Research Project Management Highlights and Impacts

Bruce Chehroudi, PhD
Advanced Technology Consultants
4 Hidden Crest Way
Laguna Niguel, CA 92677

Presentation to

Sandia National Laboratory
Combustion Research Facility
Livermore, California

April 22, 2013

Outline

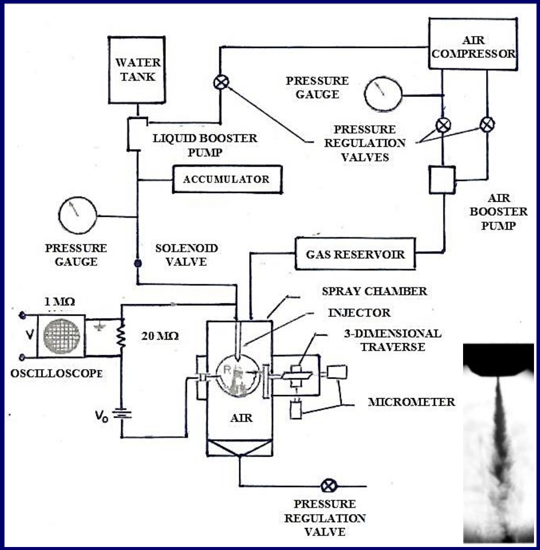
- A partial list of research activities
  - Liquid fuel spray and DISC engine
  - Swirl-stabilized combustor (gas turbine engine)
  - Interacting-jets/sprays: Simultaneous reduction of soot & NOx emissions
  - Supercritical combustion in cryogenic rockets
  - Combustion instability in liquid rocket engines
  - Nanotechnology, optics, and chemical reaction
- Conclusions

Liquid Fuel Spray: DISC Engine

- Objectives
  - Develop diagnostics in dense spray
  - Characterize dense spray region
  - Length and shape of the dense core
  - Database for modeling and simulation

- Organizational Impact
  - Maintained leading position in the field
  - Secured follow-up funding
  - Visibility in the national and international community
  - Role model in research excellence
  - Close collaboration between modeling/simulation and experimental teams in the same building (laboratory)

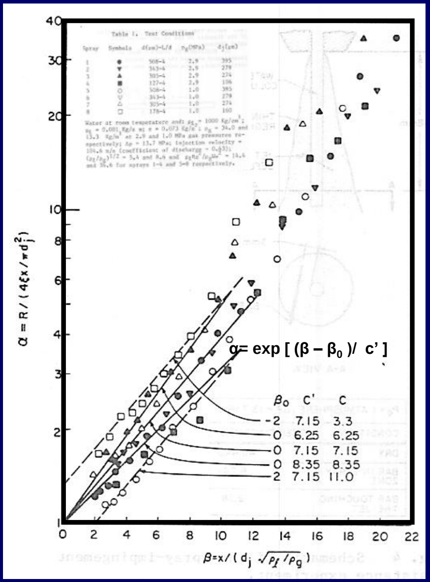
Princeton University high-pressure spray facility.



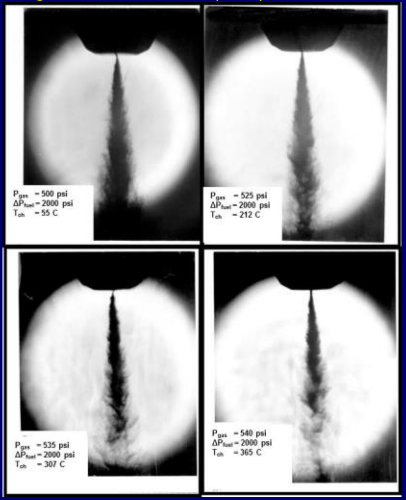
Schematic diagram of the high–pressure liquid spray facility .

Liquid Fuel Spray: DISC Engine

- Key Technical Results & Impacts
  - Winner of the *Arch T. Colwell Merit Award* from SAE (only to top 1% of all publications each year)
  - Innovative electrical conductivity approach for both length and shape of the dense-spray region
  - One of the two known such measurements in the world at the time (the other: Hiroyasu et al., Japan)
  - Modeling and simulation code validation (KIVA)
  - Core length proportional to square root of density ratio
  - Previous measurements overestimated the length
  - Theoretical and experimental results in good agreement
  - Used for engineering design purposes
  - Path from fundamental research to applications



Measured total spray electrical resistance versus axial distance for different injector designs. Chehroudi et al. (1985).



Single-hole injector producing a dense spray at different chamber pressures. Chehroudi et al. (1985).

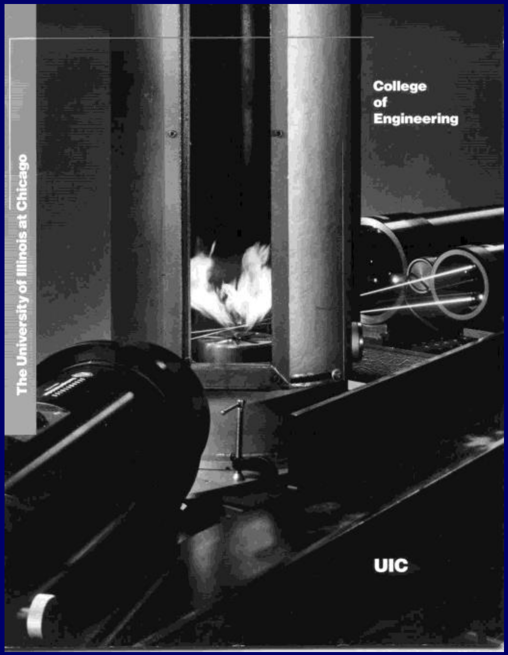
Chehroudi et al. Equation

$$L_{core} / d_{jet} = [\beta_0 + c' (1- \beta_0 /c' + 9 (\beta_0 / c')^2 /8)^{-1}] (\rho_l / \rho_g)^{1/2}$$

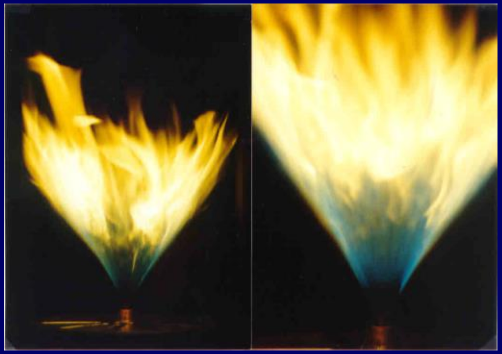
Swirl-Stabilized Combustor

Gas Turbine Engine

- Objectives
  - Designed and built facility from the ground up
  - Mechanism of swirl stabilization
  - Pollutants formation
  - Spray characterization under both reacting and nonreacting flows
  - Experimental data for modeling and simulation
  - Visualization & laser diagnostics
- Organizational Impact
  - Decorated the department's only advertising brochure: an effective marketing impact
  - Attracted additional funding
  - Used for research and education
  - Attracted other colleagues for collaborative research and proposals
  - 1 PhD and 3 MS



Swirl-stabilized combustion chamber simulating gas turbine combustion chamber

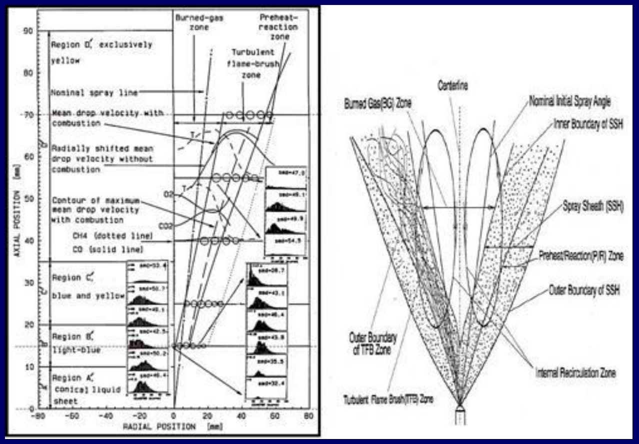


Spray flame stabilized by swirl air using a specially-designed swirler

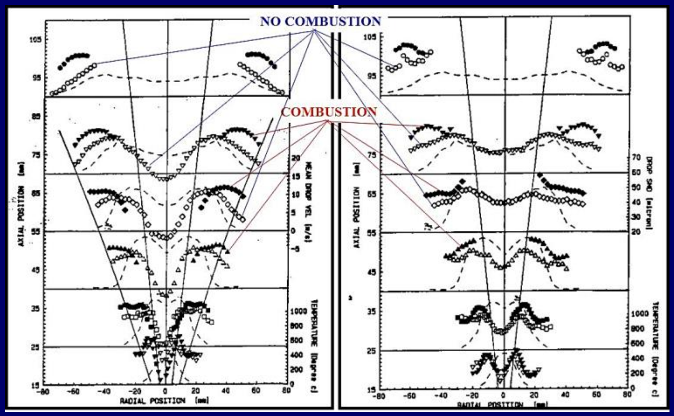
Swirl-Stabilized Combustor: Gas Turbine Engine

UIC UNIVERSITY OF ILLINOIS AT CHICAGO

- Key Technical Results & Impacts
  - *CRC Handbook of Fluid Dynamics* as significant example of applied engineering research done on the subject with many commercial applications (*W. Bachalo*)
  - Journal of Fluids Engineering: *Data Bank Contribution*
  - Effects of reacting flow on spray characteristics
  - One of the earliest data set in the literature
  - Recirculation zones and their interactions
  - Stability zone characterization
  - Anatomical features were named and distinguished under both cold and reacting flows
  - Design guidelines were proposed



Structure of the swirl-stabilized sprays under reacting condition



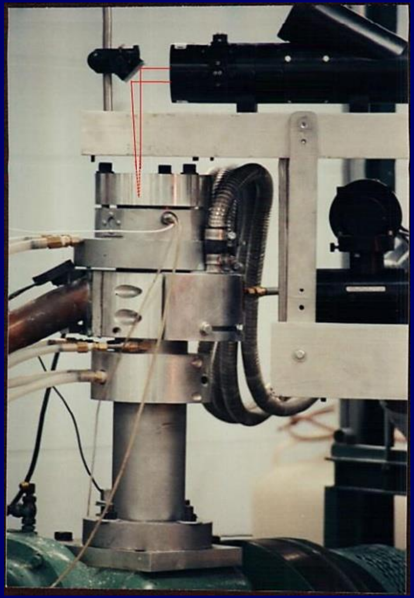
Offset plots of the mean axial drop velocity with (solid) and without (hollow) combustion at six different axial locations. Dashed curves show mean temperature profiles. Mean drop radial velocities were measured

Offset plots of the SMD with (solid) and without (hollow) combustion at six different axial locations. Dashed curves show mean temperature profiles.

Interacting-Jets/Sprays: Simultaneous soot & NOx reduction

- Objective
  - Feasibility of an innovative concept for simultaneous reduction of soot and NOx
  - Innovation at the interface
  - Fundamental understanding of the interacting sprays

- Organizational Impact
  - Enhanced visibility in innovative idea generation
  - Advanced engine laboratory for both research and education
  - Attracted funding from the industry (GM and Ford)
  - Patent filed
  - A number of publications
  - Motivated other researchers in the world to explore similar strategy
  - 2 PhD and 4 MS



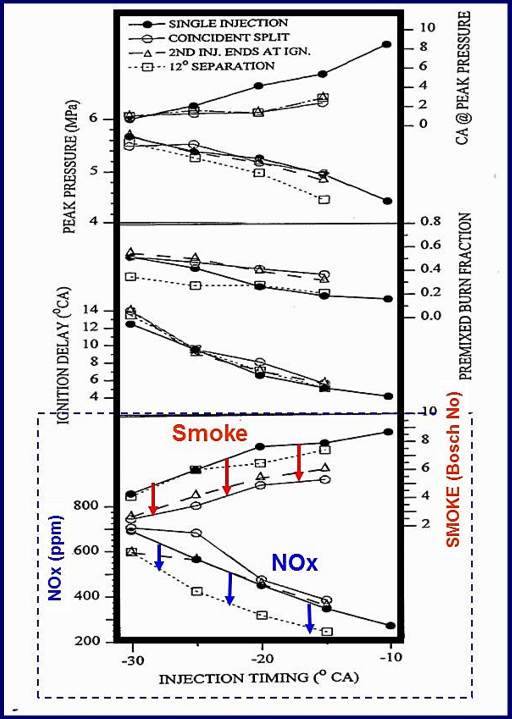
Single-cylinder engine for interacting-sprays studies

Engine head design of the interacting-sprays combustion chamber for simultaneous soot and NOx reduction

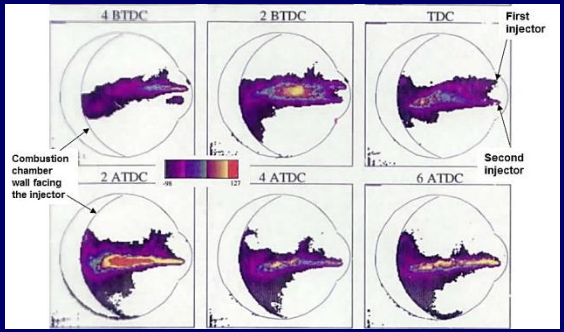
Interacting-Jets/Sprays: Simultaneous soot & NOx reduction

UIC UNIVERSITY OF ILLINOIS AT CHICAGO

- Key Technical Results & Impacts
  - The concept based on physical intuition has been proven
  - Led to follow-up studies throughout the world
  - Interacting-sprays concept appears to be complementary to other competing approaches
  - Laser diagnostics including Exciplex method revealed the nature of the interaction
  - Interaction at the right time and right place achieved the desired effects.
  - Stronger interactions between the two injection pulses (i.e., spray/spray impingement) early within the ignition delay period was critical to reduction in smoke (or soot) formation.
  - For effective NOx reduction the second injection pulse should start near the ignition delay period to lower local burned and burning gases temperatures



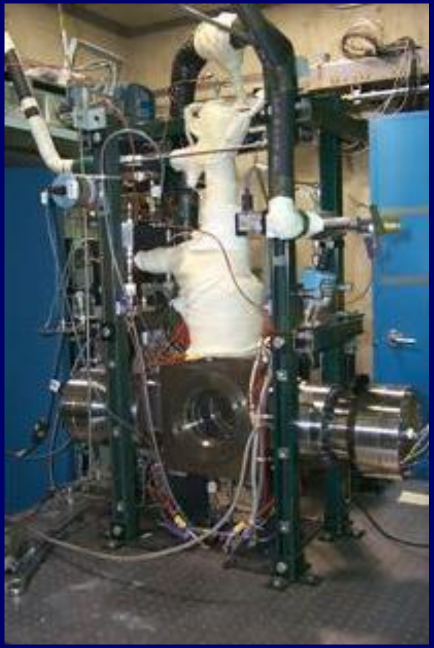
Simultaneous soot and NOx reduction potential of the interacting-sprays are shown



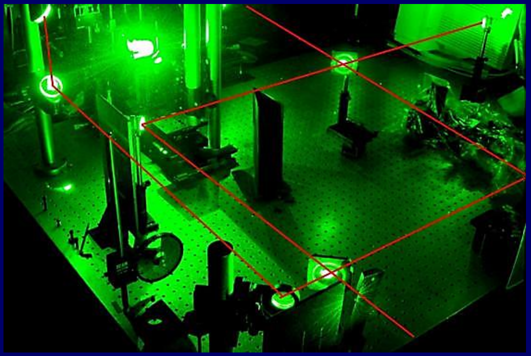
In-cylinder visualization of the interacting-spray injection system

Supercritical Combustion: Liquid Rocket Engine

- Objective
  - Understand combustion under high pressures including supercritical conditions
  - Fundamental understanding of cryogenic liquid propellant atomization
  - Database for modeling and simulation
- Organizational Impact
  - Improved design tools
  - Continued funding through AFOSR
  - Earned one of the prestigious AF awards: the *Star Team Status* (implications: secured funding for 5 years no matter what)
  - Built international reputation for the group
  - Opened up national & international collaborations
  - Expanded into another program: Combustion instability
  - Enhanced sense of pride and teamwork
  - NASA funding via AFRL, ATC, JPL joint proposal
  - 1 PhD jointly with Penn State, 1 postdocs, 1 visiting faculty



Supercritical facility at AFRL



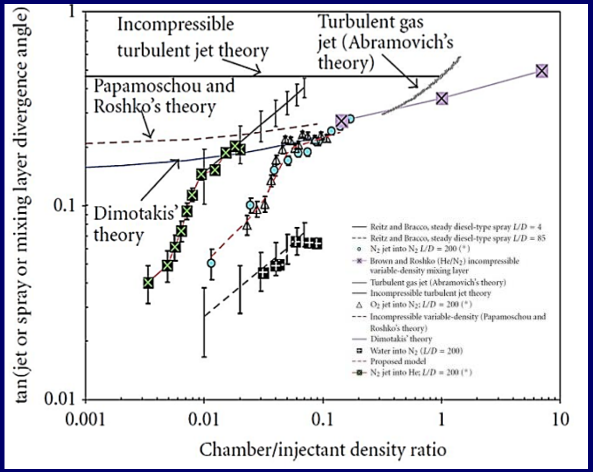
Raman scattering studies

Supercritical Combustion: Liquid Rocket Engine

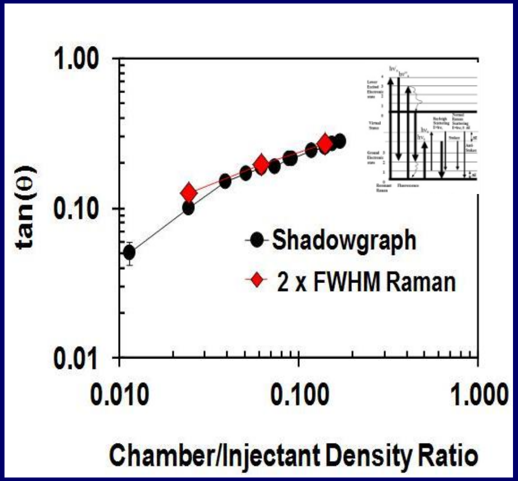
- Key Technical Results & Impacts
  - *Outstanding Technical Publication Award*
    - In recognition of performance and outstanding achievement to the Air Force Research Laboratory, Space & Missile Propulsion Division, 2002
  - *Best Technical Publication Award*
    - For outstanding and lasting contributions to aeronautical and aerospace sciences, AIAA, 2000
  - First time Achievements
    - Quantitatively demonstrated that jet growth rate (hence, mixing appetite) under supercritical conditions behaves like incompressible variable-density gaseous jets
    - Consolidated jets, sprays, mixing layers data for up to 4 order of magnitude
    - Fractal analysis of the supercritical jets
    - A physics-based model
  - Implications for modeling and simulations
  - Methodology to reconcile results from Raman and shadowgraphs
  - Raman data was used for temperature profiles

Chehroudi et al. Model Equation

$$\Theta = 0.27 \left[\tau_b / (\tau_b + \tau_g) + (\rho_g / \rho_l)^{0.5} \right]$$



Growth rate of single jets as a tangent of the visual spreading angle versus the chamber-to-injectant density ratio. Data taken by Chehroudi are indicated by an asterisk (*) in the legend.

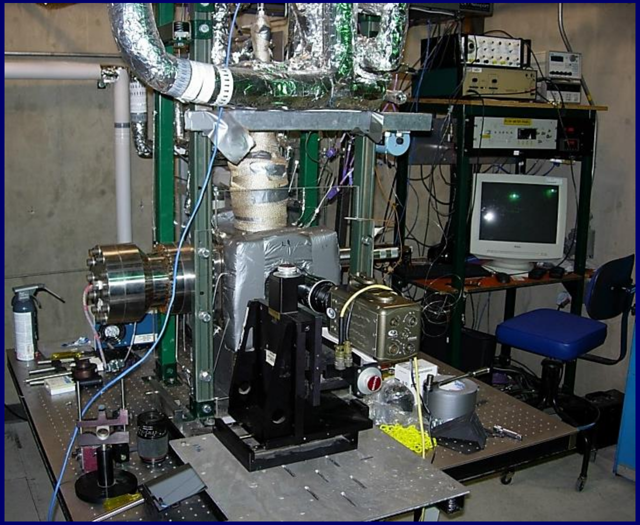


Comparison of the spray growth rate measured by Raman and shadowgraph methods

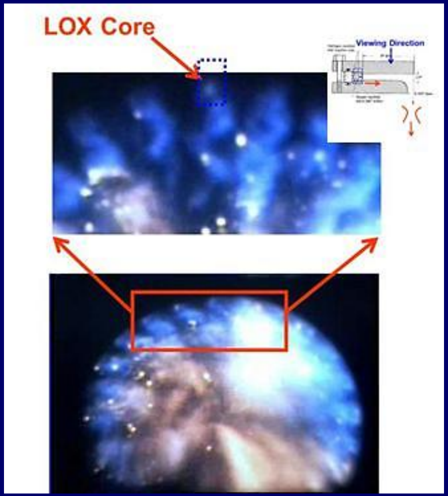
Combustion Instability: Liquid Rocket Engine

- Objective
  - Nature of the acoustic field / injector interaction
  - Develop understanding under high pressures including supercritical conditions
  - Data for modeling and simulation

- Organizational Impact
  - Led to continued funding by the AFOSR
  - Contributed heavily towards formation of combustion stability program by the Air Force
  - Established as one of the leading research groups in high pressure combustion instability
  - Enhanced collaborations with university and industry
  - Contributed towards next generation of combustion stability design tools
  - 1 PhD jointly with UCLA, 1 postdoc, 1 visiting faculty



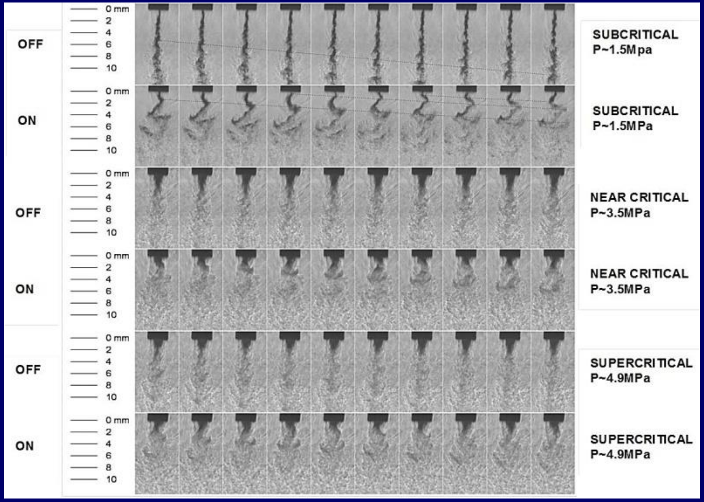
Supercritical facility for study of combustion instability in cryogenic liquid rocket engines



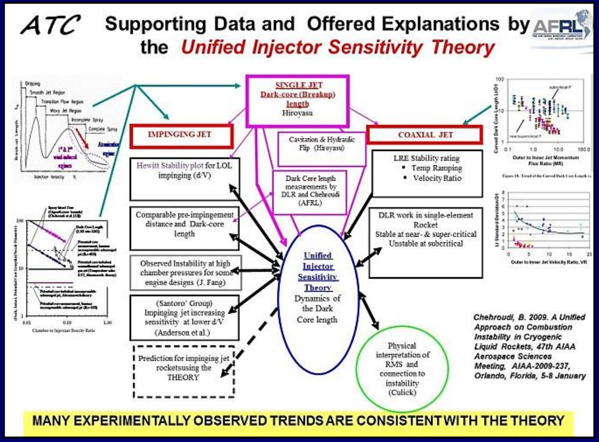
Appearance of the combustion instability intentionally induced by sudden injection of nitrogen

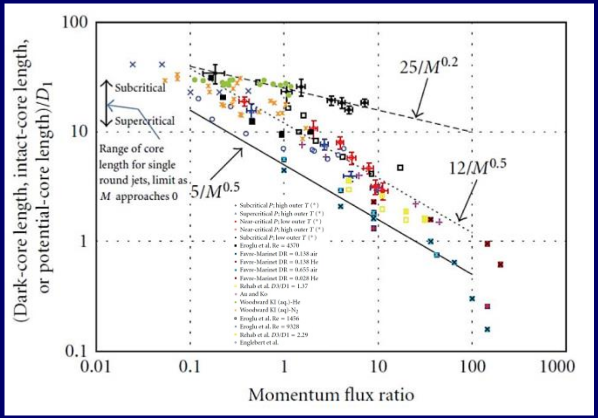
Combustion Instability

- Key Technical Results & Impacts
  - *Best Paper Award*
    - Liquid Propulsion Subcommittee, Joint Army-Navy-NASA-Air Force(JANNAF)
  - *Marshall Award*
    - Best publication of the year, ILASS_America
  - A *Unified Injector Sensitivity Theory* for combustion instability was proposed
  - Opened up a new perspective on the instability at supercritical pressures
  - Theory is consistent with all available cold and reacting flow results



Consecutive frames from high-speed movies for a coaxial injector similar to those used in Space Shuttle main engine with the acoustic driver off (rows 1, 3, and 5) and on (rows 2, 4, and 6) at ~ 3kHz.

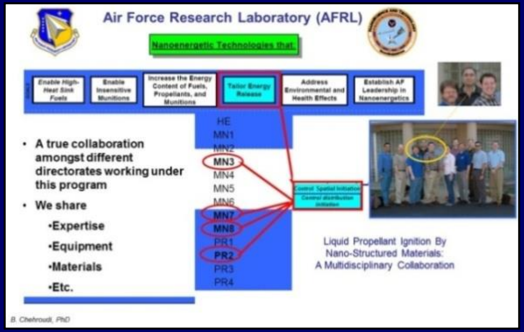




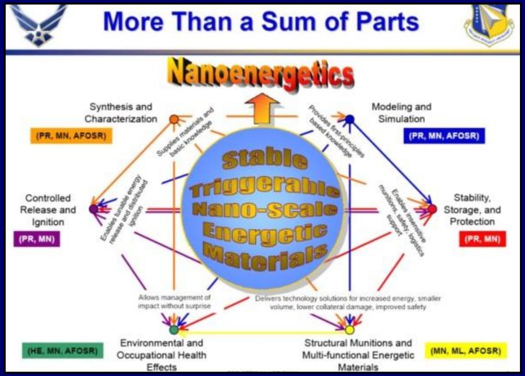
Comparison of Chehroudi's cryogenic coaxial-jet dark-core length measurements with all other relevant core length data in the literature versus momentum flux ratio

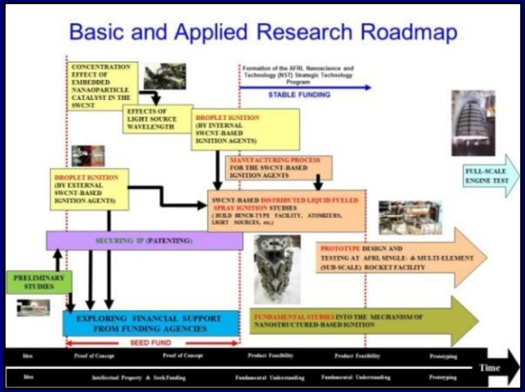
Nanoscience, Optics, & Chemical Reaction

- Objective
  - Light-activated volumetrically-distributed ignition of gaseous and liquid sprays: A paradigm shift in ignition technology
  - Explore potential for ignition-induced instability
  - Understand photo-physics of the phenomenon
  - Feasibility in applications of carbon nanotube, graphene, or other nanostructured materials for ignition/combustion



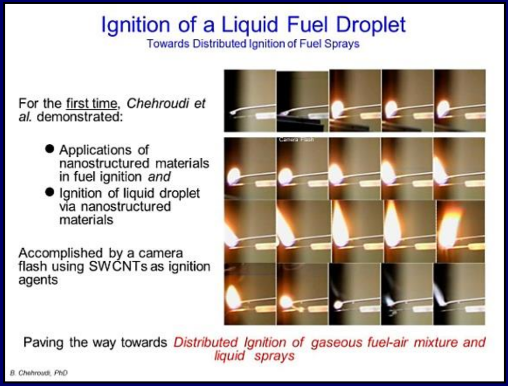
- Organizational Impact
  - The only group in the world harnessing the applications of this new phenomenon
  - Led to active participation in the AFRL Nanoscience and Technology (NST) Strategic Technology Team (STT)
  - Secured seed fund leading to a 5 year funding for the program through AFOSR/NST
  - Created & managed multidisciplinary collaboration (university/government/ industry)
  - 2 MS students (Purdue Univ & AF Academy) &1 postdoc

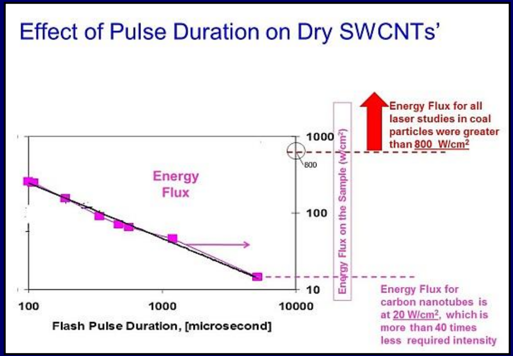


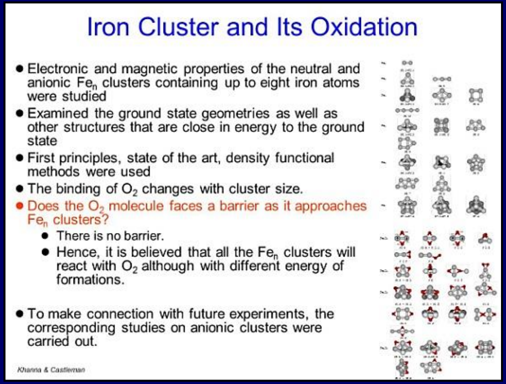


Nanoscience, Optics, & Chemical Reaction

- **Key Technical Results & Impacts**
  - Distributed ignition of a host of fuels in gas phase
  - Distributed ignition of liquid fuel sprays
  - Publicity by the *New Scientist* magazine
  - Minimum ignition energy measured for the first time, being 40 times less than any competing method
  - Light wavelength effect was of secondary importance (within visible and NIR range)
  - Preliminary work on photoacoustic
  - First principles, state of the art, density functional methods were used to understand the iron/oxygen interaction at the cluster level and see if O_2 faces a barrier as it approached Fe_n clusters.
  - Potential application for the next generation of the highly-efficient and environmentally-clean HCCI engines
  - Two patents filed at the USPTO
  - True autoignition control in homogenous fuel/air mixtures







A great candidate for LDRD at Sandia

Conclusions

- Award-winning and trend-setting scientific contributions with a broad range of applications
- User-inspired and boundary-spanning basic research with a clear path to application
- Time-tested, sustained, high-quality, innovative research work
- Effective leadership, management, and teamwork
- Wide network in academia, industry, and government
- Multidisciplinary research activities
- Broad-spectrum of research management experience with diversity in scope and scale
- Multi-organizational collaborative research at the national and international levels
- An innovative, dependable, and visionary professional/leader with entrepreneurial skills, who envisions, develops, markets and improves methods/processes to achieve desired results within schedule and budget

Questions ?