain the cause and damage from this huge explosion [H]. From this assessment of the explosion dynamics, the Inquiry recommended specific measures to prevent a recurrence [G]. The introduction of new safety standards, site layouts and technologies [F], informed in part from a scientific understanding of the explosion, has had a significant impact for the UK. The new safety measures will have helped to avert a similar explosion which had a total economic cost of around £1billion [G]. The implementation cost of all the recommendations was calculated at approximately £82M, with an estimated benefit through the reduction of risk "*in the region of £162million*" [G].

Jet-Flames

The Team's jet-flame model has been used in the important area of flare design by Shell [F] and validated in tests at the South West Research Institute. The Team's correlation of jet-flame data, with parameters drawn from the computer model, is invaluable for estimating the magnitude of oil field blow-outs, and designing non-polluting flares. After Bradley's earlier involvement in the Concorde fire Inquiry, Qinetiq asked him to use the Leeds jet-flame model to quantify upstream fuel leaks from the observed sizes of the fire plume from the Nimrod aircraft over Afghanistan. This confirmed magnitudes of fuel leakage after in-flight re-fueling. The subsequent Haddon-Cave Report [I] resulted in the Nimrod being withdrawn from service, averting the possibility of further crashes and potential loss of life.

Impact on Society, Culture and Creativity

The stretched turbulent flame codes are freely available and are being used by other groups. They are embodied in the THOR fluid dynamics code of the Daresbury Laboratory, developed in collaboration with the Leeds group. The Team contributed to BBC programmes, for radio on oil field blow-outs and for TV on the Olympic flame (2012). The findings on the limitations of Octane Numbers have had international repercussions throughout the automotive and oil industries.

5. Sources to corroborate the impact (indicative maximum of 10 references)

A. Statement from Manager, Research, Jaguar Land Rover, regarding efficient engines.
B. Statement from Technical Director, GE Precision Engineering, regarding efficient engines,
C. JLR invests £355M in UK low emissions engine plant. http://www.smmt.co.uk/2011/09/jaguar-land-rover-invests-355-million-in-uk-low-emission-engine-plant/ website accessed and saved 19.10.13
D. Digest of UK Energy Statistics, Department of Energy and Climate Change, Energy consumption in the United Kingdom: 2012.Chapter 1, Energy. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/65881/5949-dukes-2012-exc-cover.pdf Website accessed and saved. 28.8.13.
E. Statement from Senior Research Science Consultant, Aramco, regarding octane number limitations and new approaches.
F. Statement from Technology Manager, Fuel Science, Shell Global Solutions, regarding development of new fuels, safety, jet flames.
G. Buncefield Major Incident Investigation Board, "The Buncefield Incident 11 December 2005 Final Report", Volumes 1 and 2, Crown Copyright, Dec. (2008). http://www.buncefieldinvestigation.gov.uk/reports/
H. Statement from Chief Technical Advisor to European Commission, regarding all aspects of Buncefield explosion.
I. Charles Haddon-Cave QC, (2009). "An independent review into the broader issues surrounding the loss of the RAF Nimrod MR2Aircraft XV230 in Afghanistan in 2006." Ordered by the House of Commons. http://www.official-documents.gov.uk/document/hc0809/hc10/1025/1025.pdf Website accessed and saved 28.8.13.