Enchanting Waves

G. Jagadeesh

Since 1909

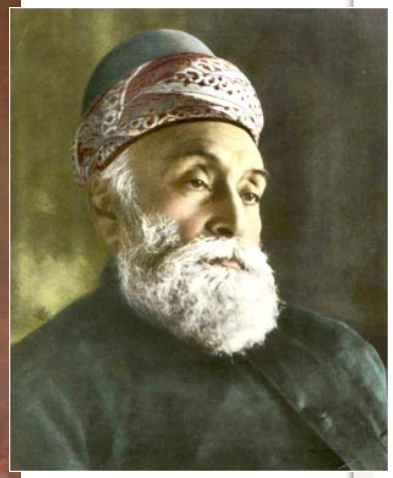
LABORATORY FOR HYPERSONIC AND SHOCKWAVE RESEARCH

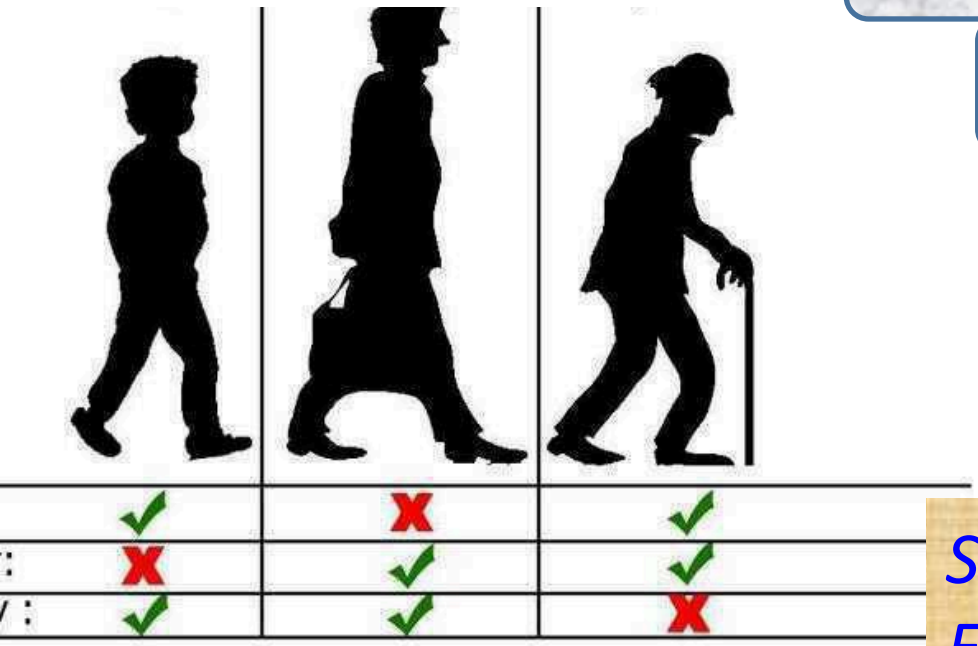
Applied Modeling & Simulation Seminar Series, NASA Ames Research Center, 2/4/2015

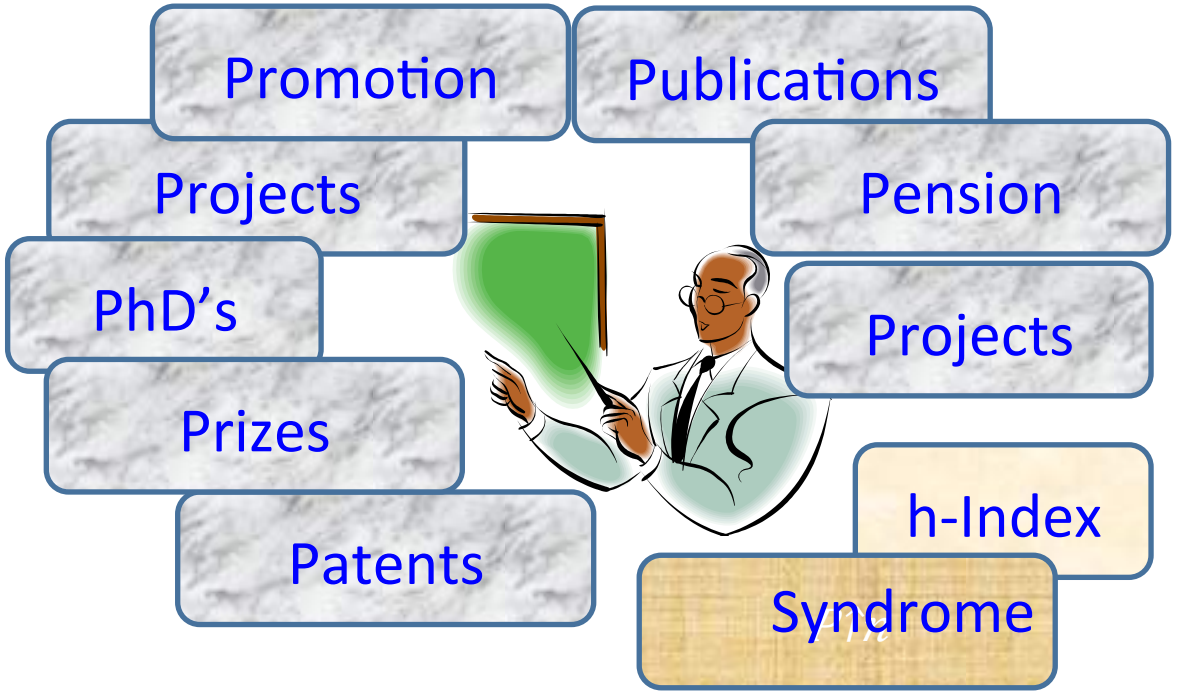
Thanks a million to all my colleagues And students

Bodhi tree sapling in front of LHSR is from the original tree under which Bhagawan Budha achieved Enlightenment about 2500 years ago in Bodhgaya

Founding Fathers of IISc





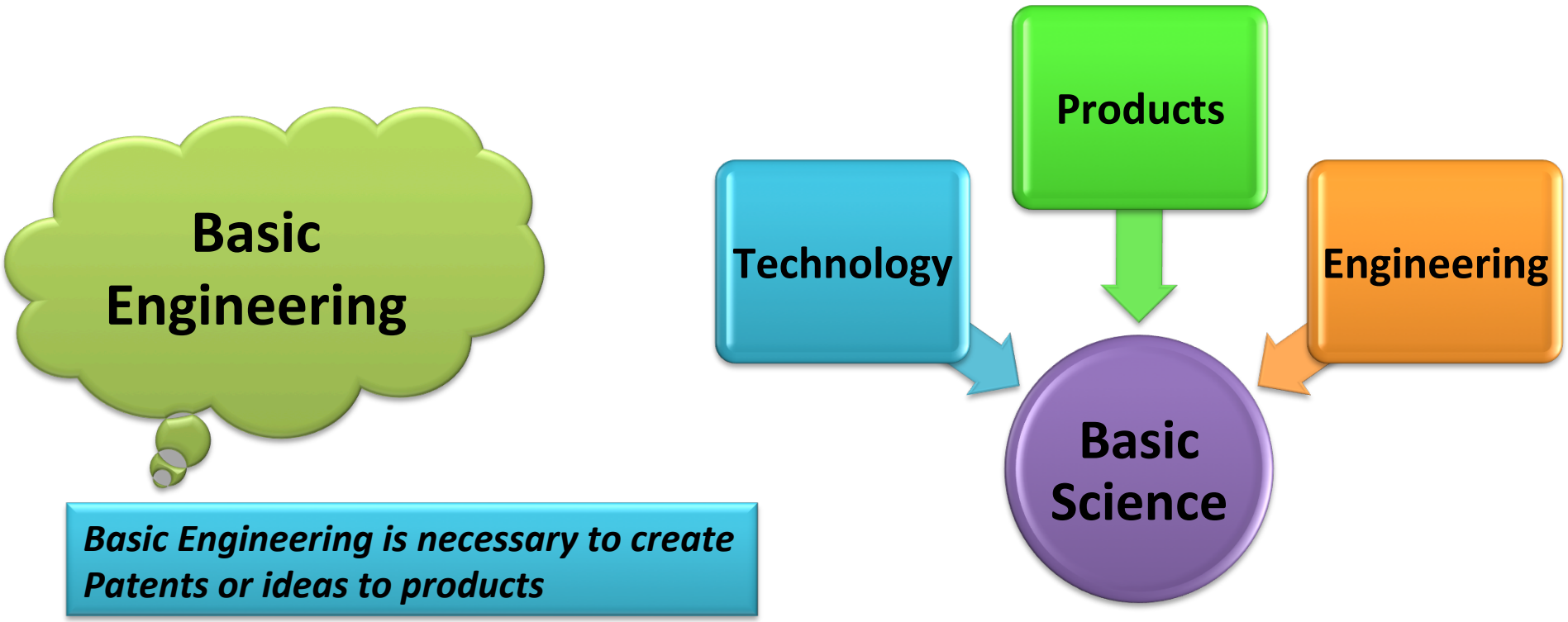


Is research really enjoyable????

Science is all about asking the question
Engineering is all about asking WHY NO
It becomes a technology when we stop
asking questions and we presume it wo

- Convert the INTELLECTUAL CAPITAL to products
- Transforming KNOWLEDGE into WEALTH

Ultimate manifestation of scientific knowledge are products useful to humanity at large…



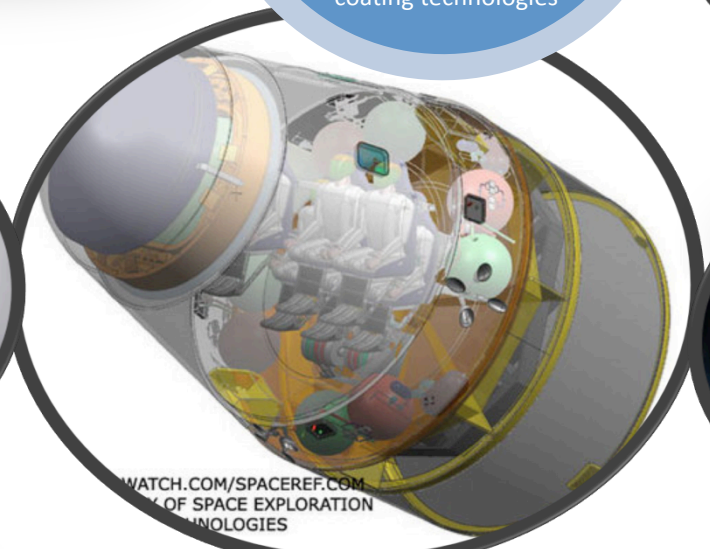
Basic Engineering is necessary to create Patents or ideas to products

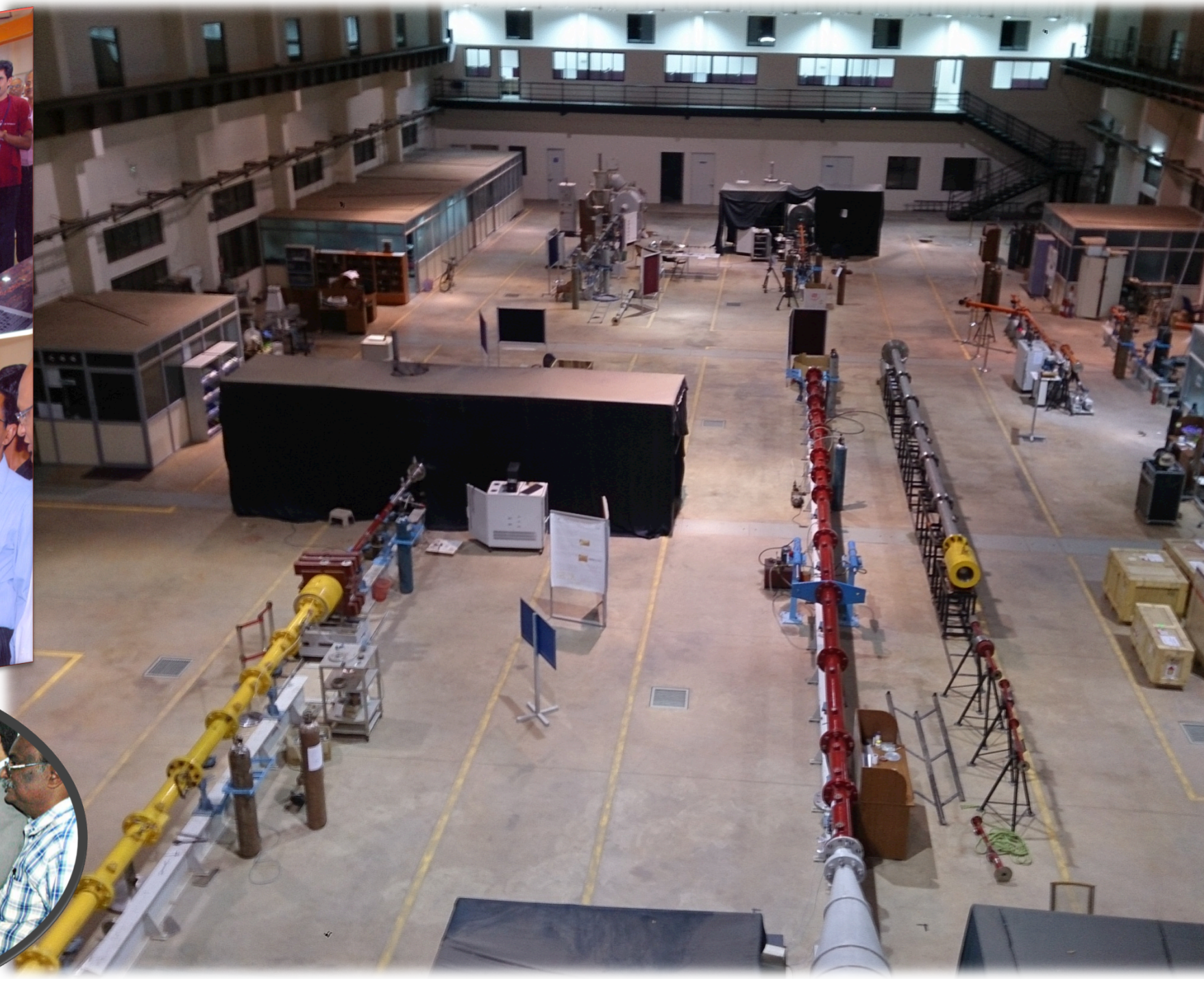
Needleless drug delivery systems

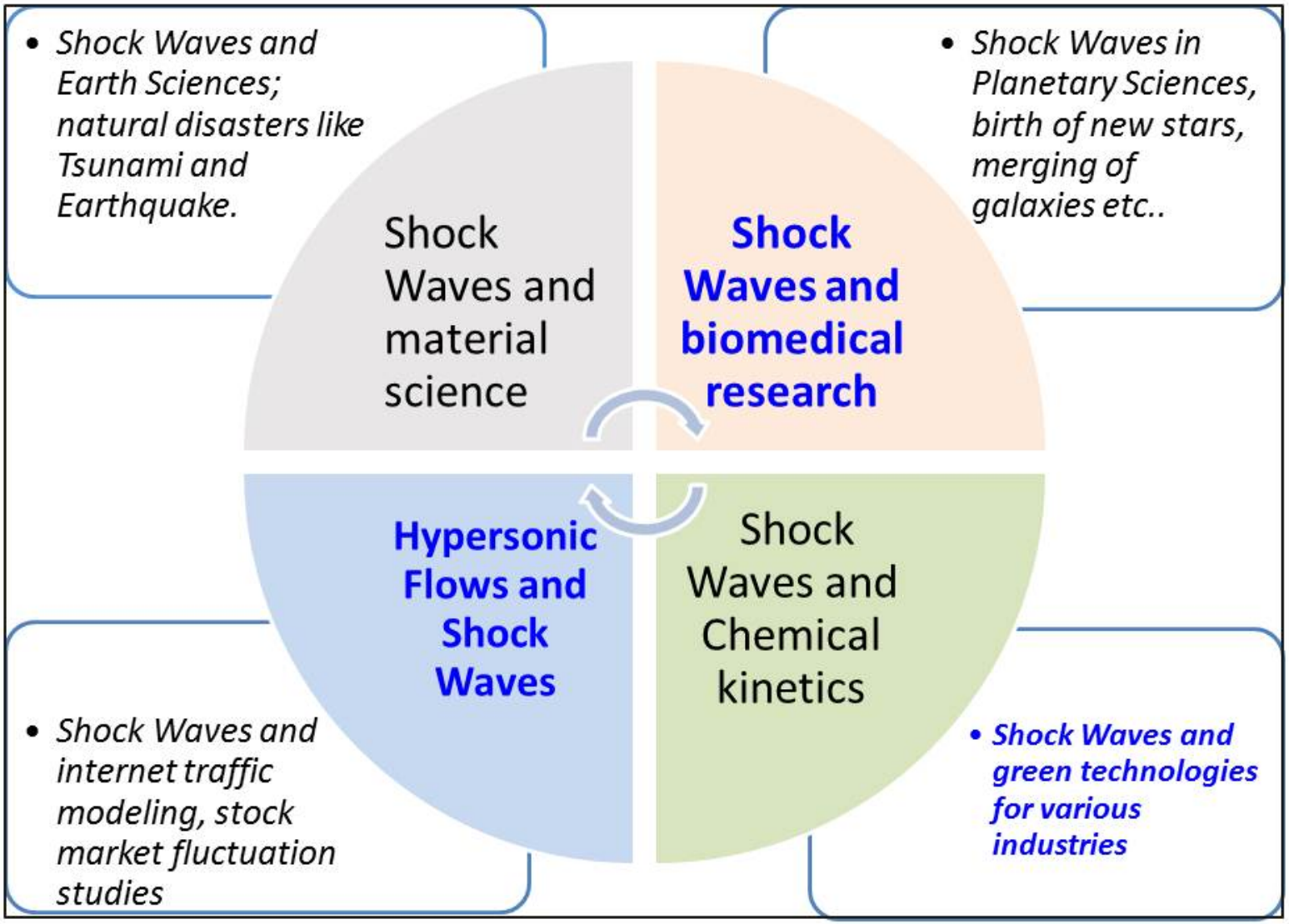
Bamboo Treatment using shock waves

Hypersonic flow control and Smart coating technologies

VISION…



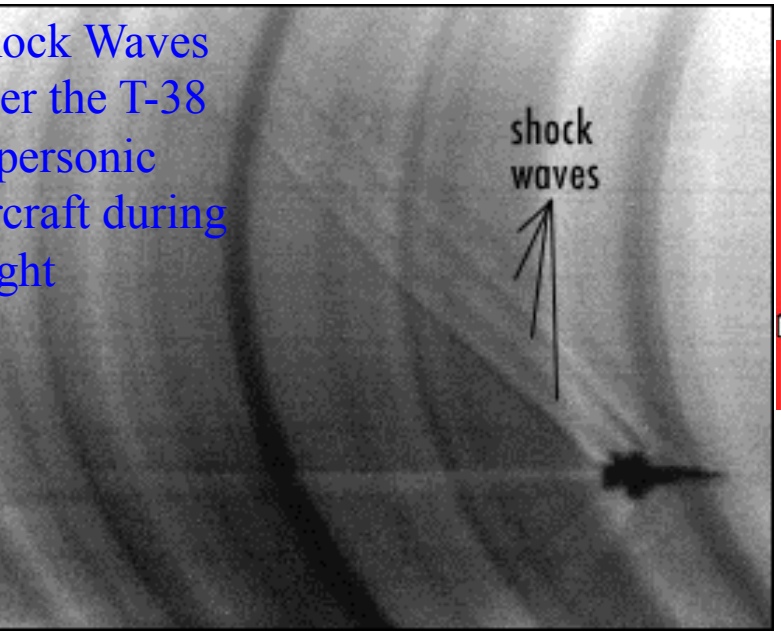


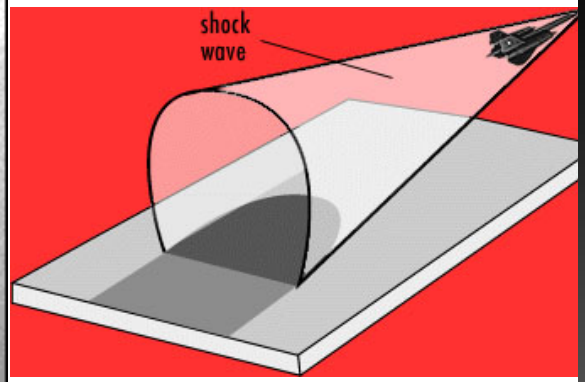

• Shock Waves and Earth Sciences; natural disasters like Tsunami and Earthquake.
Shock Waves and material science
Shock Waves and biomedical research
• Shock Waves in Planetary Sciences, birth of new stars, merging of galaxies etc..
Hypersonic Flows and Shock Waves
Shock Waves and Chemical kinetics
• Shock Waves and internet traffic modeling, stock market fluctuation studies
• Shock Waves and green technologies for various industries

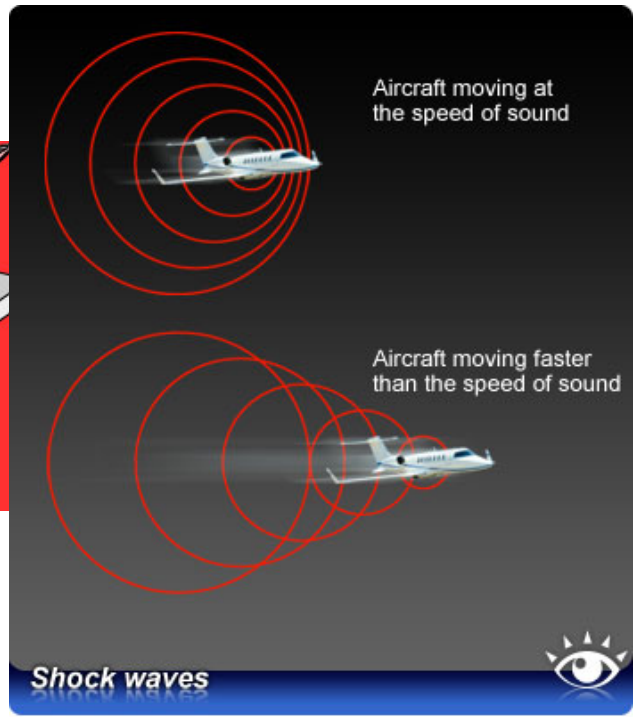
Enchanting Waves

he shock waves are strong perturbations in aerodynamics that propagate at supersonic spe
ndependent of the wave amplitude.

ypical shock thickness is of the order of 10^{-6} *m*.





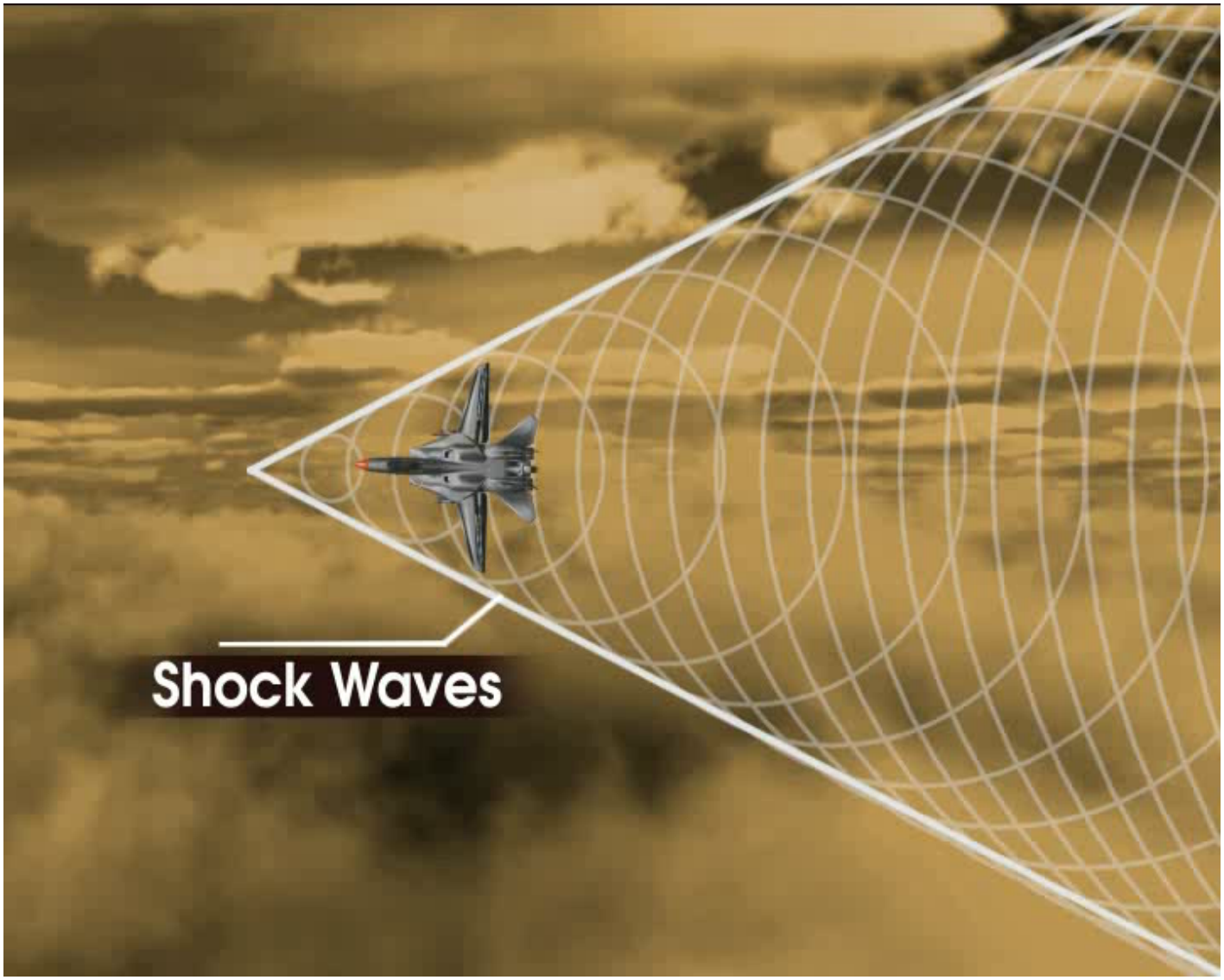


e of the unique features of shock wave propagation in any medium (solid, liquid or gases) is th
ity to instantaneously enhance the pressure and temperature of the medium irreversibly leading
ny fascinating scenarios.

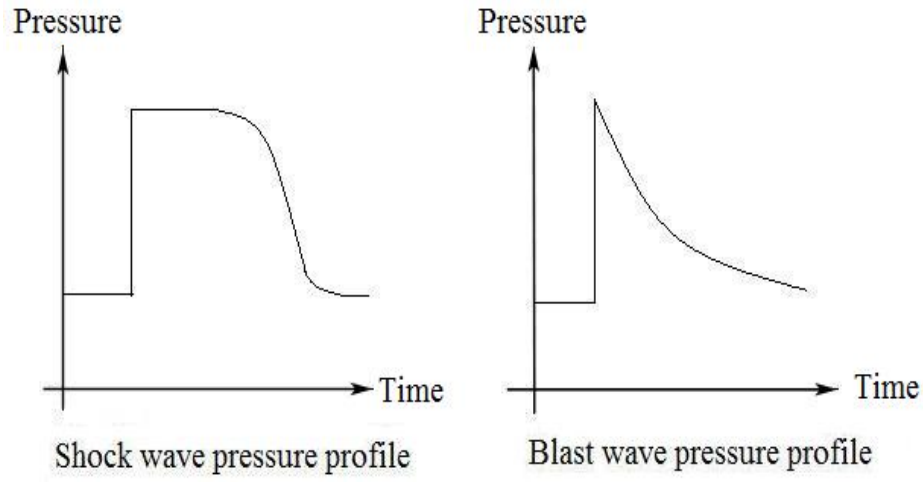
earchers world over are exploiting this behaviour of shock waves to develop novel experimental a
deling tools/technologies that transcend the traditional boundaries of basic sciences a
gineering.

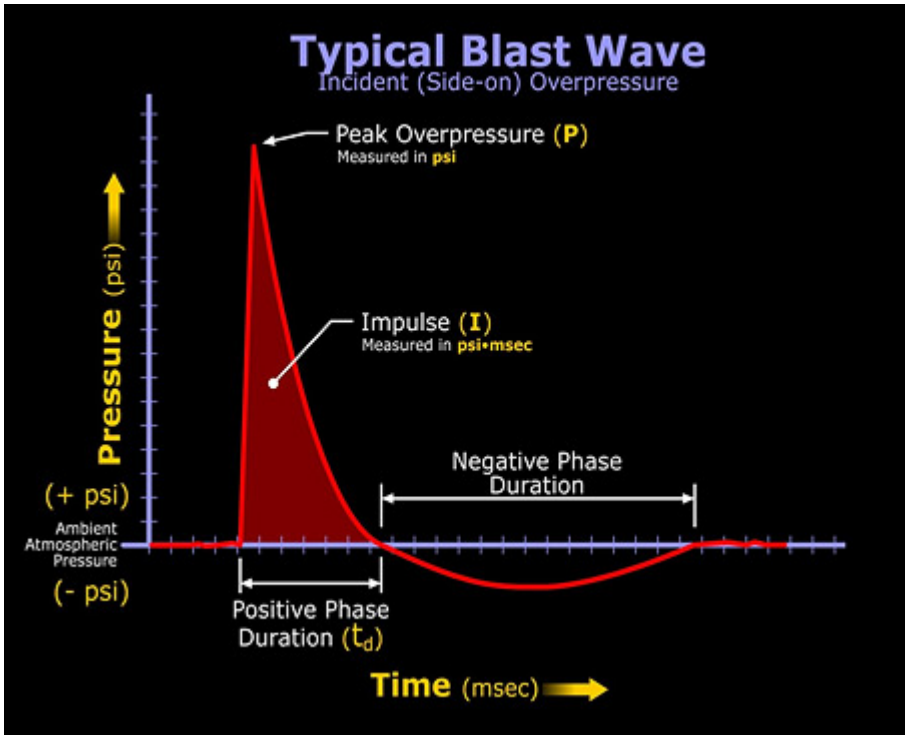
Shock Waves in real life scenarios

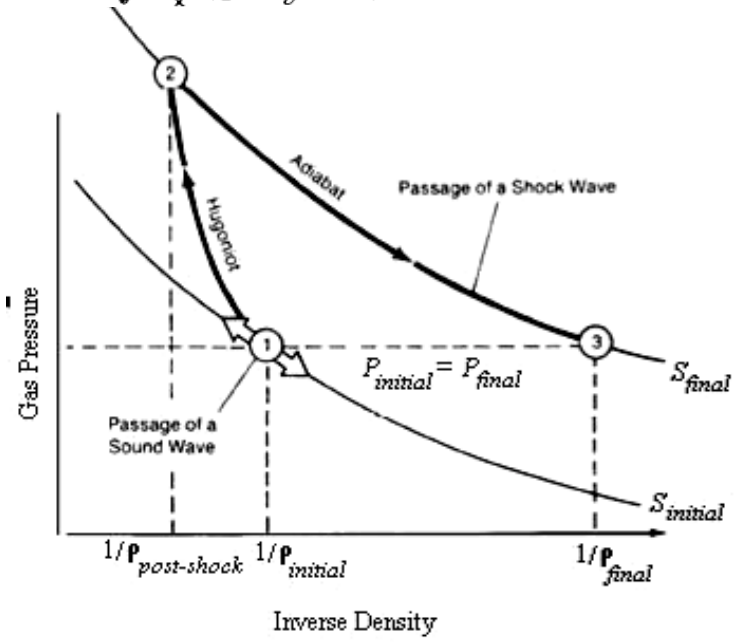
(NavSource Naval History)


Shock Waves

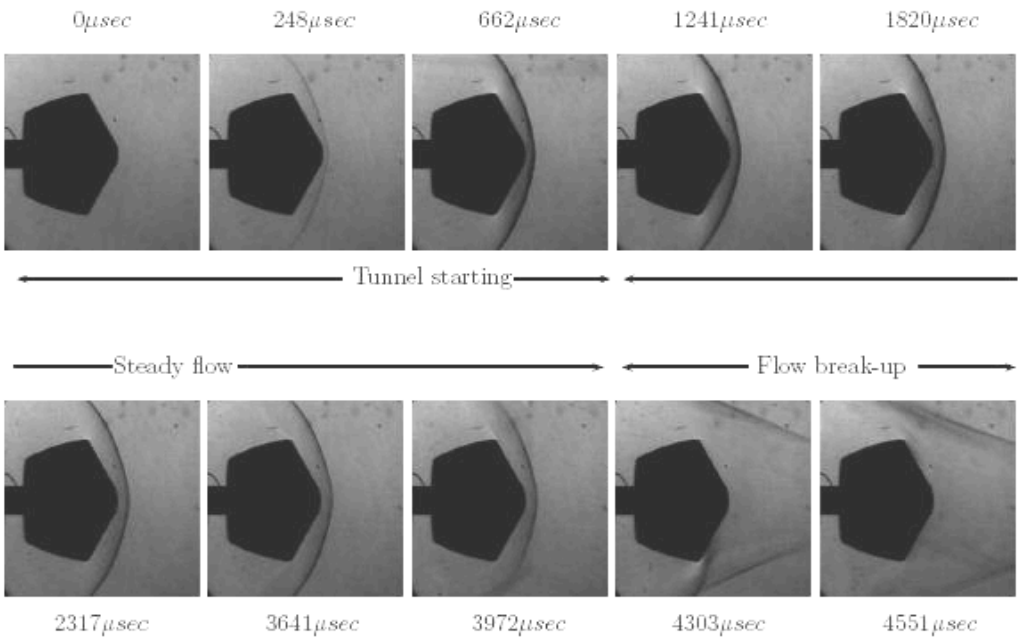
Physical implications of shock propagation

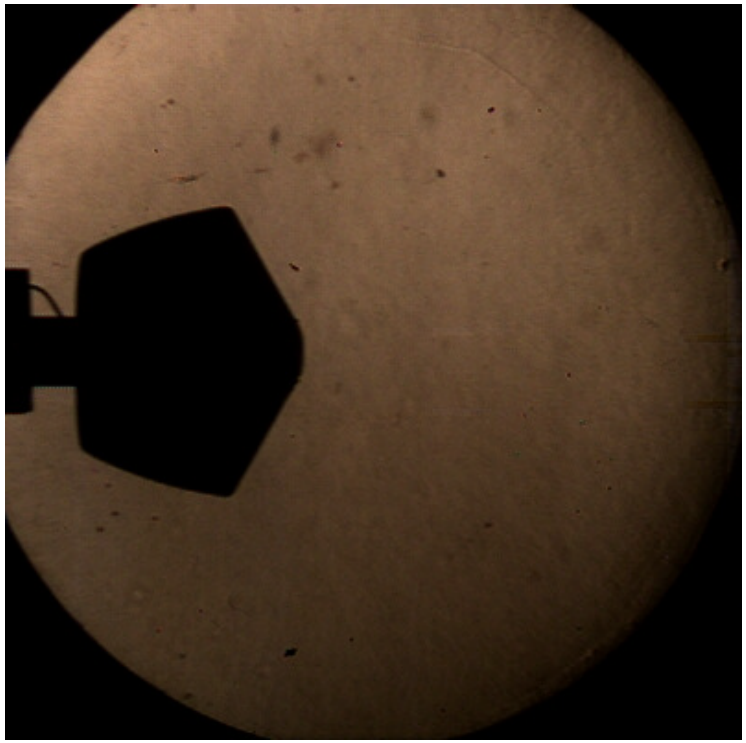


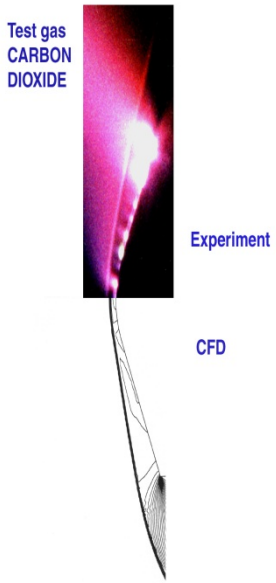


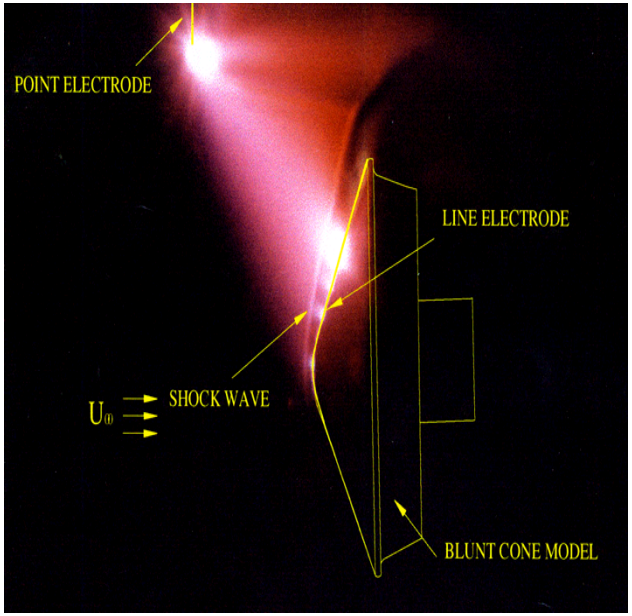


Seeing is believing !







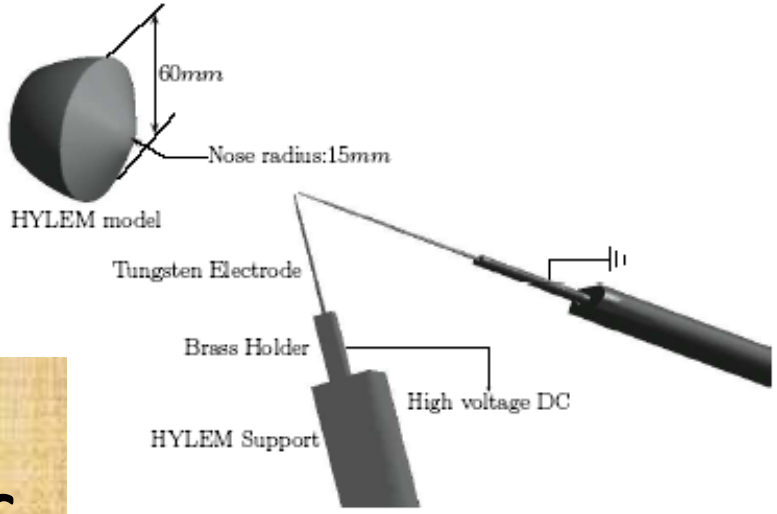


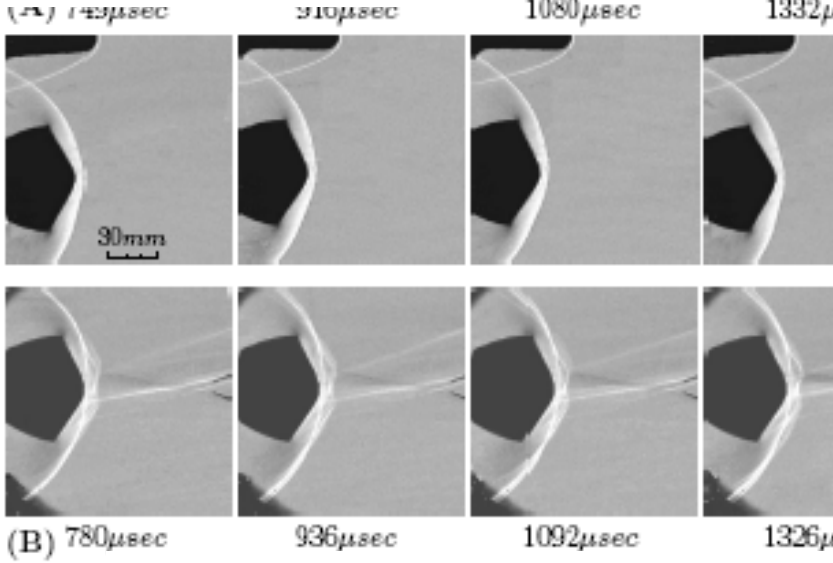
The Joy of seeing shock waves in the lab!

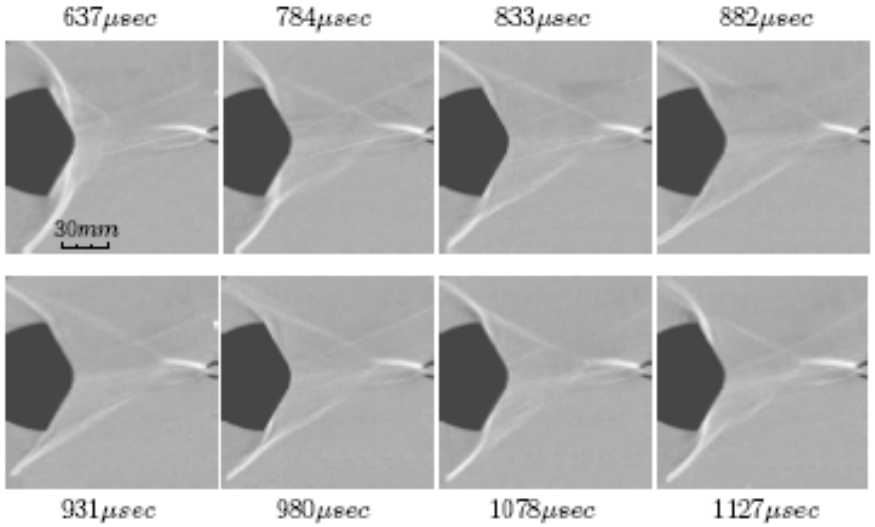
Effect of concentrated energy deposition on the aerodynamic drag of a blunt body in hypersonic flow

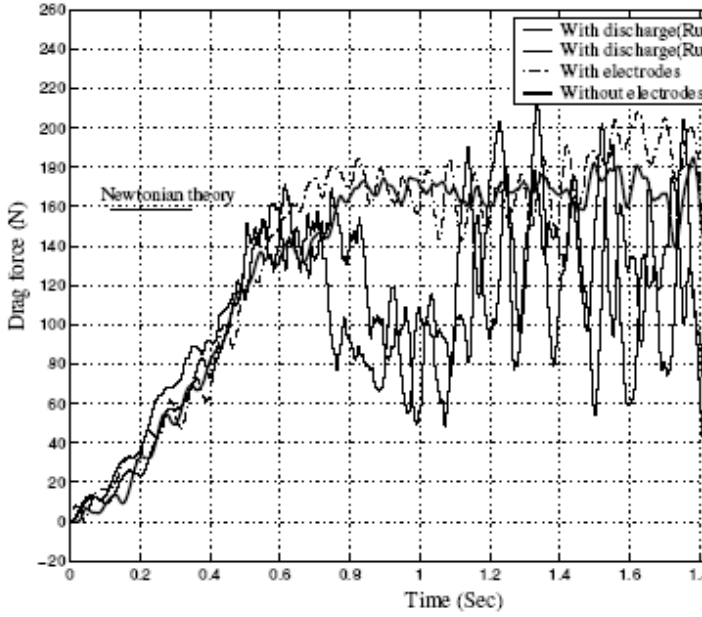
K. Satheesh and G. Jagadeesh
Department of Aerospace Engineering, Indian Institute of Science, Bangalore-560 012, India

Waves
ypersonic

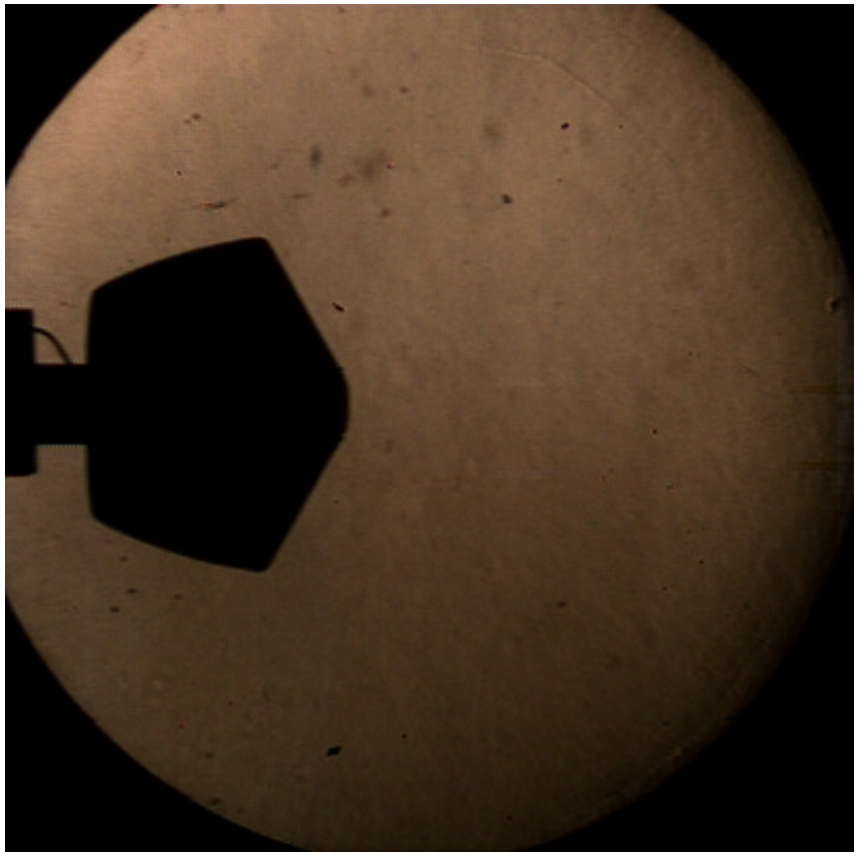


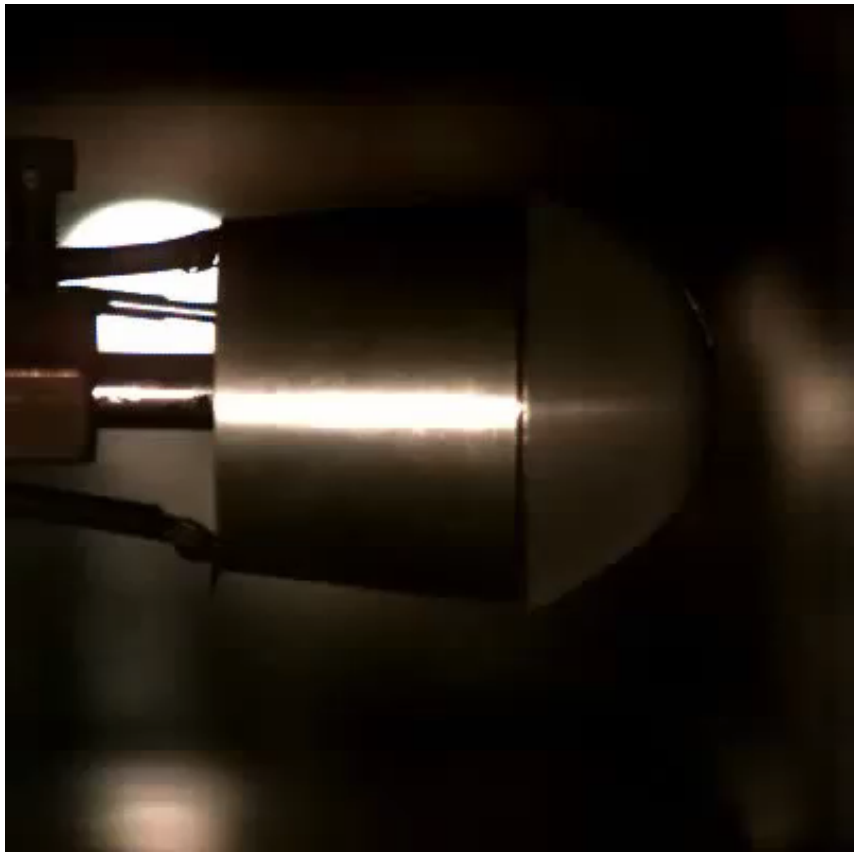






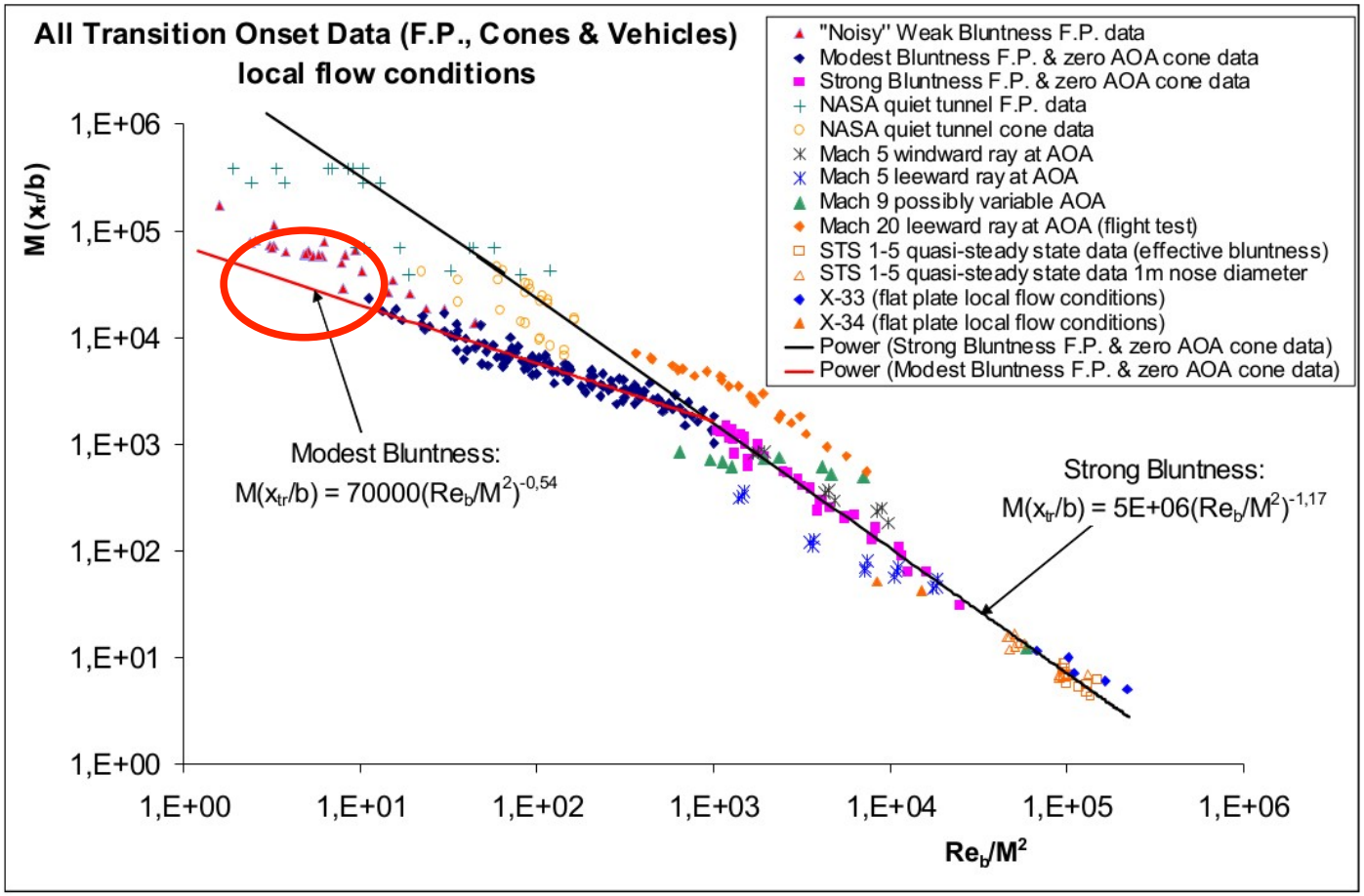
Reducing aerodynamic Drag using Smart Coatings





Vinayak Kulkarni, G. M. Hegde, G. Jagadeesh, E. Arunan and K.P.J. Reddy "Novel technique for hypersonic drag control using heat addition in the shock layer" Indian Patent Application 1583/CHE/2007

Hypersonic flow Transition Onset Correlation



G. Simeonides

Laminar-Turbulent transition correlation in supersonic / hypersonic flow - attached vs separated flows

ICAS 2008

No shock tunnel data in existing correlations. Red marks the area of our focus.

Experimental conditions – Shock Tunnel HST4

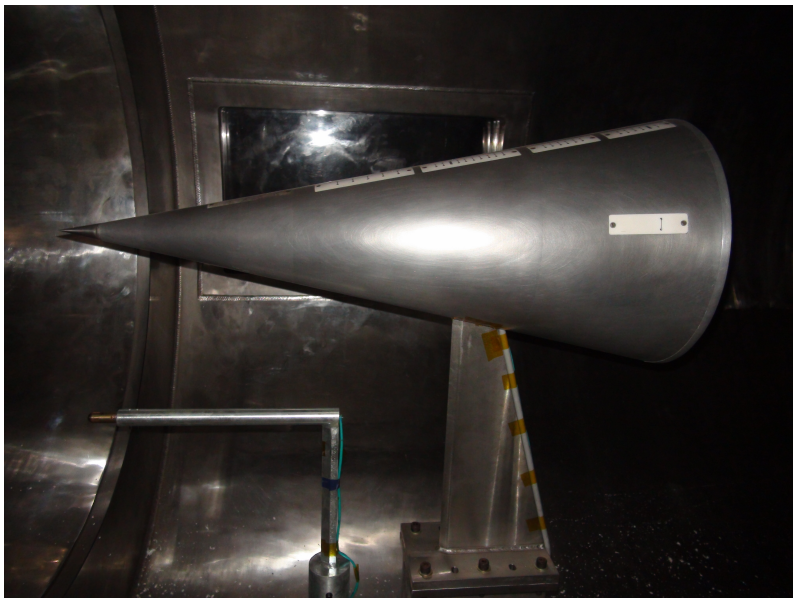
Shock tube length- 17 m
Internal Diameter - 165 mm
Outer Diameter - 200 mm

Nozzle exit Mach no. - 7
Nozzle exit dia. - 1 m
Reynold no. range - Upto 4 million/m

Enthalpy range - Upto 2 MJ/kg

Test time - 2-3ms

Experimental conditions – 800mm cone



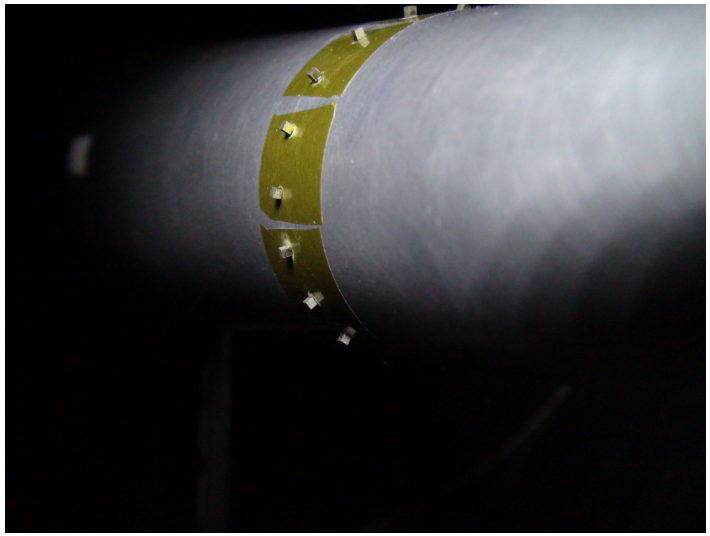
Cone angle – 24 deg

Cone axis length – 800mm

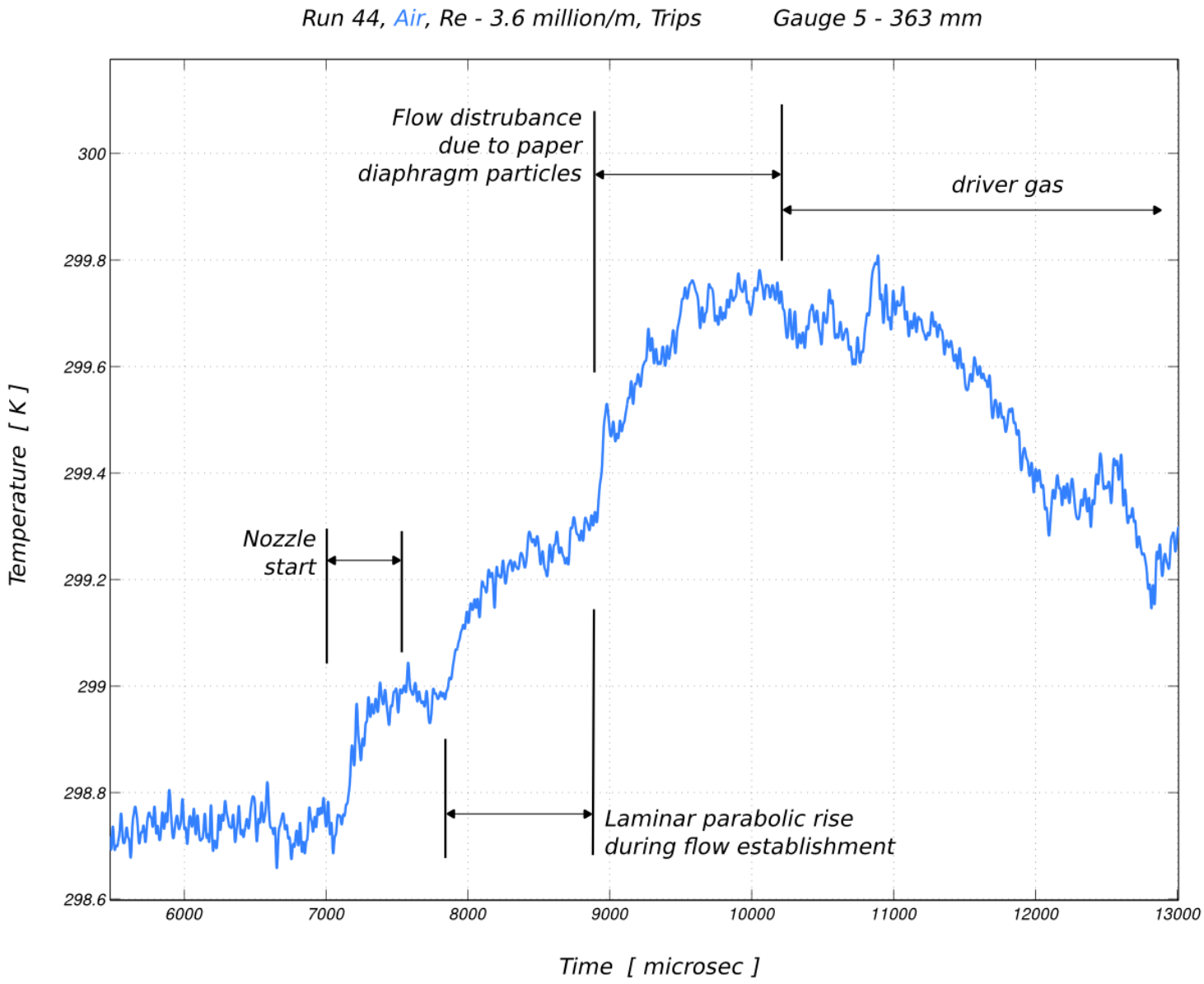
Aluminium alloy body with slots cut for MACOR inserts.

Platinum thin film sensors can be arranged along a ray.

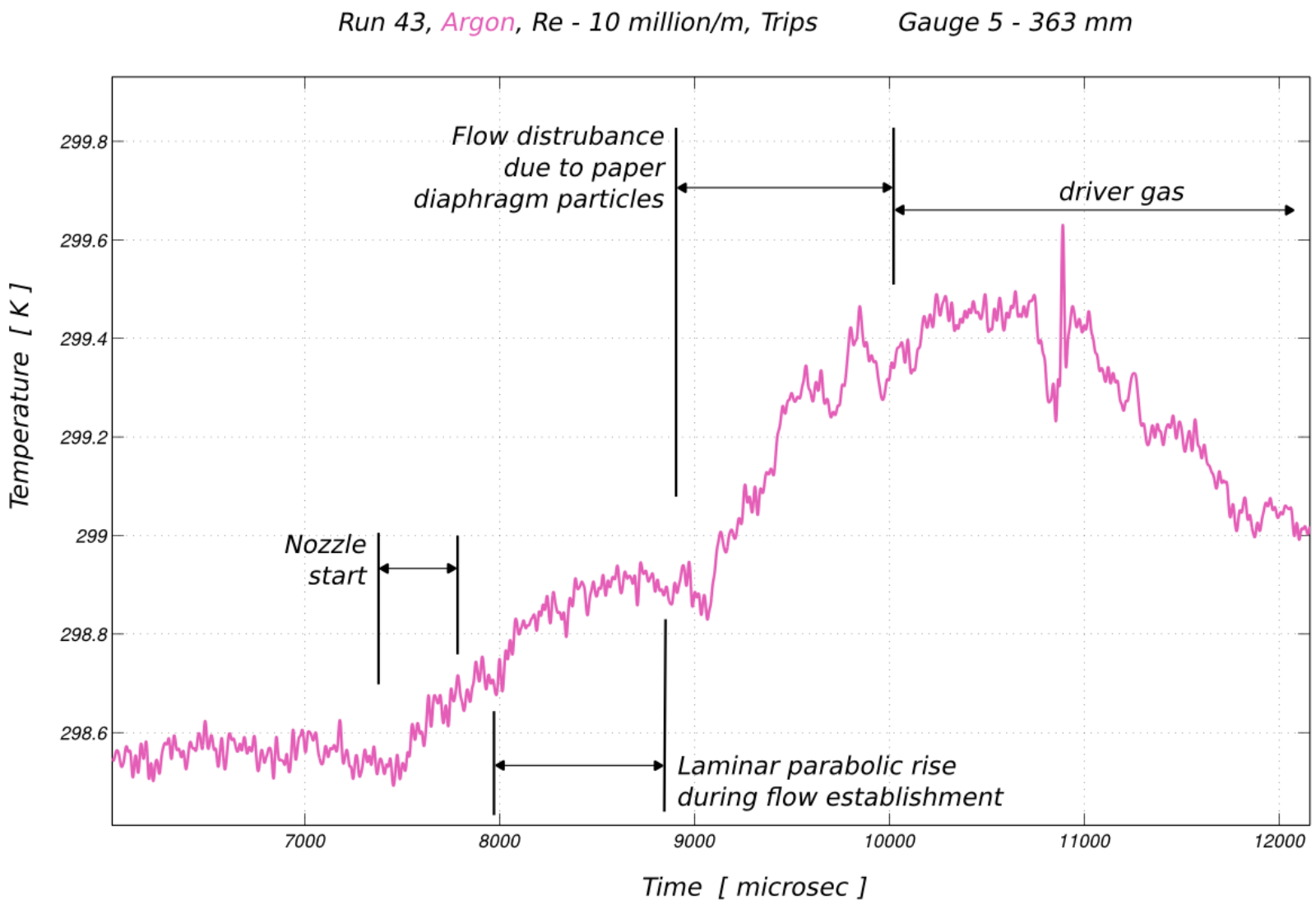
Experiments also conducted with sandpaper and isolated trip elements.



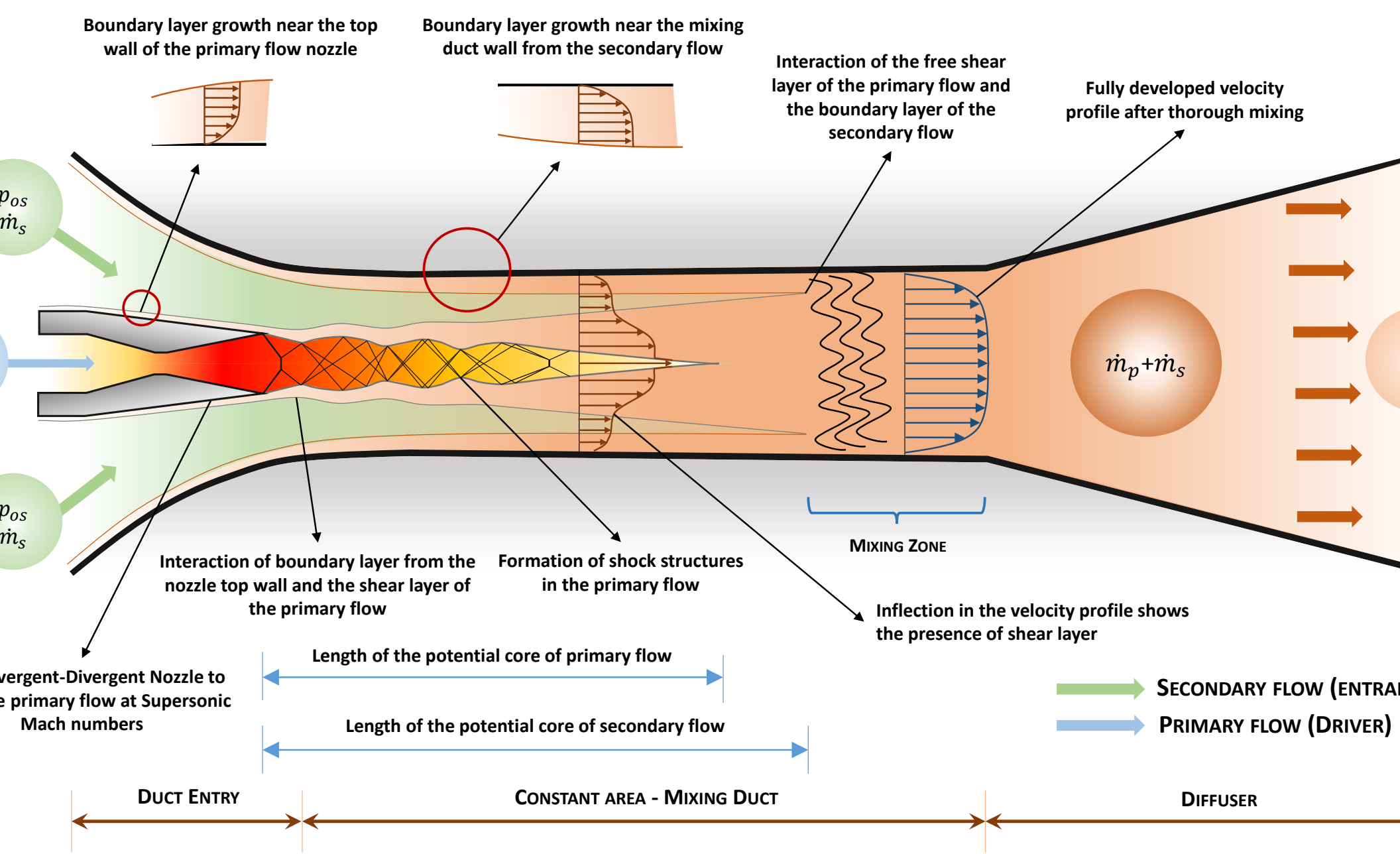
Air with isolated trip elements – Thin film signal



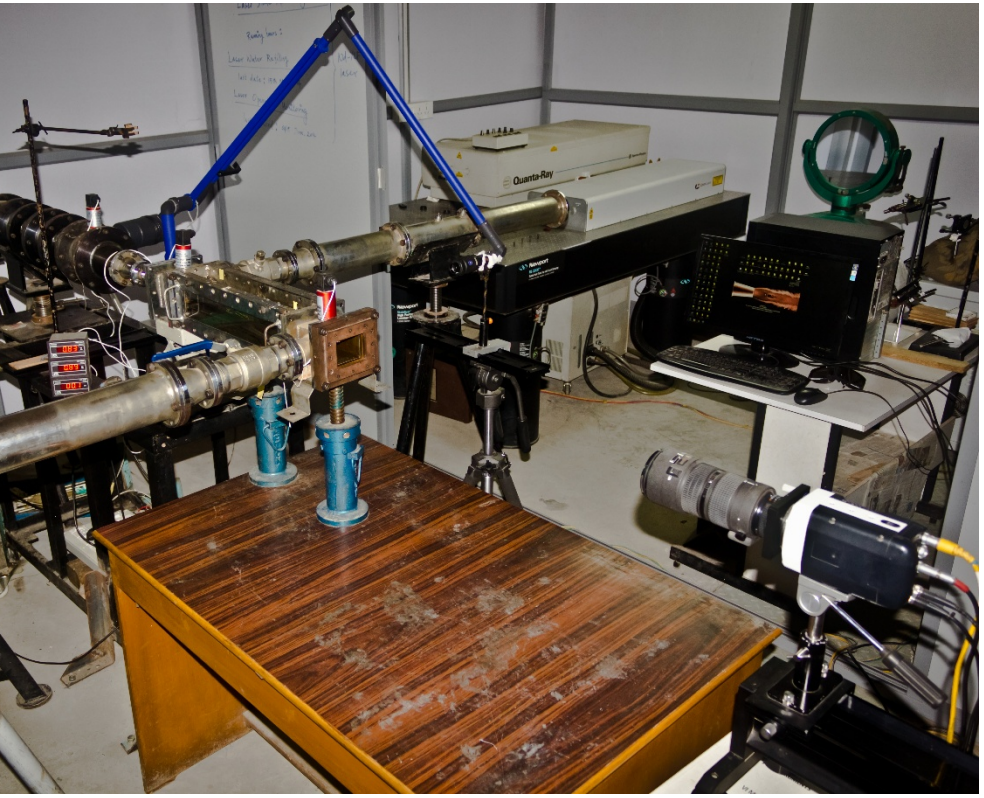
Argon with isolated trip elements – Thin film signal



Studies on supersonic mixing layers



vergent-Divergent Nozzle to
e primary flow at Supersonic
Mach numbers



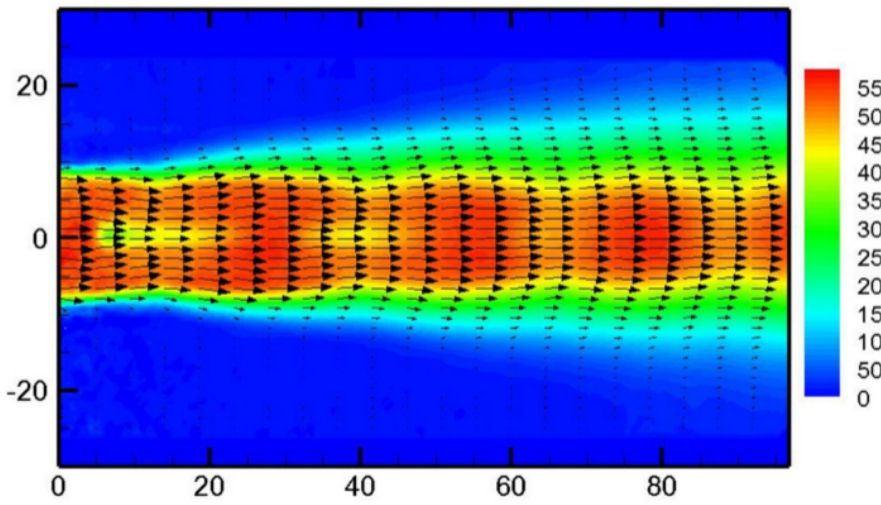


FIGURE 2: TIME AVERAGED PIV IMAGE OF AN AXI-SYMMETRIC CONVERGENT DIVERGENT CONICAL NOZZLE
MACH NUMBER OF 2.3 AT A PRESSURE RATIO OF 5.89 BAR. THE CONTOURS REPRESENT THE VELOCITY FIEL
IN M/S AND THE VECTOR ARROWS REPRESENT THE FLOW DIRECTION (AXIS DIMENSIONS ARE IN MM)

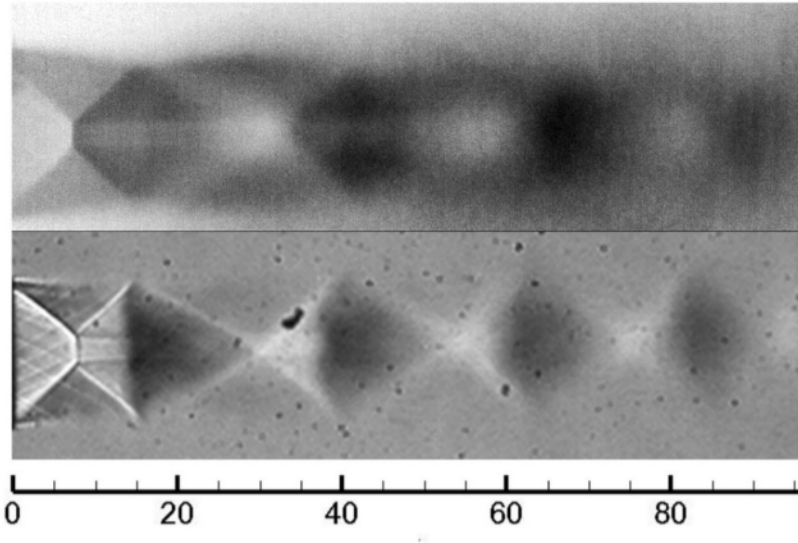


FIGURE 1: COMPARISON OF TIME AVERAGED QUALITATIVE (A) PLANAR LASER MIE SCATTERING (PLM
(B) SCHLIEREN IMAGE IN AN AXI-SYMMETRIC CONICAL CONVERGENT-DIVERGENT CONICALNOZZLE FOR A
NUMBER OF 2.3 AT A PRESSURE RATIO OF 5.89 BAR. FLOW IS FROM LEFT TO RIGHT. (AXIS DIMENSION IS IN

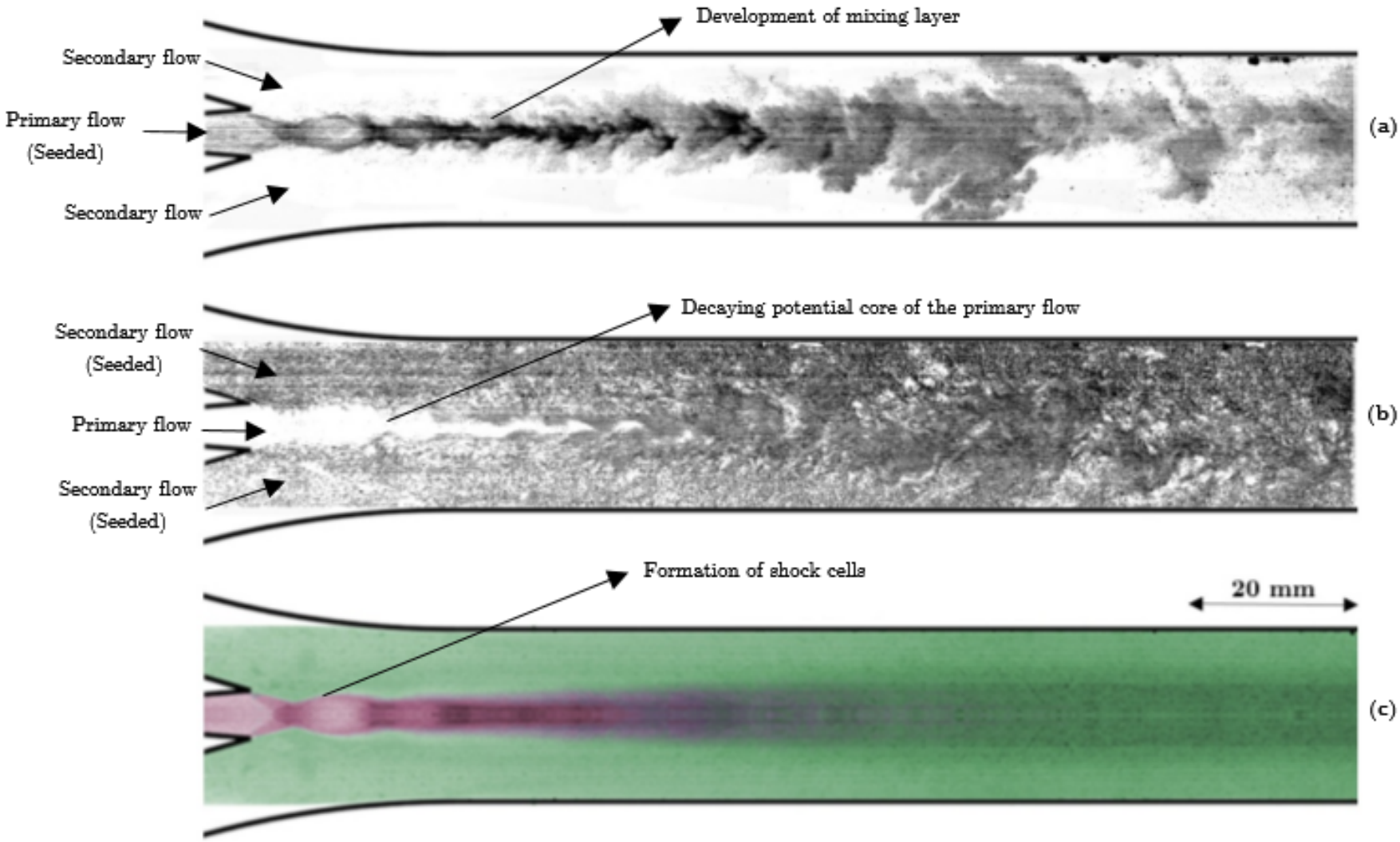
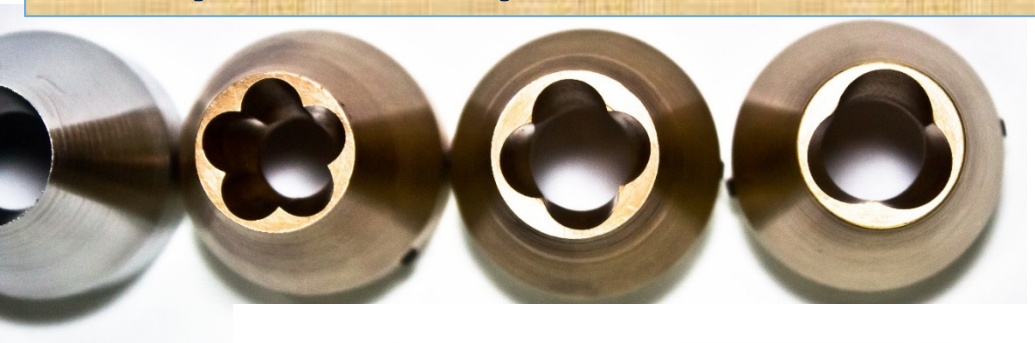
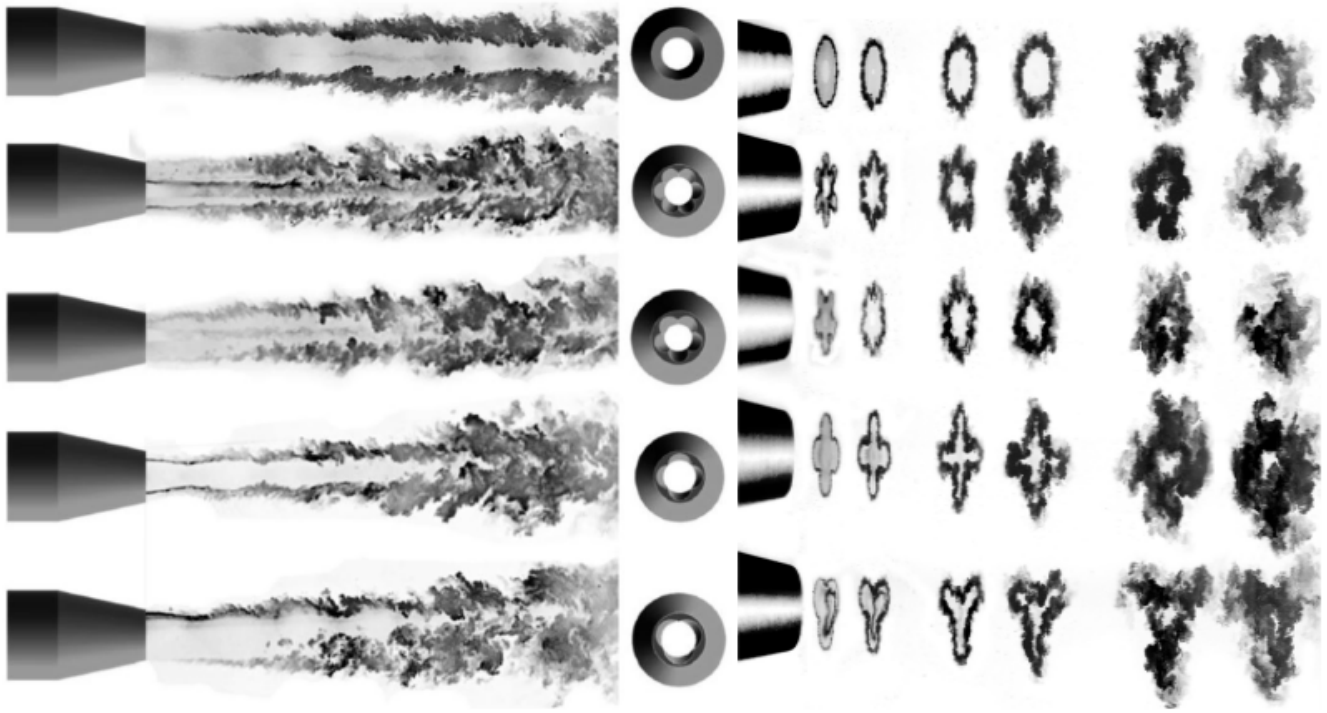


Figure 1: (a) Instantaneous PLMS image of the seeded primary flow (b) Instantaneous PLMS image of the secondary flow (c) Time averaged, superimposed image of primary (pale pink) and secondary (light green) flow (different color scales are used for the sake of clarity). Flow is from left to right at an operating total pressure of 5.89 bar with a design Mach number of 2.0 in the primary flow nozzle.

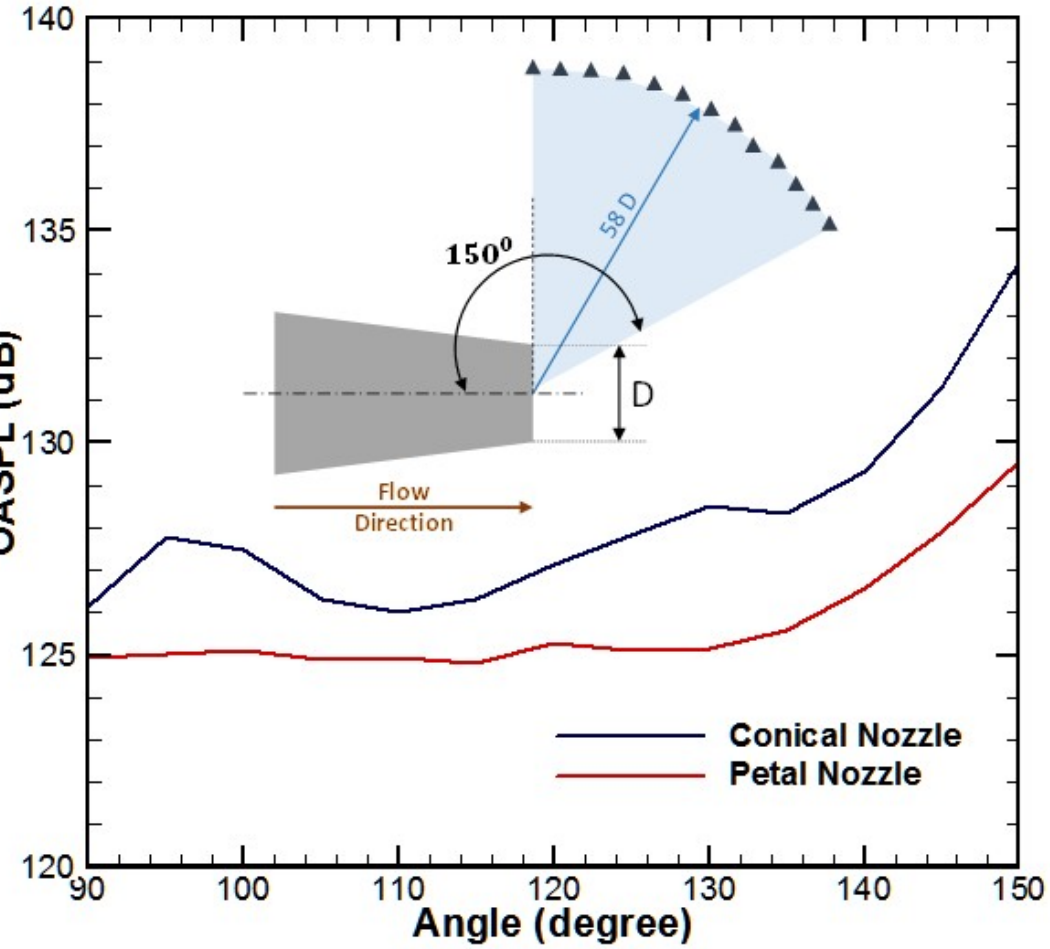
Petal Nozzles for enhanced mixing at supersonic speeds

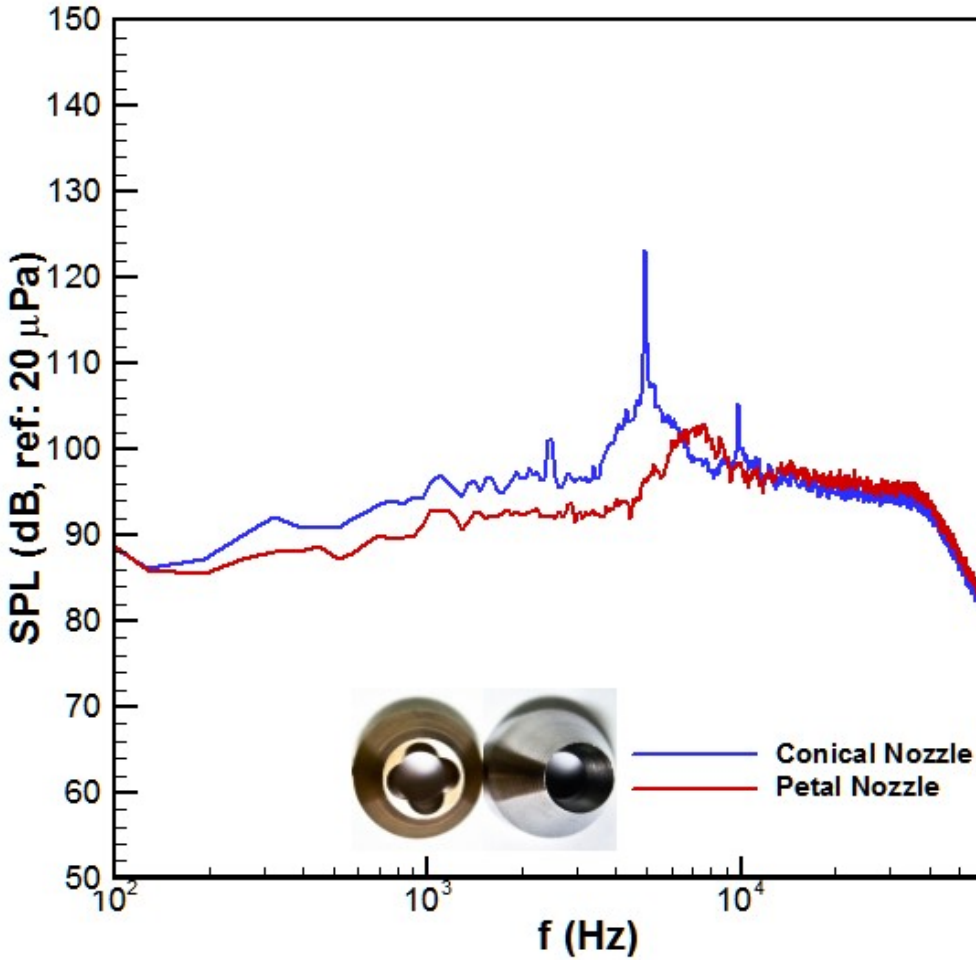




Supersonic scree
Reduction using
Elliptically tipped
nozzles

FIGURE 2: Stagnation pressure 6 bar-g (a) Central axial plane images of conical, 6(M=2.5), 5(M=2.5), 4(M=2), 3(M=2) petal nozzles (b) Transverse cross sectional views at 10, 20, 40, 60, 100 & 140 mm from nozzle exit of 6(M=2.5), 5(M=2.5), 4(M=2), 3(M=2) petal nozzles

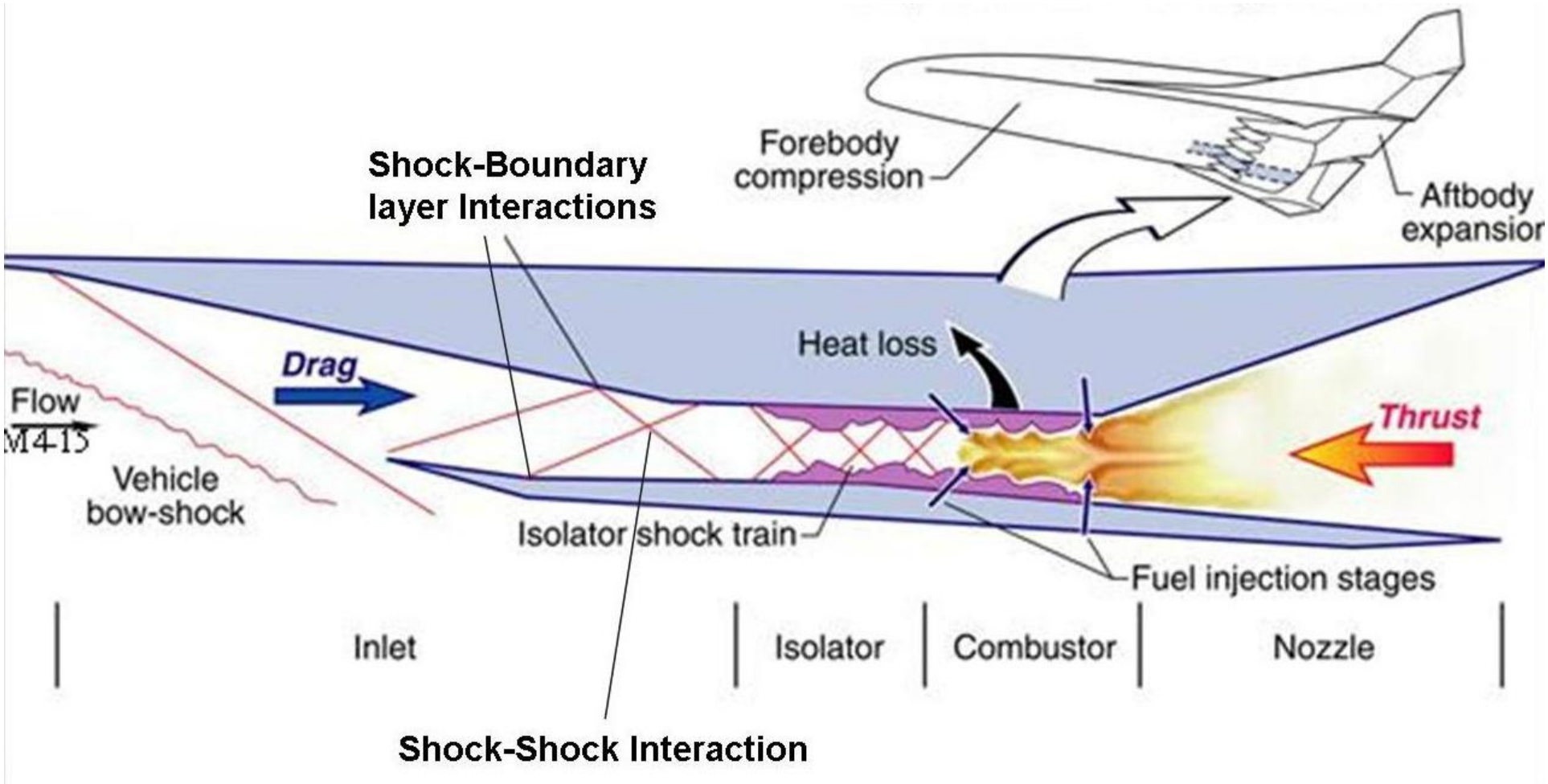




Design Mach Number of the Nozzle: 2.0
Operating Pressure Ratio: 4.28

Aero-Acoustics Characteristics of the Conical and the Petal Nozzle

Chemistry of fuel virtually dictates the success of Supersonic Combustion process



Chemical kinetics modeling for JP7

OBJECTIVE :

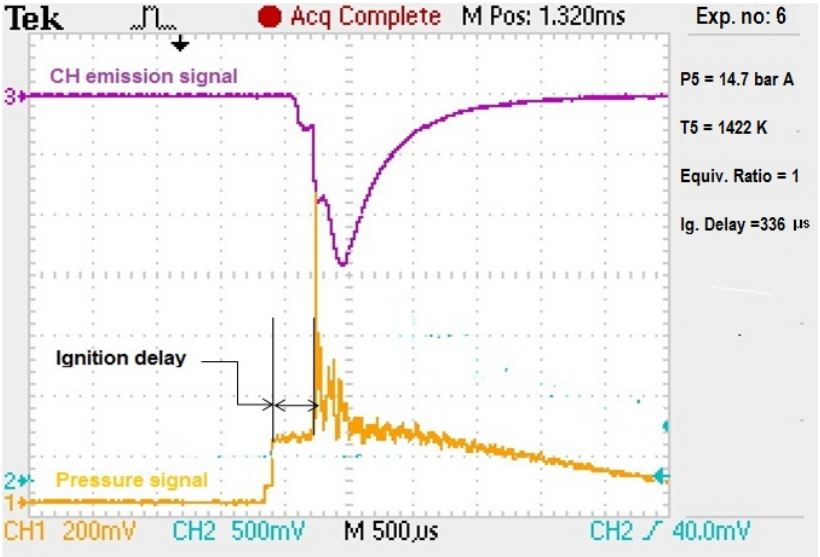
1. Experimentally measure the ignition delay using “CST”.
2. Model the reduced chemistry of the fuel based on ignition delay.
3. Study the effect of chemical kinetics on a “generic hypersonic combustor” using CFD tools.

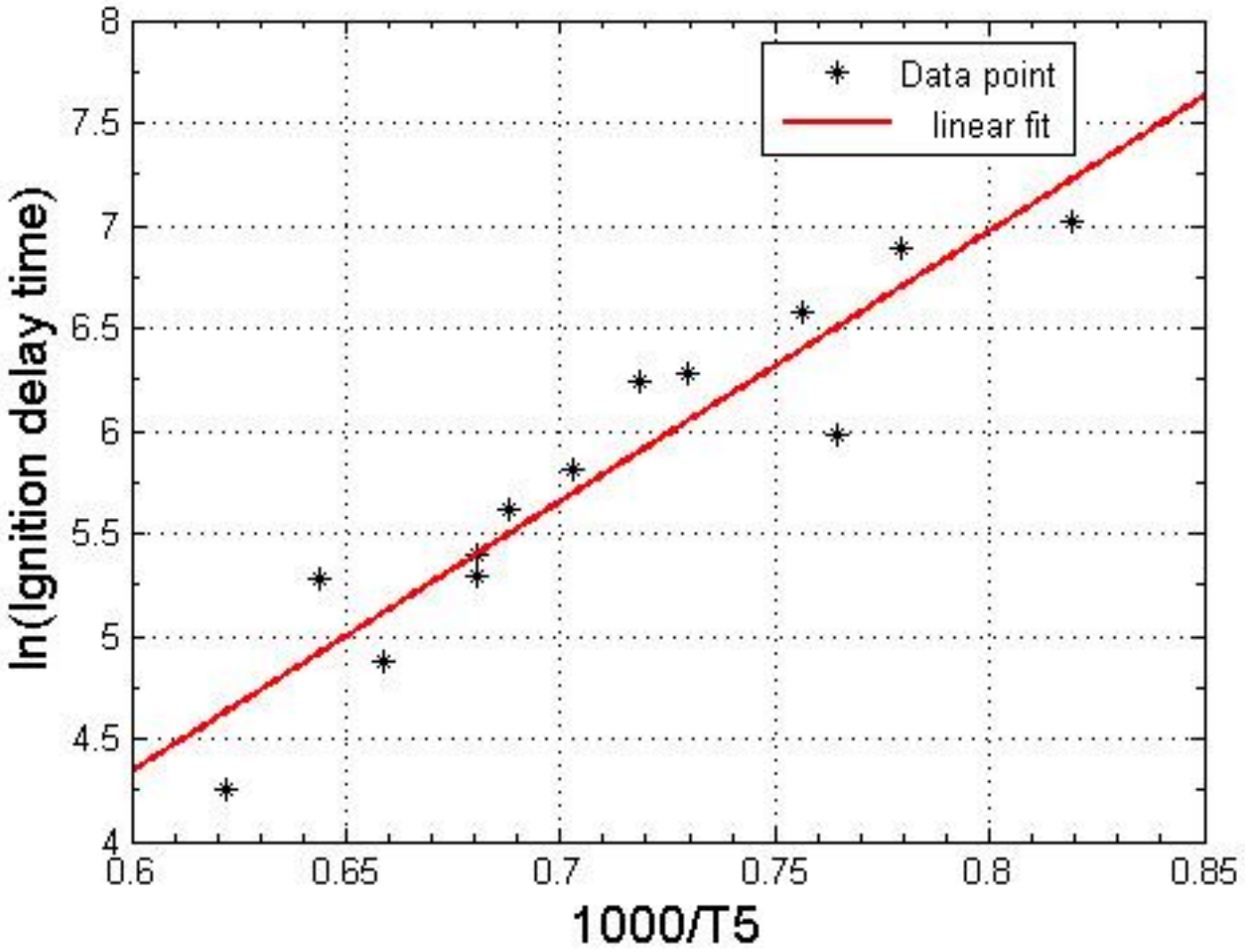
FUEL:

1. Sample fuel is called JP7(Equivalent)
2. It is a combination of 33 hydrocarbon molecule
3. Fuel was indigenously developed in DRDL.
4. It’s a potential fuel for hypersonic program.

Experiment

1. Pressure(P5) varies between 12 to 18.7 bas (abs.)
2. Temperature(T5) varies between 1220K to 1610K
3. Parameters monitored
    1. *Three pressure channels*
    2. *One temperature channel*
    3. *CH emission via mono-chromator*
4. Ignition delay in the range 70 to 920 **µs**
5. Results obtained are plotted

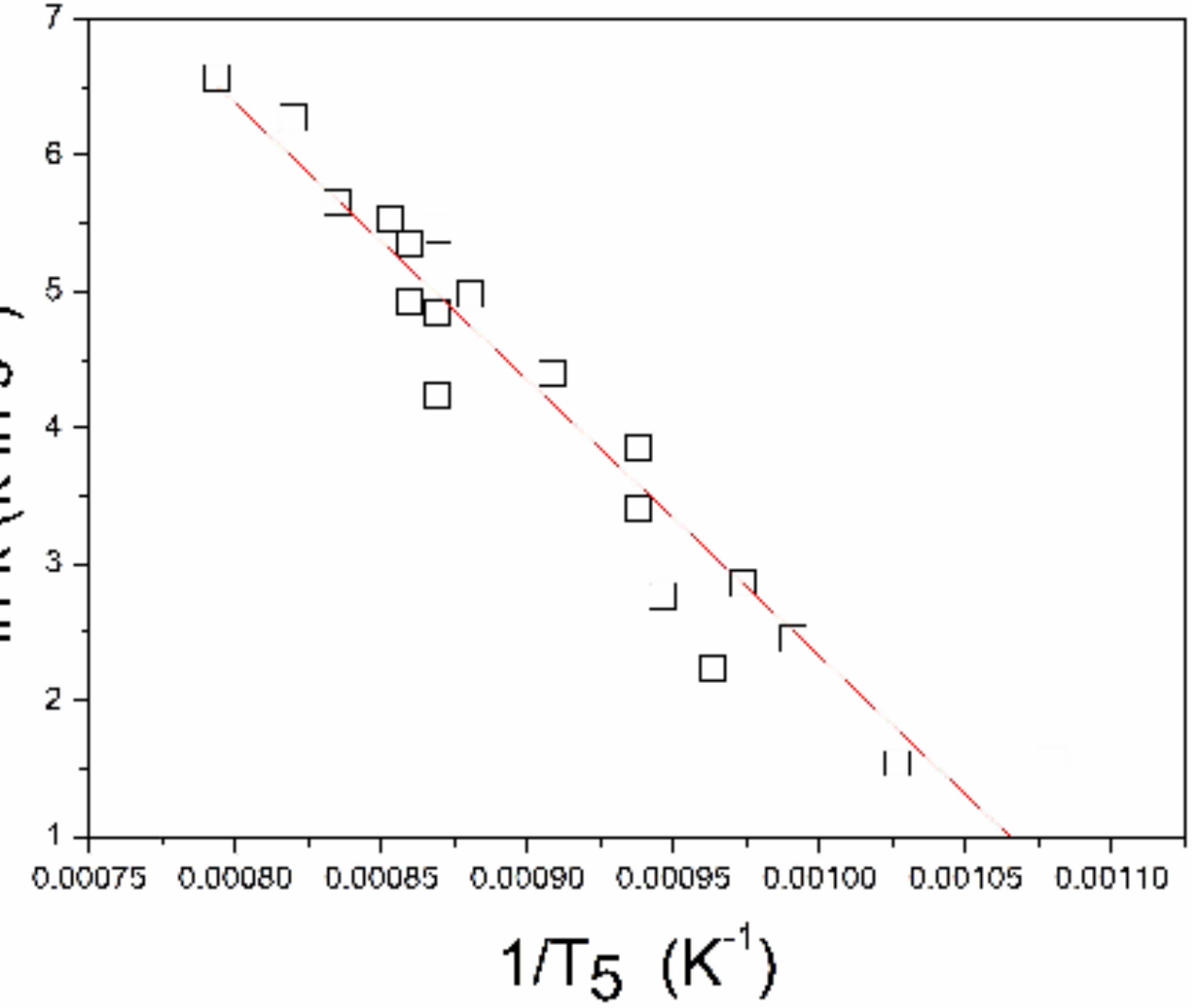




Plot1: ignition delay(μs) Vs Temperature

MODELING OF REDUCED CHEMISTRY BASED ON IGNITION DELAY IS UNDER PROGRESS

Arrhenius plot for overall decomposition of 3-carene



$$k = 10^{(9.82 \pm 0.52)} exp(\frac{-40.28 \pm 2.61}{RT})$$

sed pyrolysis and
ation mechanism

nits are in cm^3-mole-
cond, K, cal-mol^{-1}

Sl.No.	Reaction	A	n	E_a
1	C10H16 = C10H16(T)	1.00E+16	-0.45	55000
	REV /1.0E+08 0.6 0.0/			
2	C10H16(T) = C10H16(A)	2.40E+12	0	24590
3	C10H16(A) = C10H16(F)	1.10E+13	0	38180
4	C10H16(F) = C10H15 + H	1.94E+17	0	60000
5	C10H15 = C9H12 + CH3	1.13E+17	0	60000
6	C9H12 = C4H5(i) + C5H7	1.16E+16	0	55000
7	CH3+H=>CH2+H2	6.03E+14	1.2	15100
8	CH2+CH2=>C2H2+H+H	2.04E+15	1.2	10990
9	C4H5(i) + H = C4H6	6.00E+13	0	-200
10	C4H5(i) + CH3 = C5H8	6.00E+11	0	-1300
11	C5H7 + H = C5H8	8.00E+12	0	-2460
12	C4H5(i) => C4H5(n)	7.37E+15	0	60480
13	C4H6 + H = C4H5(n)+H2	3.40E+11	0.3	6000
14	C4H5(n)= C2H2 + C2H3	9.00E+13	0	46900
15	C4H5(n) + C2H2 = C6H6 + H	2.00E+13	0.52	3740
16	C2H3 = C2H2 + H	6.50E+13	0	3299
17	C2H3 + C4H5(n) = C6H8	2.00E+14	0.7	100
18	C7H8 + H = C7H7 + H2	2.20E+12	0	8200
19	C7H7 +CH3 = C8H10	1.20E+12	0	50
20	C3H3 + C3H3 = C6H6	3.00E+11	0	0
21	C5H7=C2H3+C3H4	6.00E+16	0	68000
22	C4H5(n) + C3H4 = C7H8 + H	6.00E+13	0.52	3700
23	C2H3+C2H3=C4H6	2.00E+13	0	0
24	C3H4 + H = C3H3 + H2	9.00E+10	0	1500
25	C4H5(n)+H=C4H6	1.00E+13	0	0
26	C3H3 + C3H3 = C6H5 + H	5.00E+12	0	0
27	C6H5+CH3=C7H8	6.00E+13	0	0
28	C5H7+C3H4=C8H10+H	5.00E+13	0	3000
29	C2H3+C3H3=C5H6	4.00E+16	0	0
30	C3H3+H=C3H4	6.00E+12	0.0	0.0
31	H+H+M=H2+M	3.80E+05	0	0

Shock waves and Solid State Chemistry

Material Used in Thermal Protection System

Silica tiles (< 1400°C)

Carbon / Carbon composites (< 1600°C)

Carbon -Silicon Carbide composite (< 1600°C)

Metallic TPS (< 1200°C)

Ultra High Temperature Materials Ceramics (UHTC)

CeO_2, ZrO_2, $Ce_{0.5}Zr_{0.5}O_2$, $Ce_{1-x}Cr_xO_{2+\delta}$, TiO_2, SiO_2, Si_3N_4 and SiC

C/SiC, SiC/SiC composite (< 1800°C)

Zirconium Di-boride/Hafnium Di-boride and their composite (>2500°C)

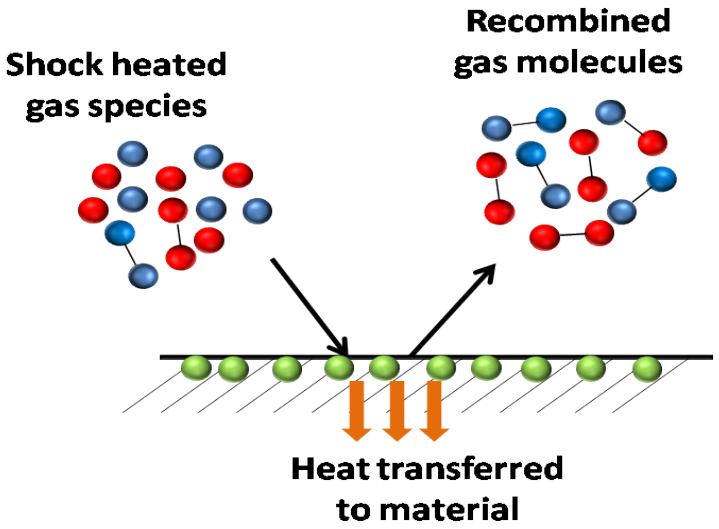
Strong Shock Absorbing Materials (above 25 G Pa)

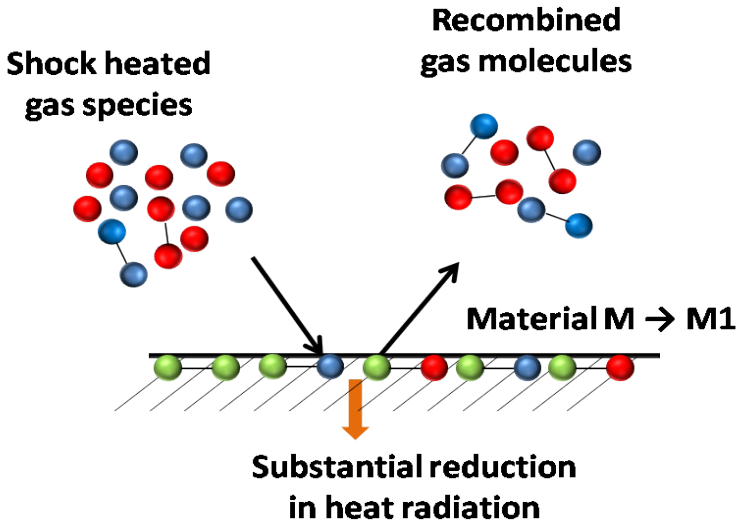
MoS_2, $MoSe_2$, WS_2, etc.

Nano-powders

Nano Diamond Carbon , C_{60}, Graphite Nano particles, Glassy carbon, YSZ, TiO_2 , SiO_2, SWCNT etc..

Surface Re-combination Reaction
(2 and 3 body surface chemical reactions)





Catalytic surface reaction

$$SiO_2\,(s) + N_2\,(g) \longrightarrow SiO_2\,(s) + N_2$$

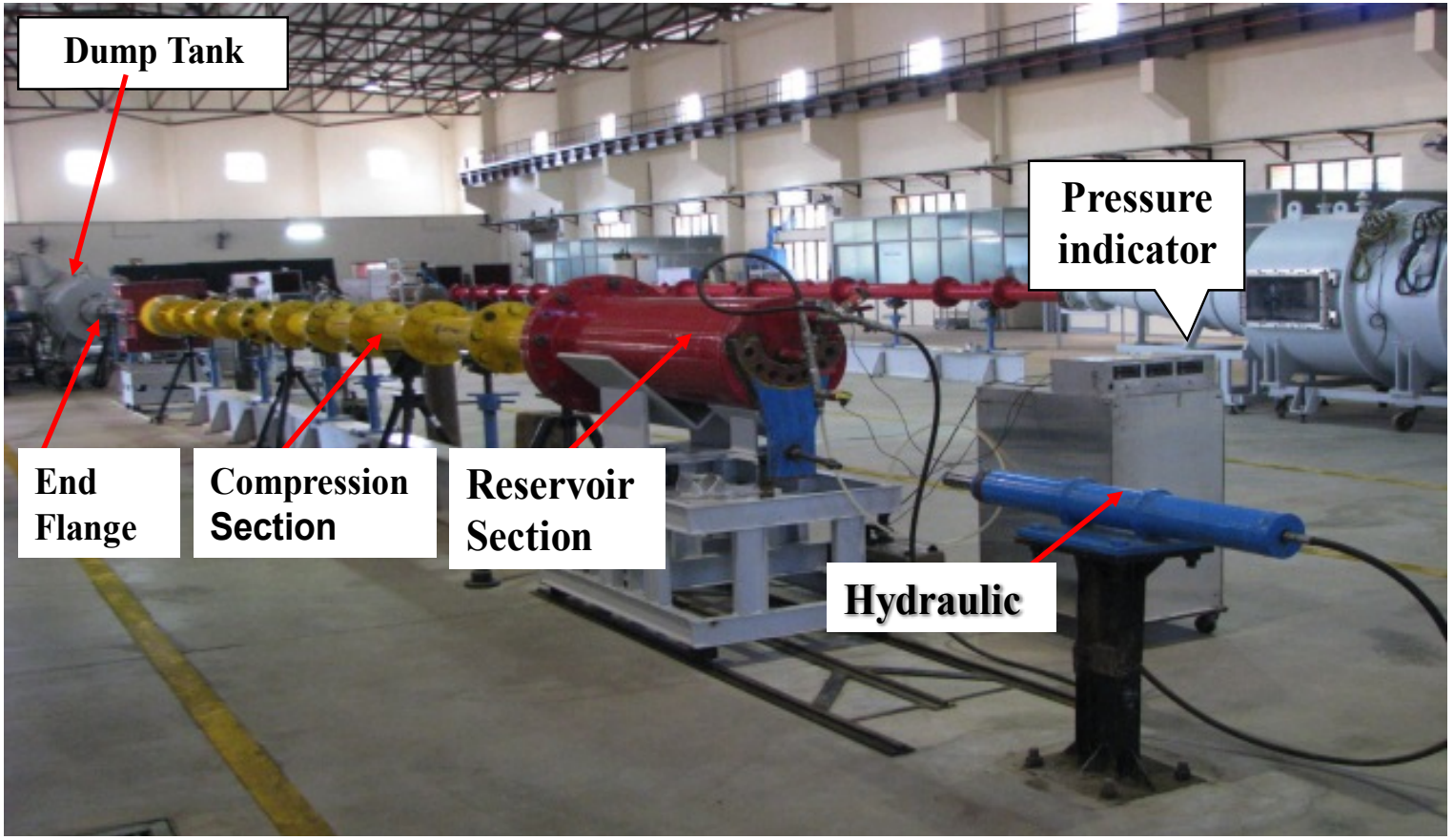
$$SiO_2\,(s) + N + N \longrightarrow SiO_2\,(s) + N_2$$

Non-catalytic surface reaction

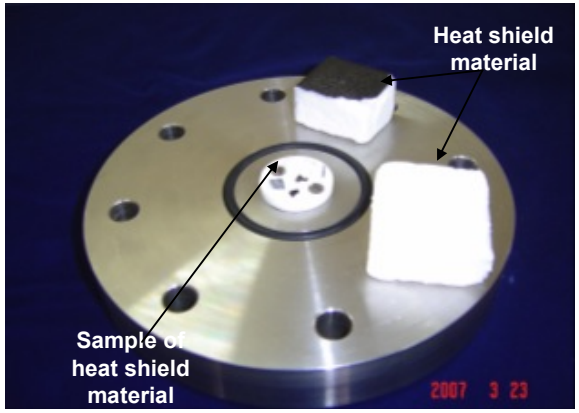
$$SiO_2\,(s) + N_2 \longrightarrow SiON_x\,(s) + O_2$$

$$SiO_2\,(s) + N + N \longrightarrow SiO_2\,(s) + N_2$$

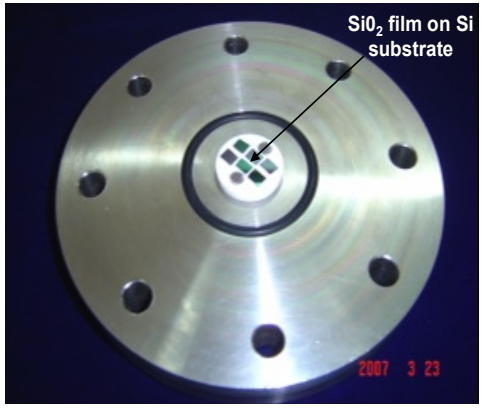
Shock strength in FPST will have temperature of 5000 -15000 K for a given test gas at about 20 MPa pressure for 2-5 ms duration



HST3 (FPST) facility at the Laboratory for Hypersonic and Shock wave Research (LHSR), Aerospace Engineering Department



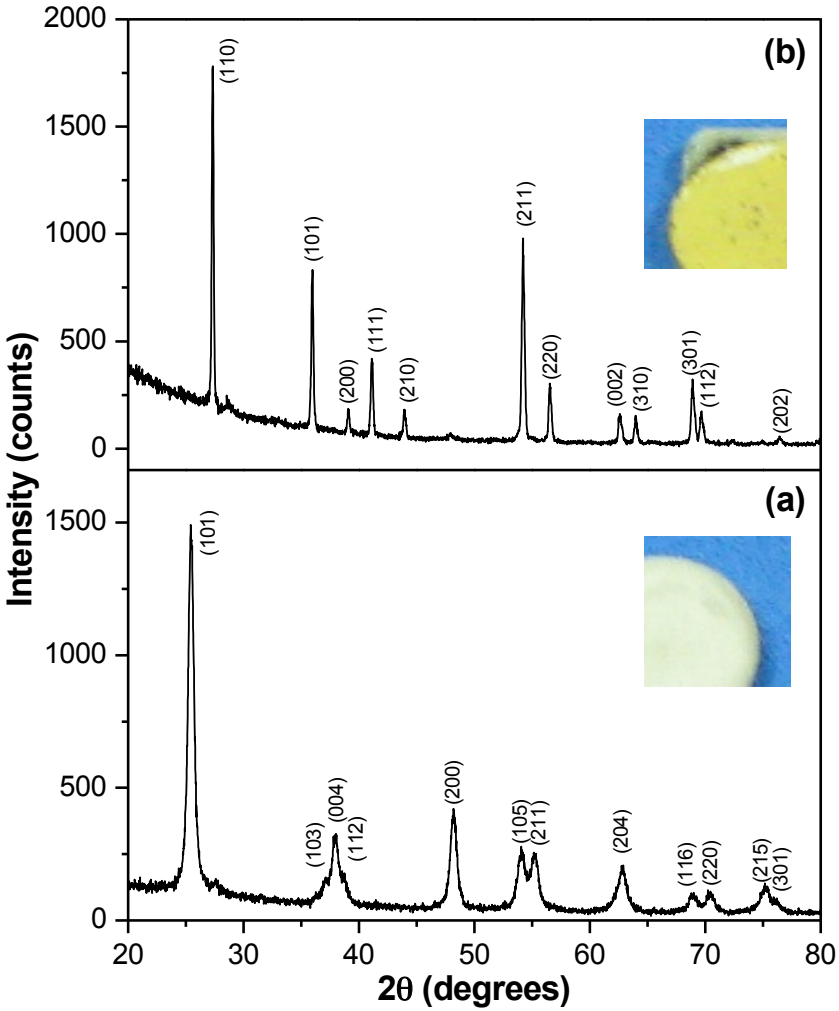
Heat shield material



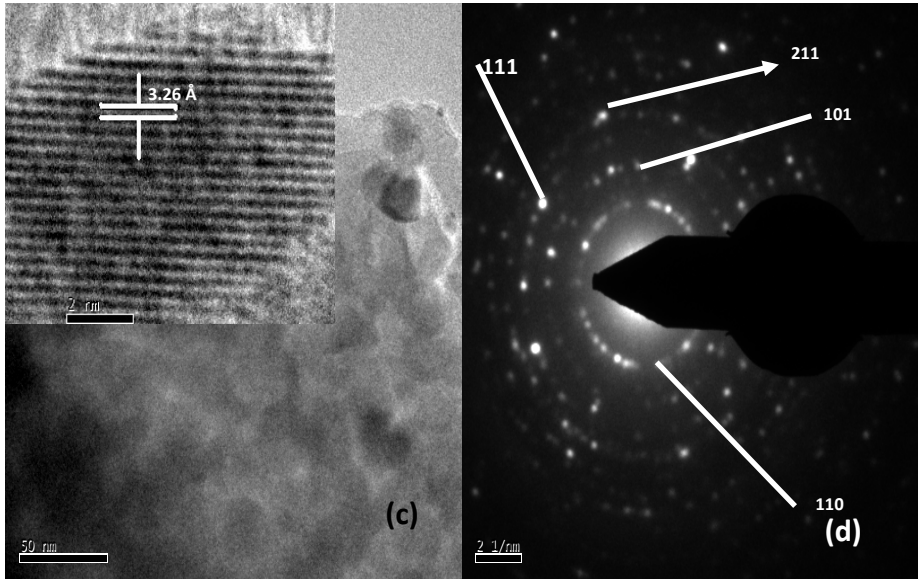
SiO_2 thin film sample

Experimental Data					Calculated Values		
Sample	Test gas P_1 (bar)	ΔT (μs)	P_2 (bar)	P_5 (bar)	V_S (m/s)	M_S	T_5 (K)
SiO_2 film	0.1 bar N_2 γ=1.4	200	8.68	69.74	2537	7.31	7353
Si_3N_4 film	0.1 bar O_2 γ=1.4	210	7.2	71.0	2272	6.5	6200
Silica Tiles (SiO_2) White	0.1 bar O_2 γ=1.4	191	9.97	67.42	2617	7.54	7812

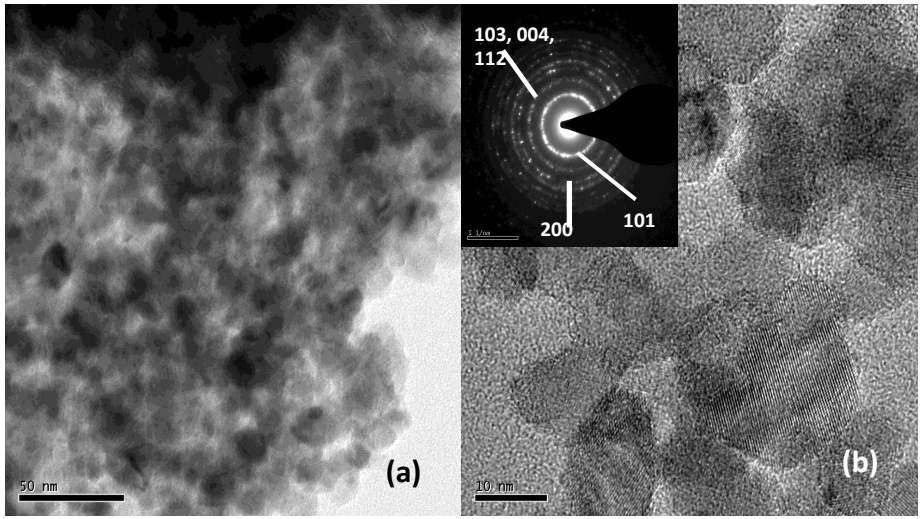
Non-catalytic and Phase Transformation Study using high enthalpy shock tube



Powder XRD pattern of TiO_2 (a) anatase before shock and (b) rutile after shock in presence of N_2



TEM of N doped rutile TiO_2 after shock



TEM of anatase TiO_2 before shock

Synthesis of $CeCrO_3$

1st step:

Synthesis of Fluorite $Ce_{1-x}Cr_xO_{2+\delta}$ by Hydrothermal method (Ferroelectric/piezoelectric material) :

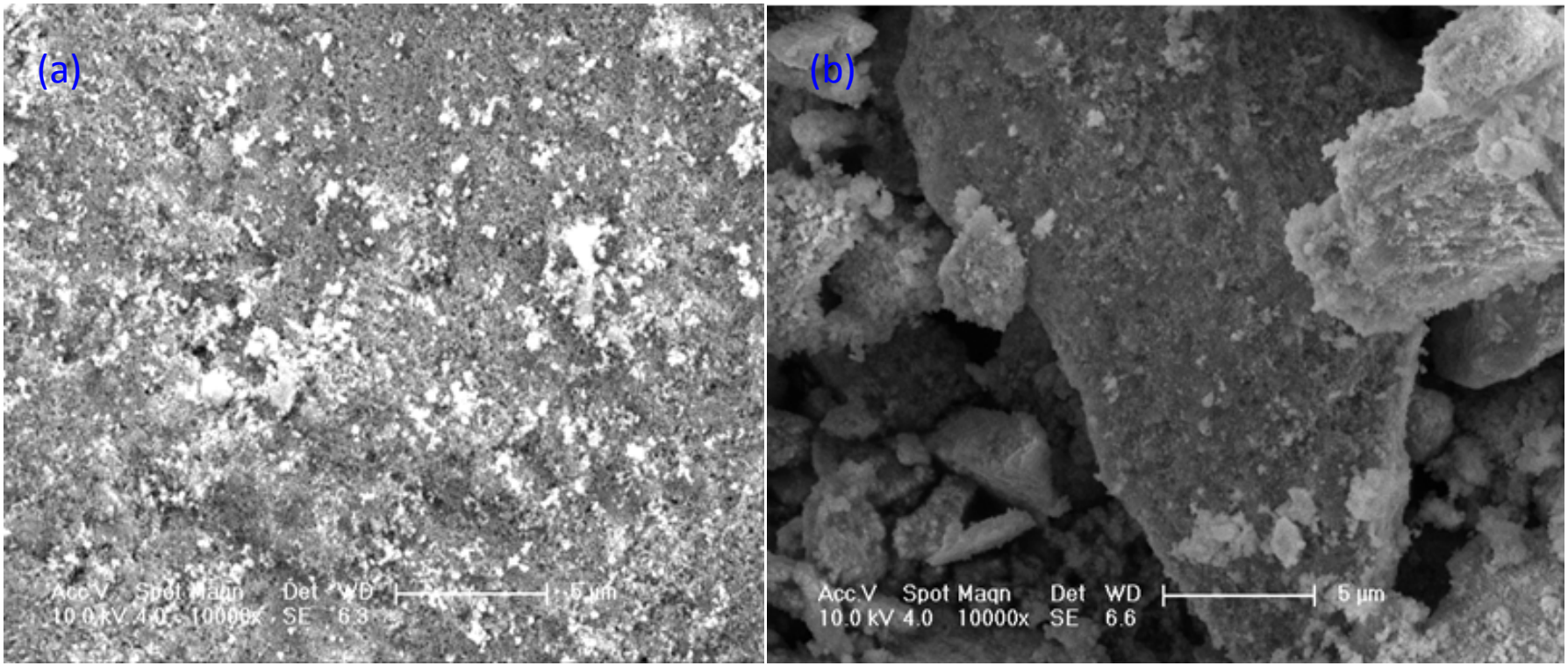
$Ce_{0.5}Cr_{0.5}O_{2+\delta}$ is an oxygen storage material, it is known to release oxygen on heating

2nd step:

Reaction in presence of High temperature Ar gas (11760 K) in a shock tube

$$2Ce_{0.5}Cr_{0.5}O_{2+\delta} \rightarrow CeCrO_3 + (0.5 + \delta)O_2$$

SEM Micrographs



$Ce_{0.5}Cr_{0.5}O_{2+\delta}$ (before shock)

CeCrO3 (after shock)

Synthesis of Strong Shock absorbing inorganic nano-materials like MoS_2 (MX_2)

opagation of such shock wave in nano-materials results in very high ear stress within micro seconds.

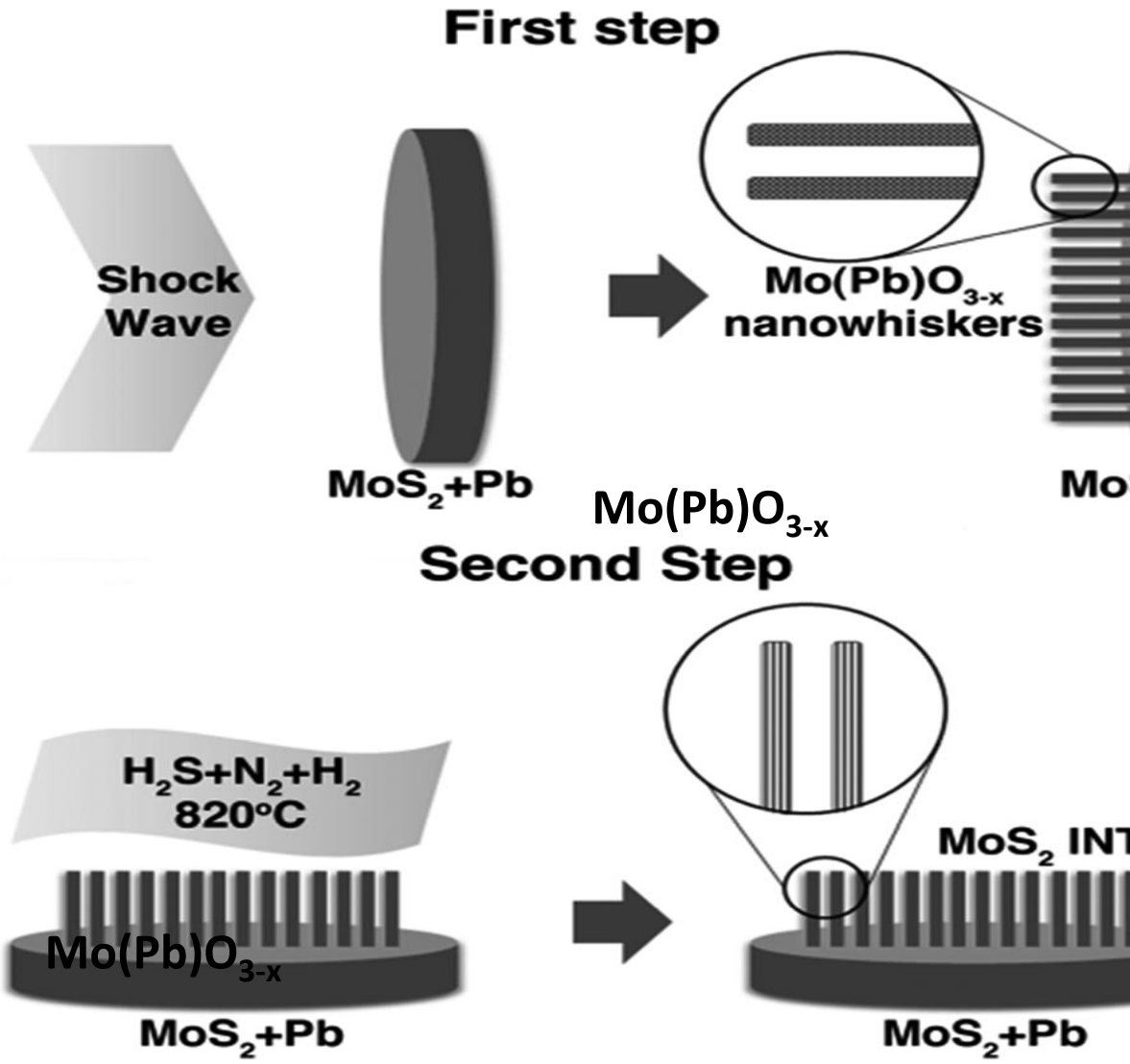
Tenne and co workers observed that fullerene-like cage structures notubes materials could be obtained from laminated/layered MX_2 o or W; X=S Se or Te) compounds.

organic fullerene (IF) nano-materials like MoS_2 and WS_2 are strong en with stand shock pressures up to 25 GPa and investigation shows sm e IF size, the better the shock absorbing property. These materials mense potential to be used as solid-state lubricant in automobile rospace industries.

norganic fullerenes are found to be better when compared to carbon uctures

step Synthesis of MoS_2 ubes
Shock Waves with Lead as h Promoter

tep: Shock treatment of MoS_2 + presence of (Ar + O_2) gas re produces Mo(Pb) O_{3-x} nano-ers



Schematic of the formation mechanism of MoS_2 nanot

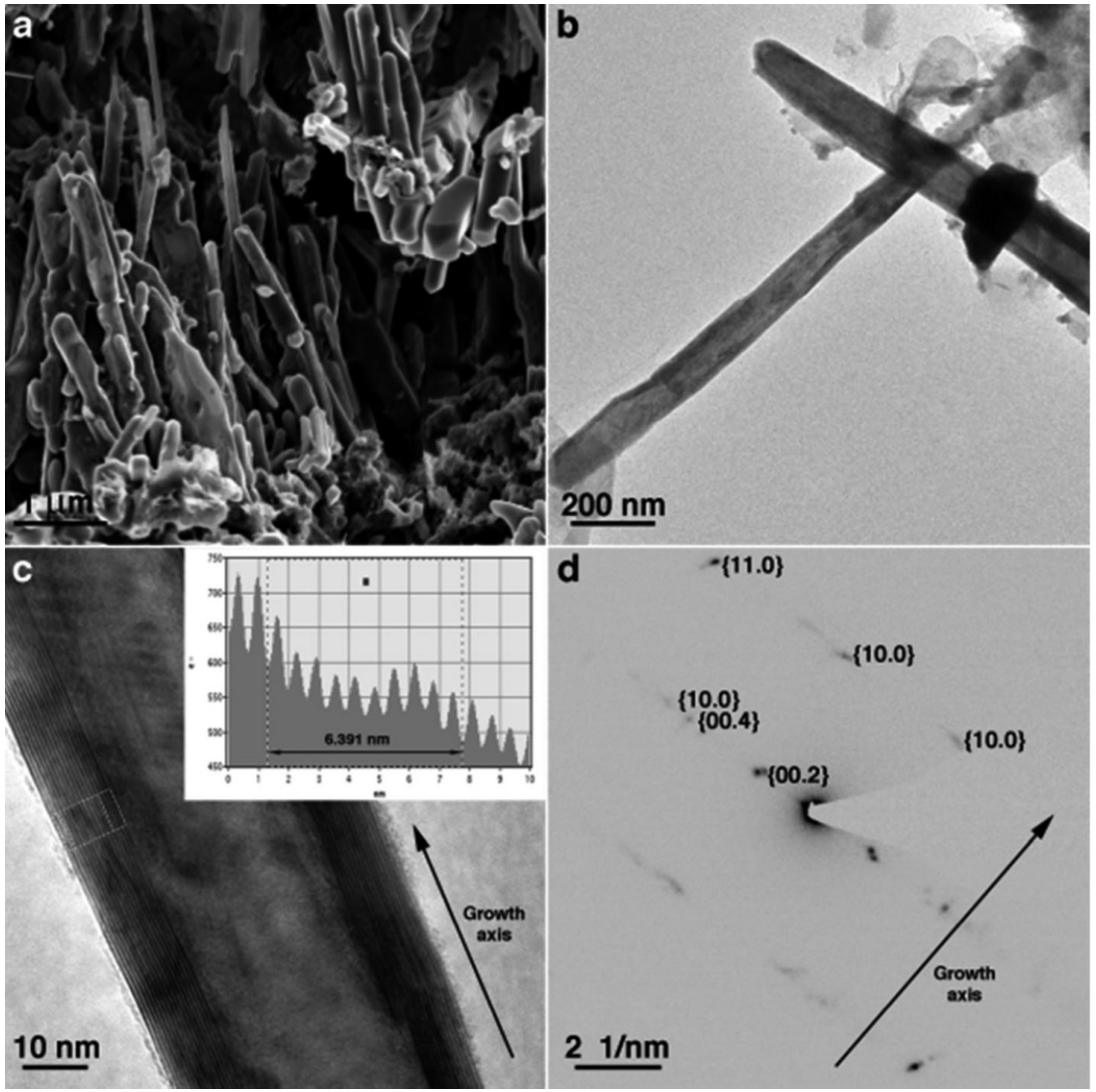
Micrographs of representative MoS_2 nanotubes after the exposure of Pb-stabilized MoO_{3-x} *nano-whiskers to* H_2S *gas* at 820 °C

(a) SEM image,

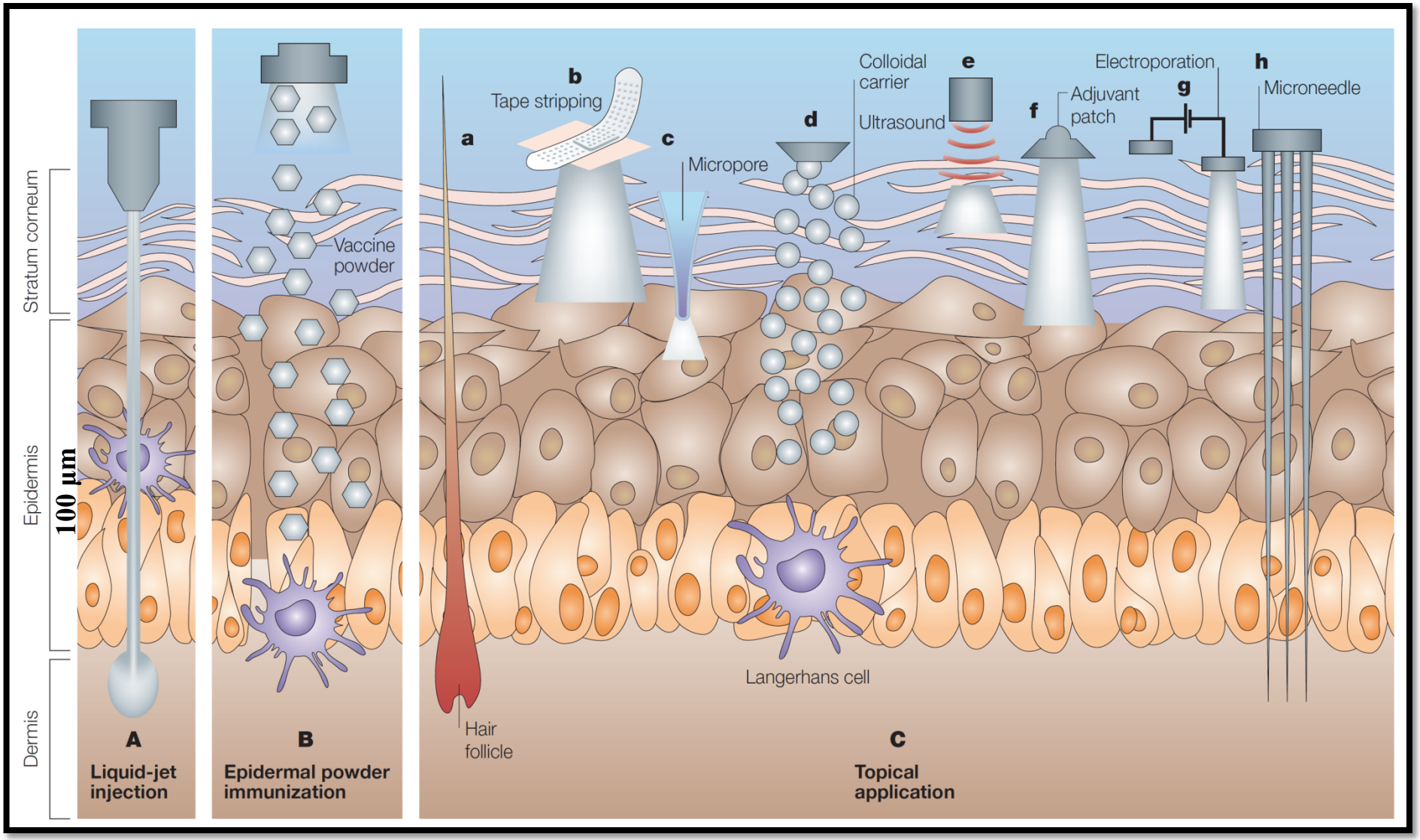
(b) lower magnification TEM image,

(c) high magnification TEM image of a single INT-MoS2,

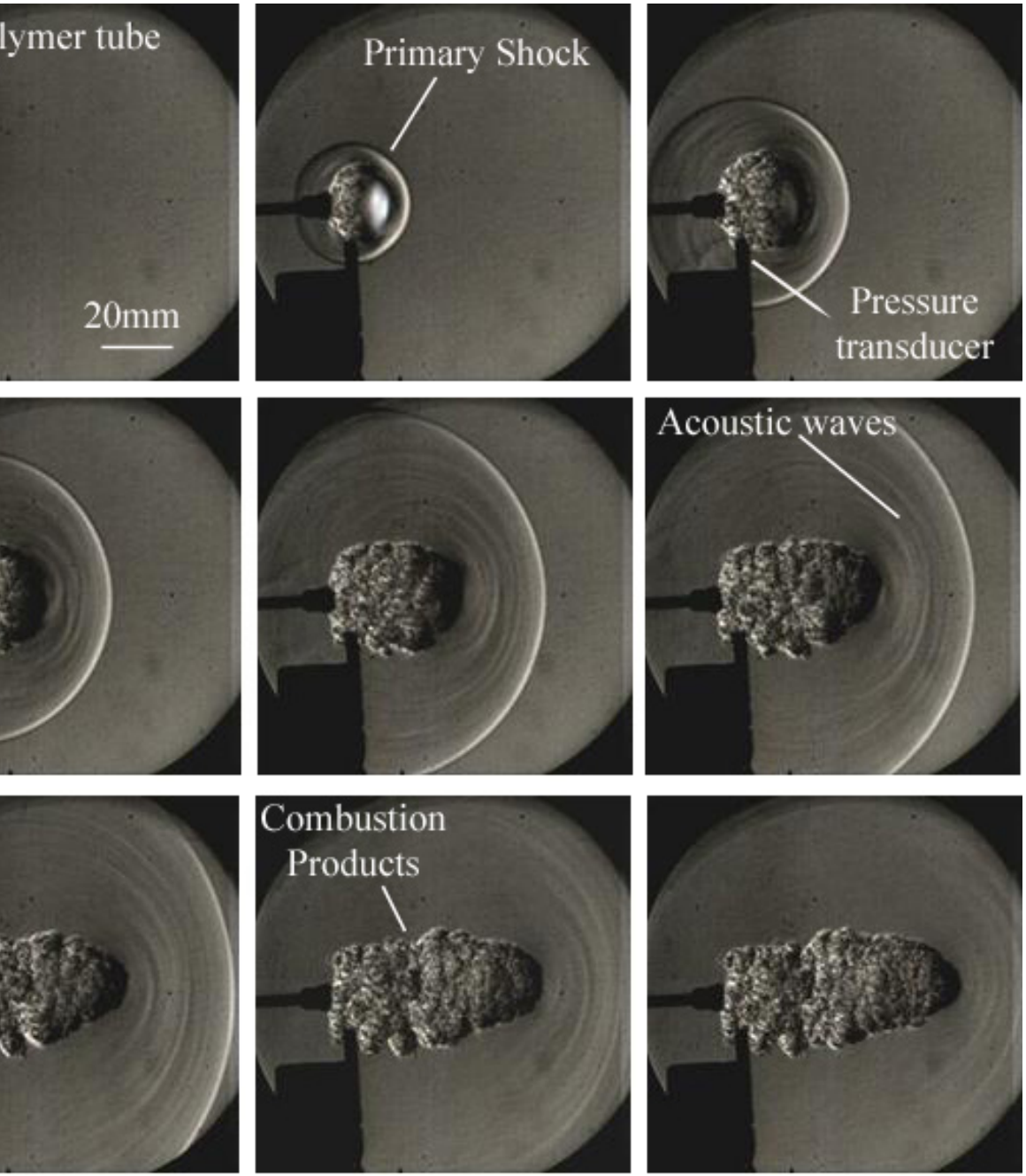
(d) electron diffraction pattern of the INT-MoS_2 shown in (c).

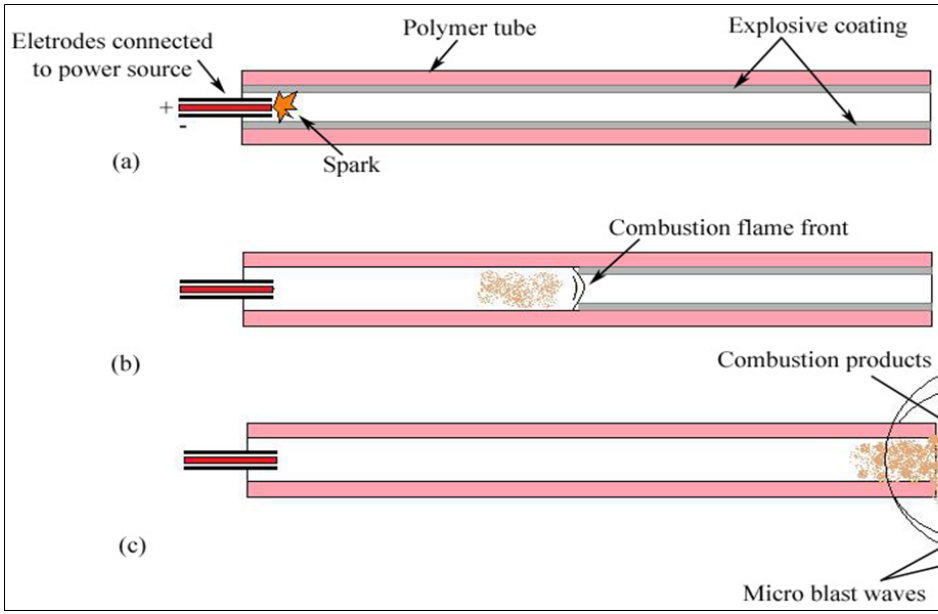


Shock Waves and Biology



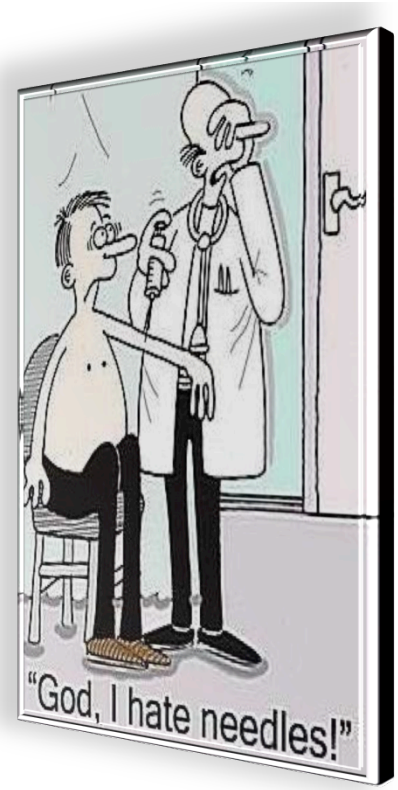
Samir Mitragotri, *Nature Reviews Immunology* (2003)



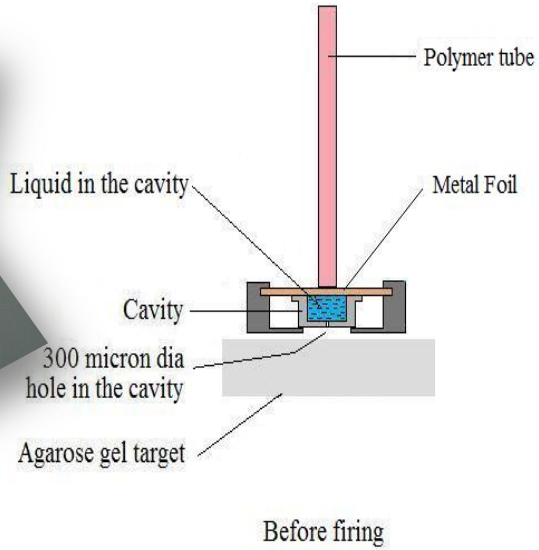


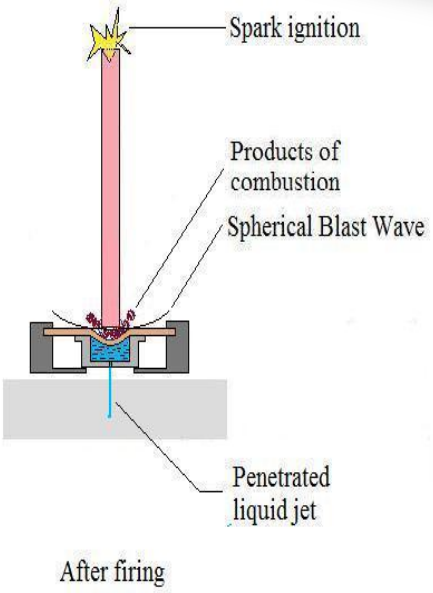
Changing Paradigms of Shock Wave Research From Micro-Explosions To Drug Delivery !

LHSR blast 100 pT!



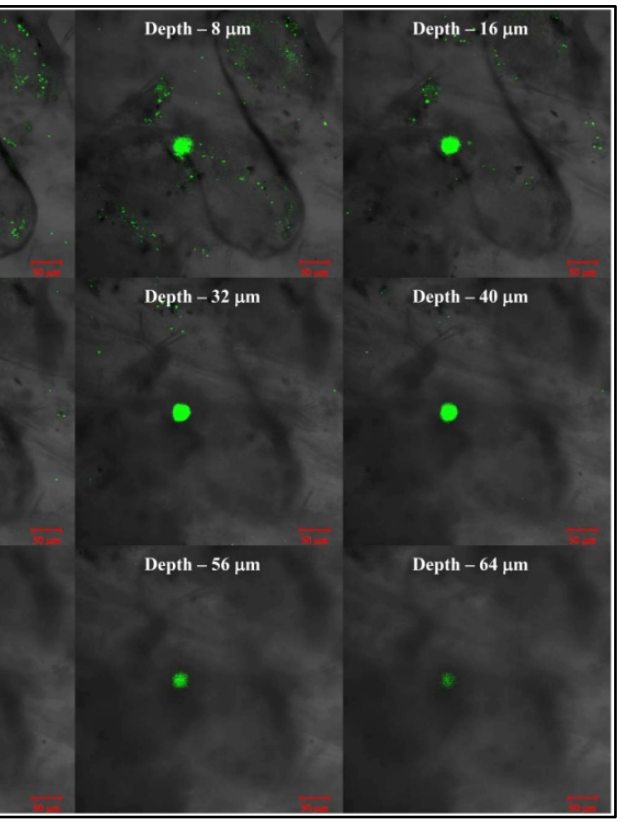
Needleless drug delivery

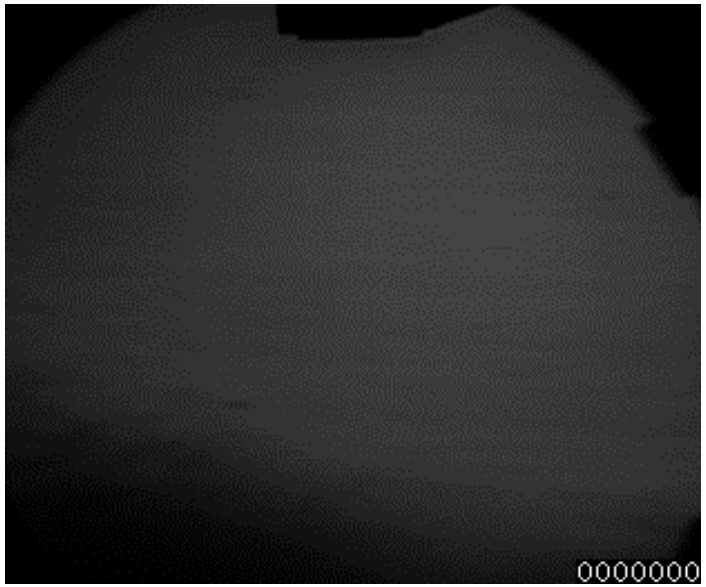




Vaccine delivery using shock waves

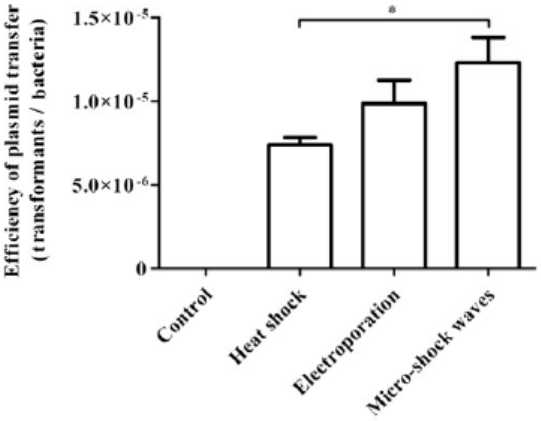
se skin – confocal image

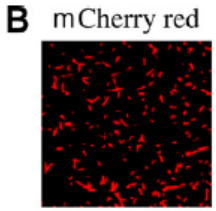


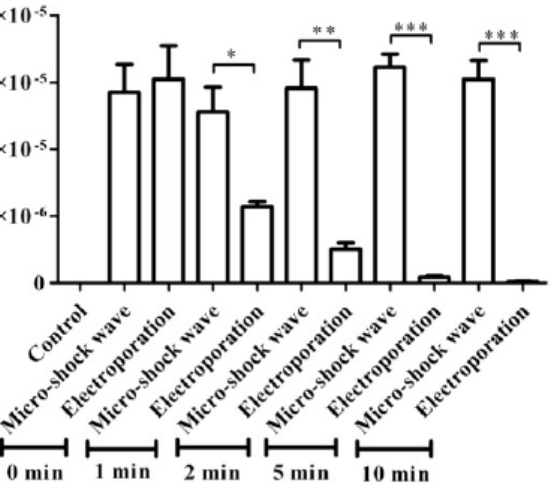


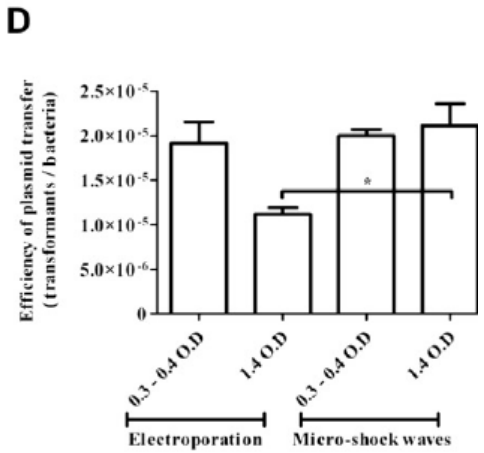
Centre for in-vivo imaging system & Sri Devi Acknowledg

Bacterial transformation using micro-shock waves/G. Divya Prakash et al./Anal. Biochem. 419 (2011) 292–301

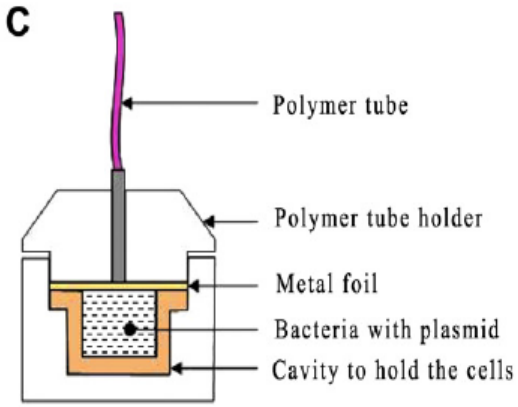


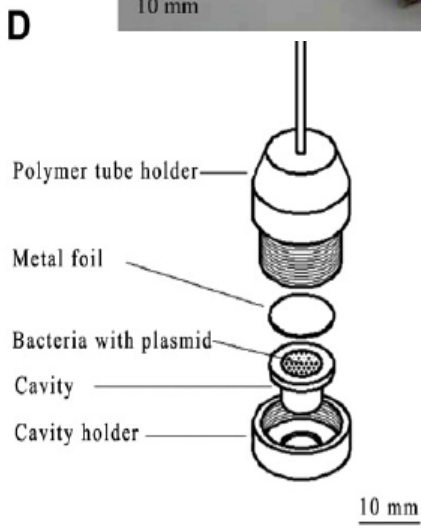




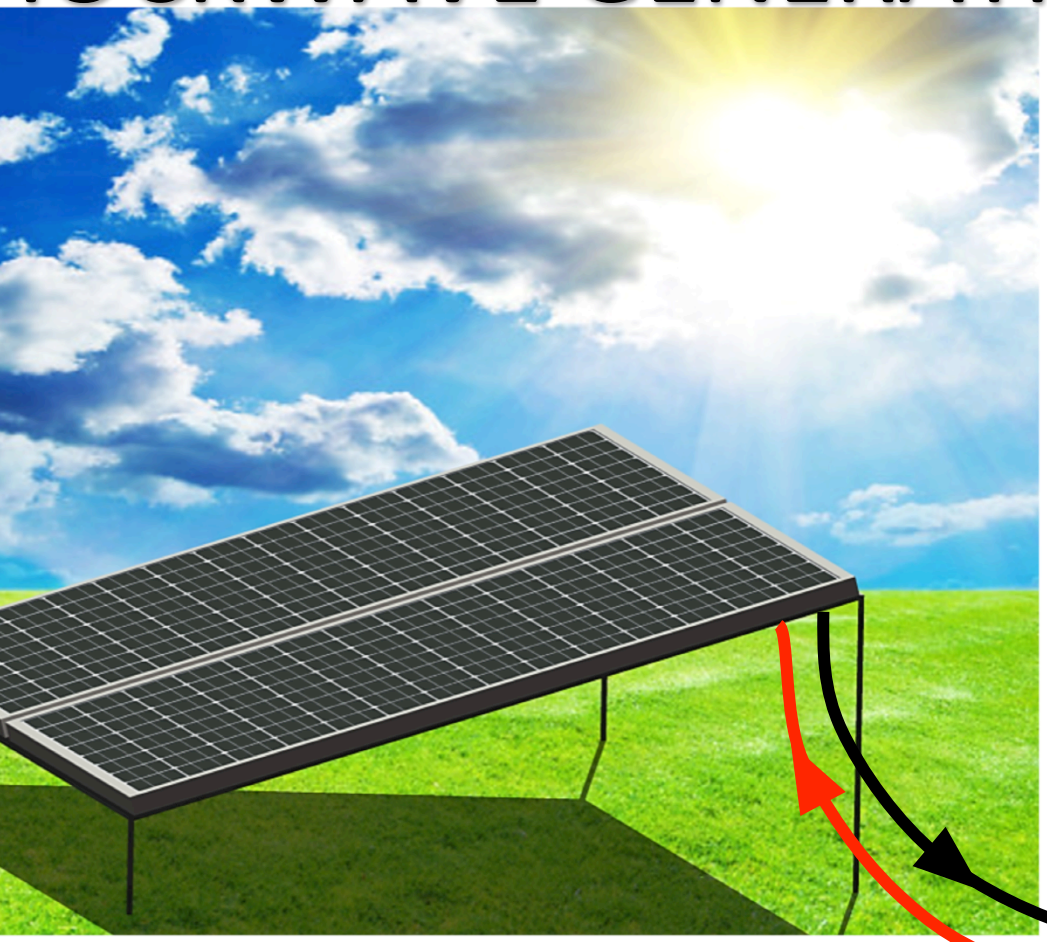


G.Jagadeesh "Apparatus and method for genetically transforming cells" US Patent 8,232,093, 2012.

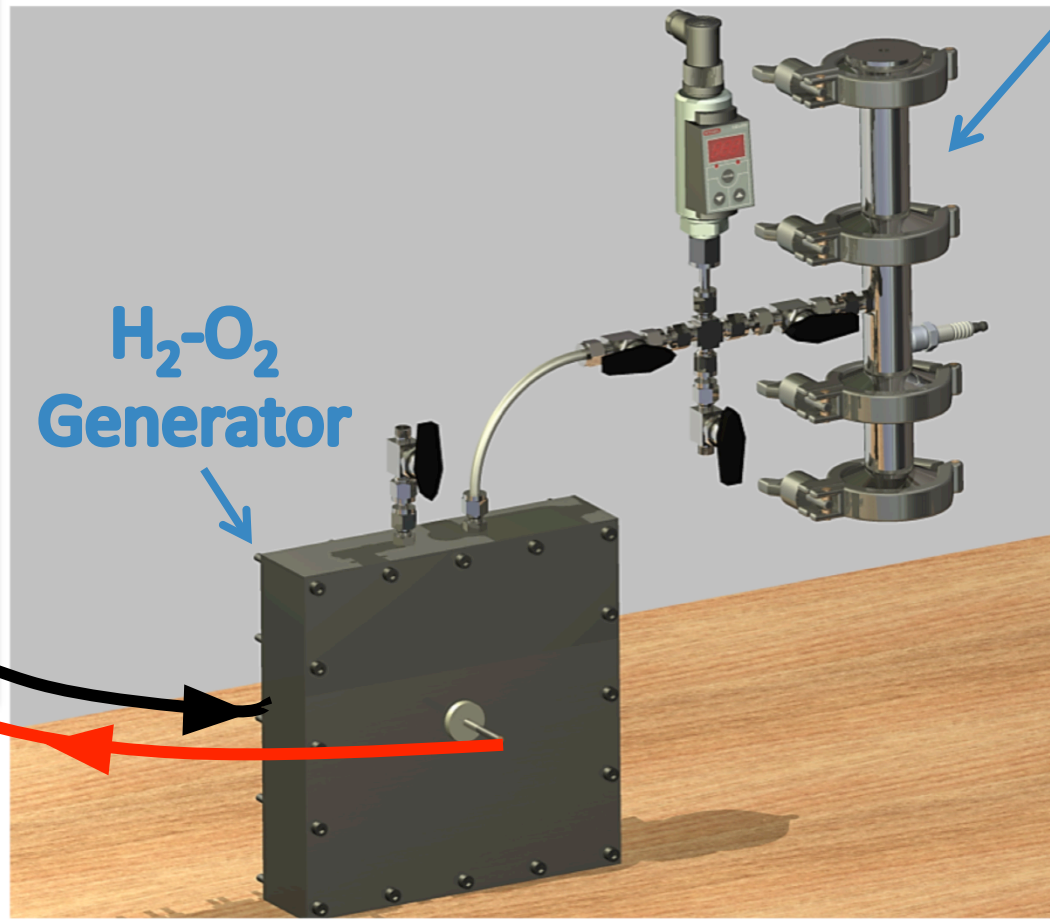




HOCKWAVE GENERATION USING SOLAR POW



6
sho



0W solar panels can generate shock waves with overpressures of *300 k*

ADVANTAGES

$$Electrolysis: 2H_20 \rightarrow 2H_2 + O_2$$
$$Combustion: 2H_2 + O_2 \rightarrow 2H_20, Energy = 241.8kJ/mol$$

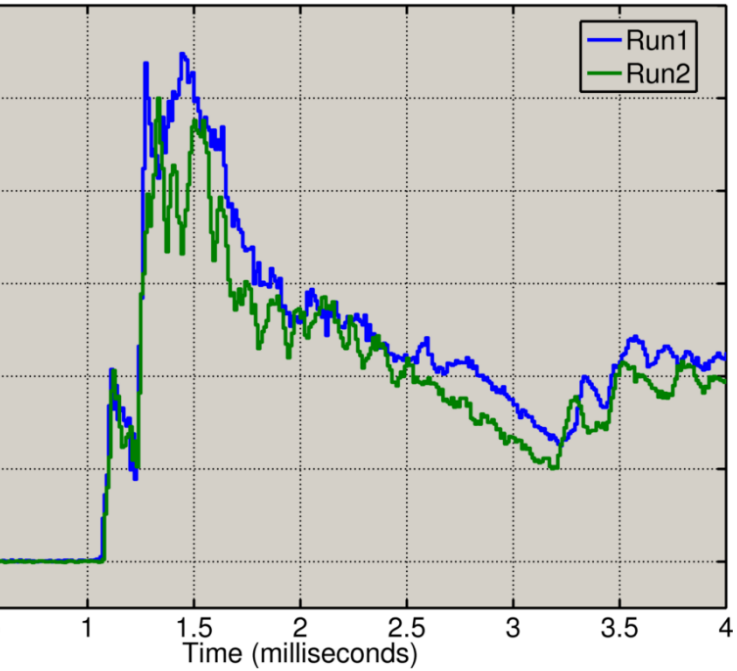
ses a renewable energy source

trength of the explosion can be controlled

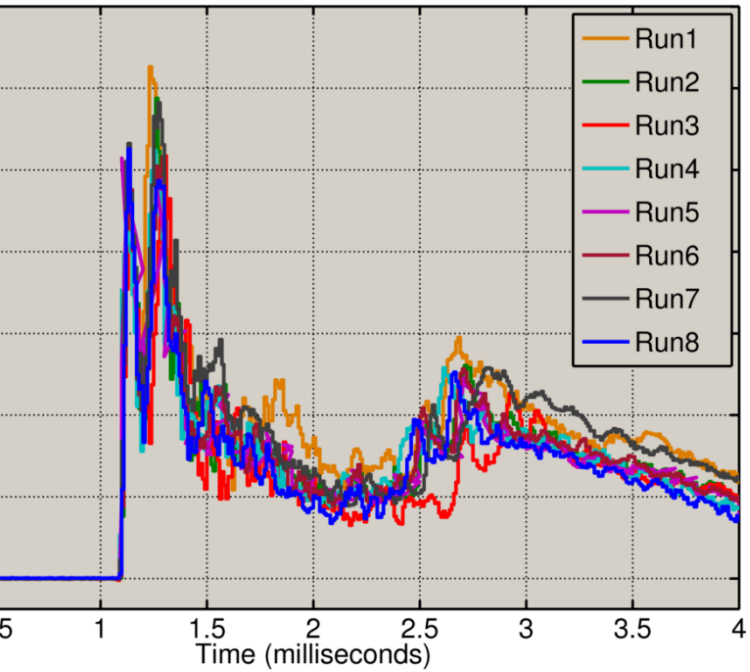
epending on requirement either shock waves or blast waves ca
roduced

y product of the explosion is water

ombustible H_2 - O_2 mixture is generated in-situ



Shock tube mode

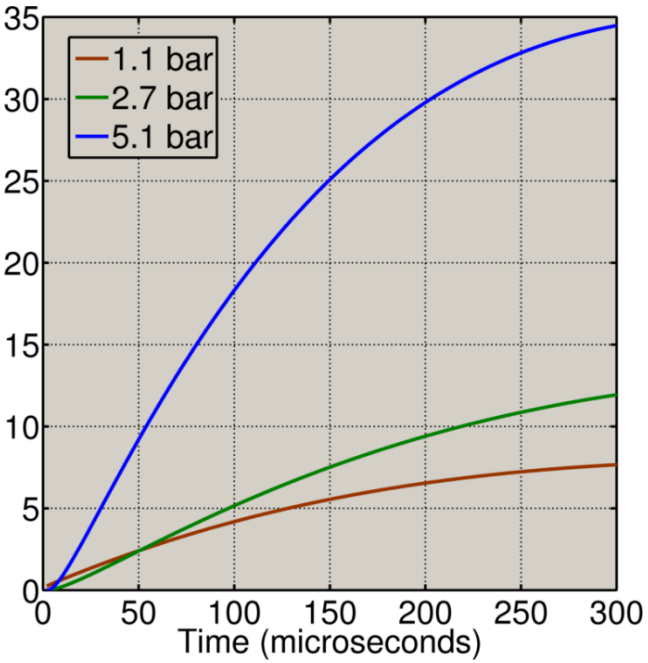


Combustion mode

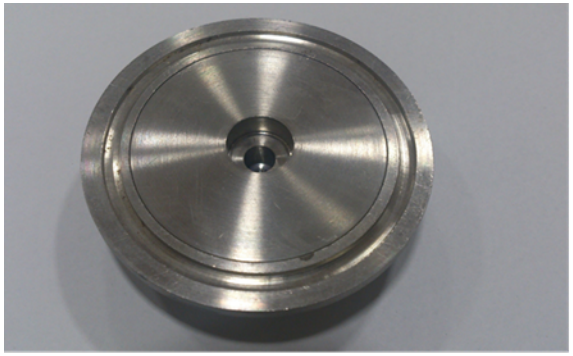
Schlieren of open en of shock tube

NESSING THE ENERGY
HE BLAST WAVE

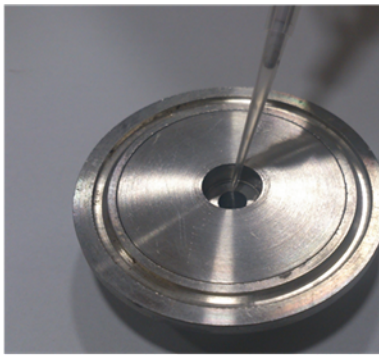
rgy in the blast wave at
ous fill pressures of H_2-O_2



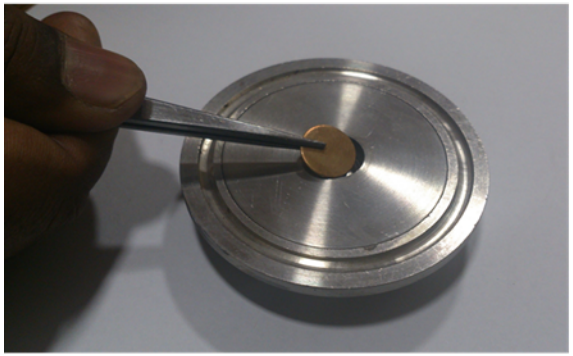
The energy is found by tracking the
rajectory of the shockwave (Jones et. al.)



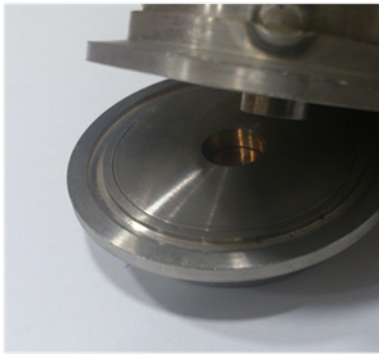
Cavity with a 300 micron hole
at the bottom



Cavity is filled with
using a pipett

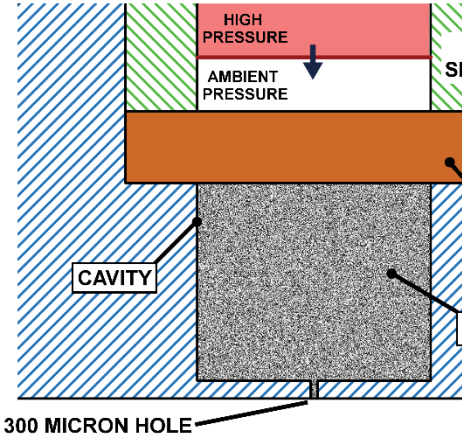


A brass foil is placed over
the liquid surface

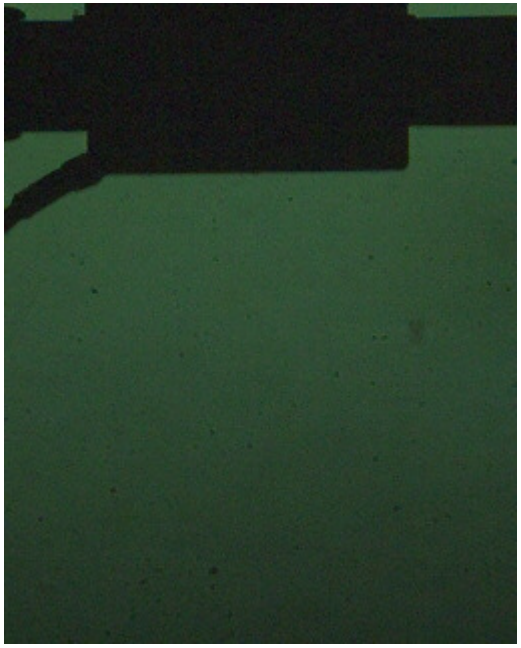


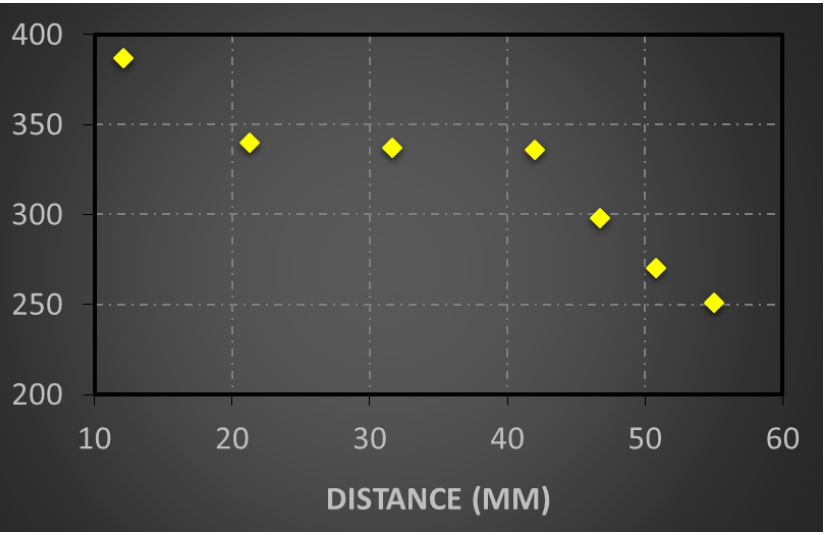
The entire arrangemer
to the end of the bla

Volume of liquid
in the cavity = 200 µl

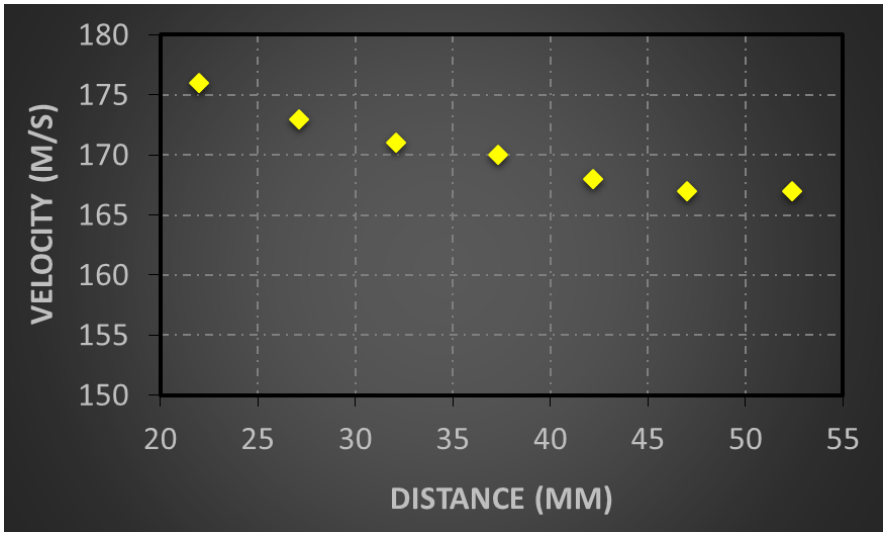


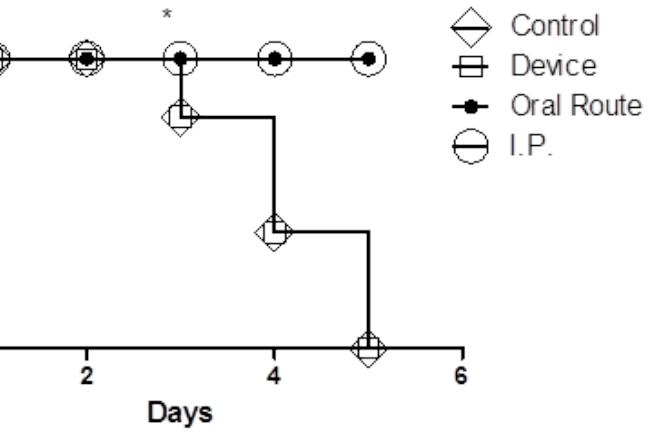
Single Hole

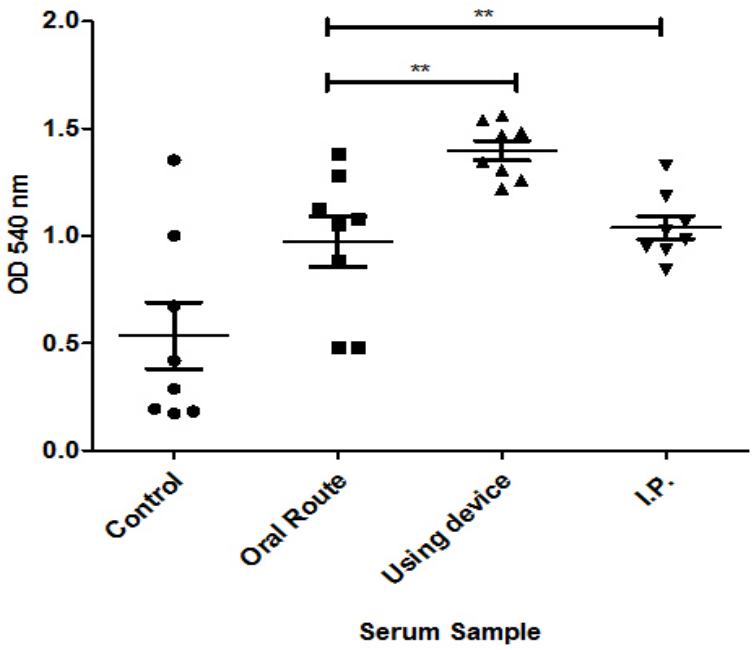


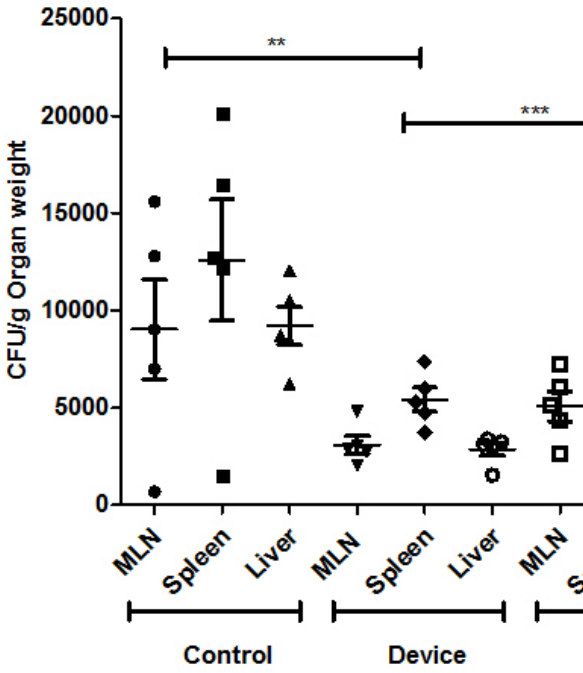


Multiple Hole









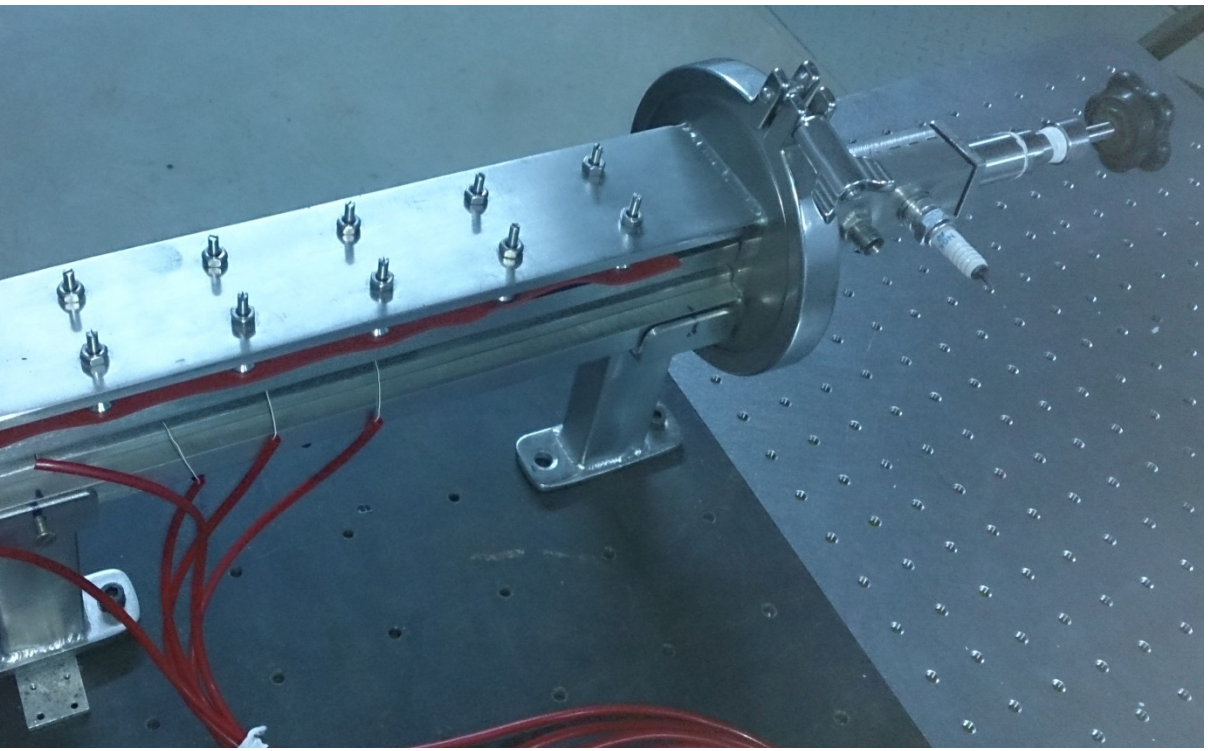
iency of vaccine delivery using the device.

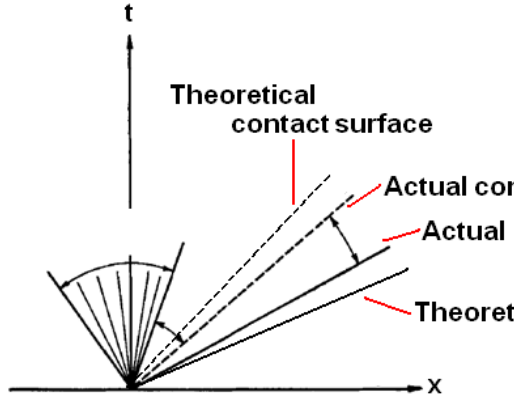
(n=5 per group) were infected with lethal dose (10^8 CFU/mouse) of virulent *Salmonella* orally 5 day immunization as described in the previous experiment and the survival of mice were checke 0001 (Log rank test)]. **(c),** Single dose of DV-STM-07 was delivered using device, orally and throug oute and the serum IgG levels were tested against *Salmonella* specific Lipopolysaccharide (LPS ELISA; PBS delivered using the device was used as control; bar show the mean value of th riments. Error bar show standard deviation (s.d.). (*P* value - Student's *t*-test). **(d),** DV-STM-07 wa nistered to mice using the device and via oral route. Phosphate buffered saline (PBS) delivered usin evice was used as control. 1 week post immunization mice were infected with a lethal dose (10^7 CFU se) of virulent strain of *Salmonella.* 5 days after the oral challenge MLN, spleen and liver wer tically dissected for checking the *Salmonella* burden .Statistical significance is specified as ***P*<0.00

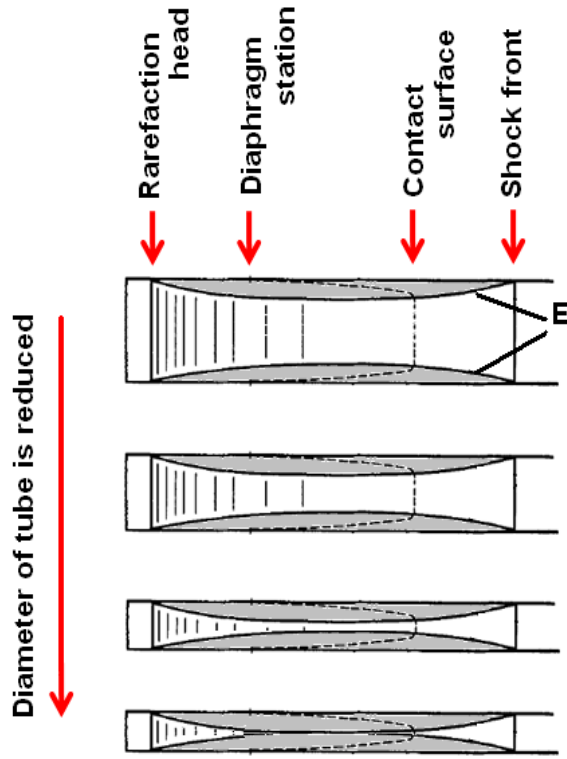
OCKWAVE GENERATION AND PROPAGATION
MINIATURE SHOCK TUBES

cross section of shock tubes under investigation
x 2mm square
x 6mm square
n x 10mm square

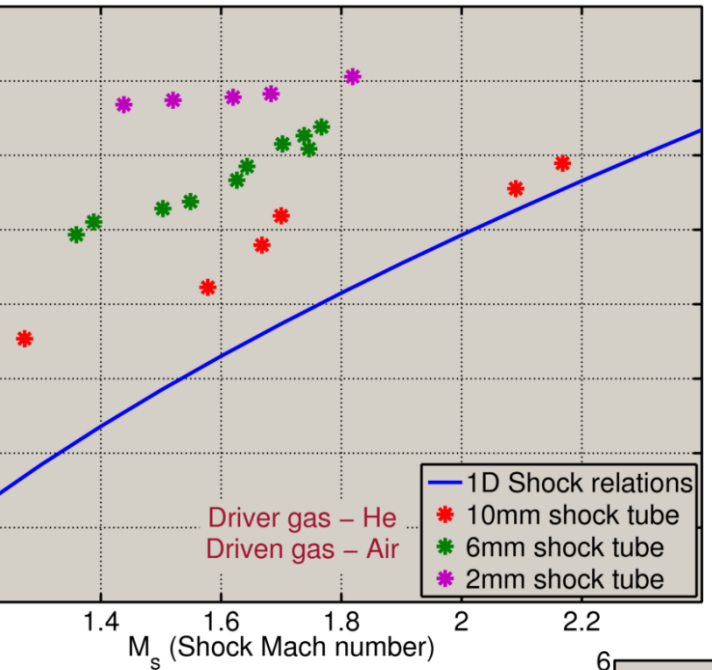
EXPERIMENTAL SETUP

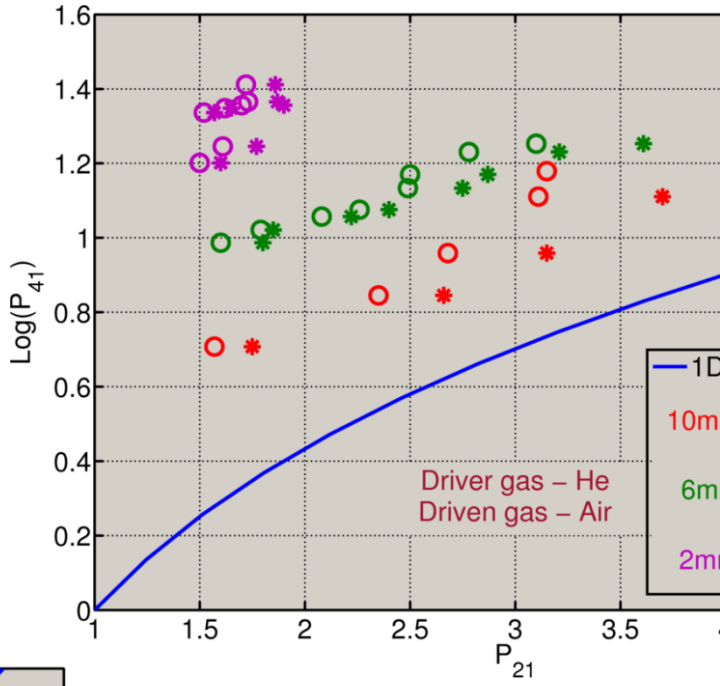


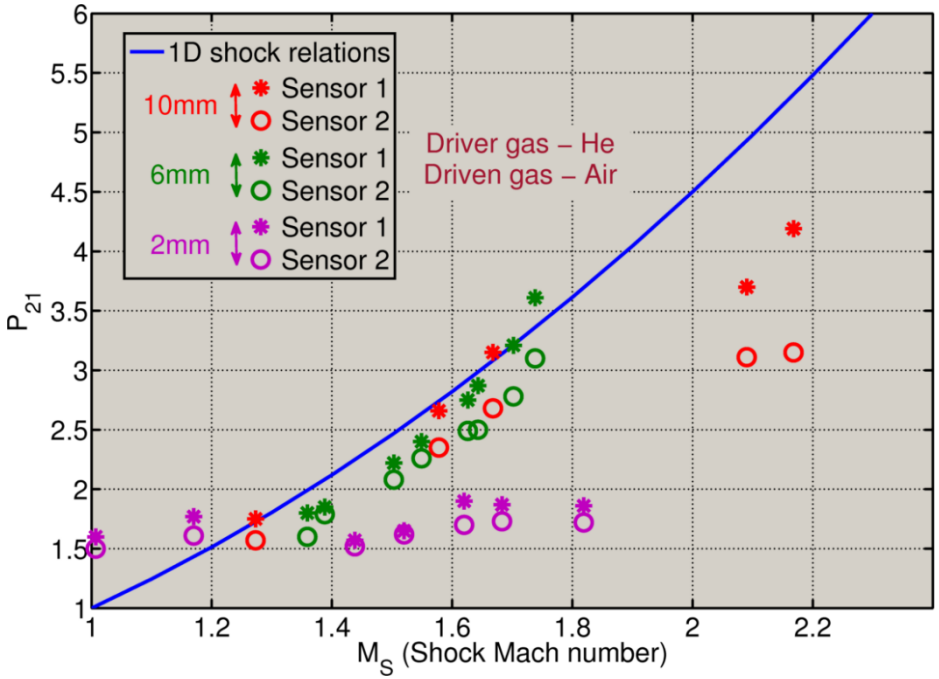




CALIBRATION OF THE DIFFERENT DIAMETER SHOCK TUBES







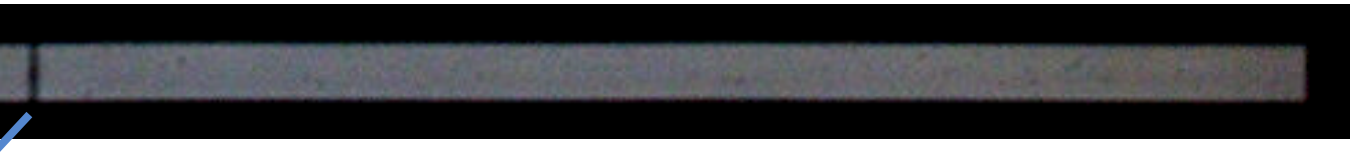
VISUALIZATION OF DRIVEN SECTION OF SHOCK TUBES

Driver gas – Air, Driven gas – Air, $P_{41} = 15$

10mm x 10mm shock tube

e lines

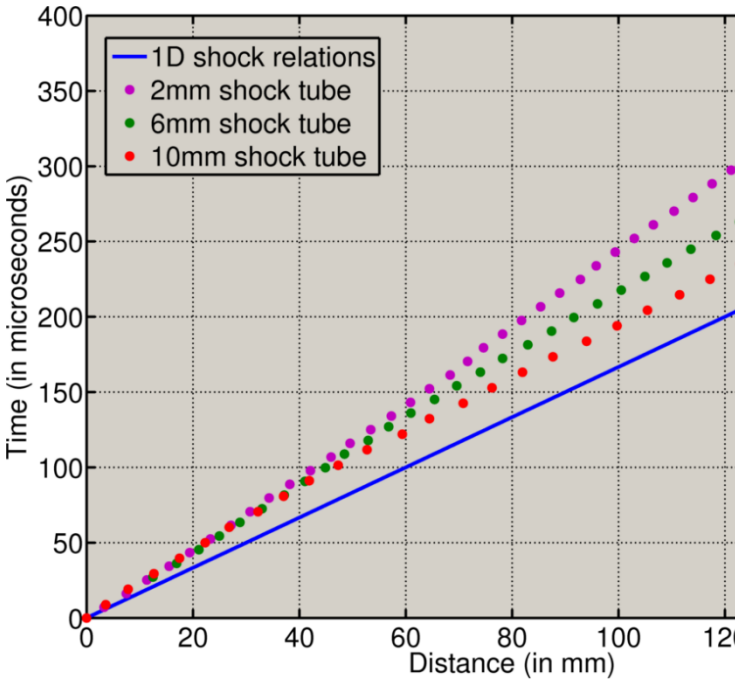
6mm x 6mm shock tube



e lines

2mm x 2mm shock tube

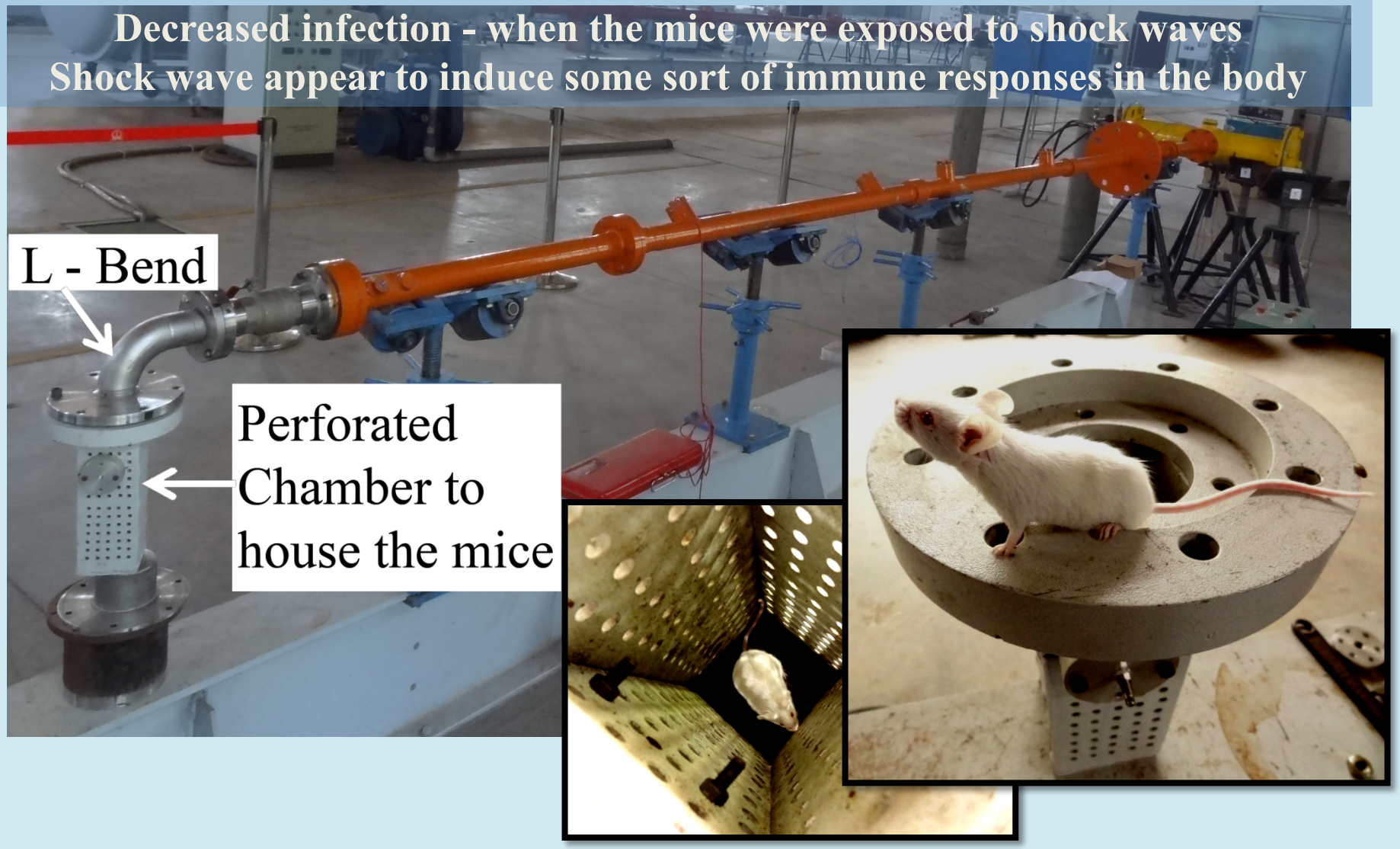
e lines

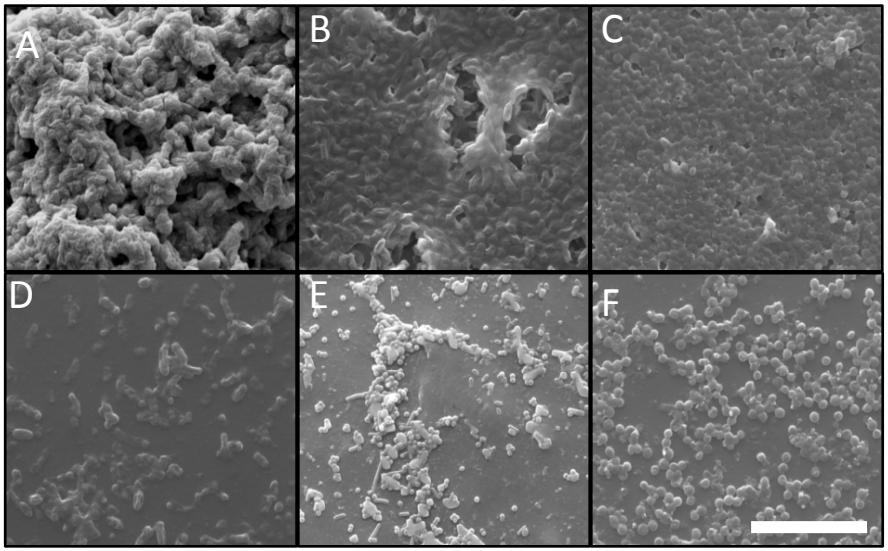


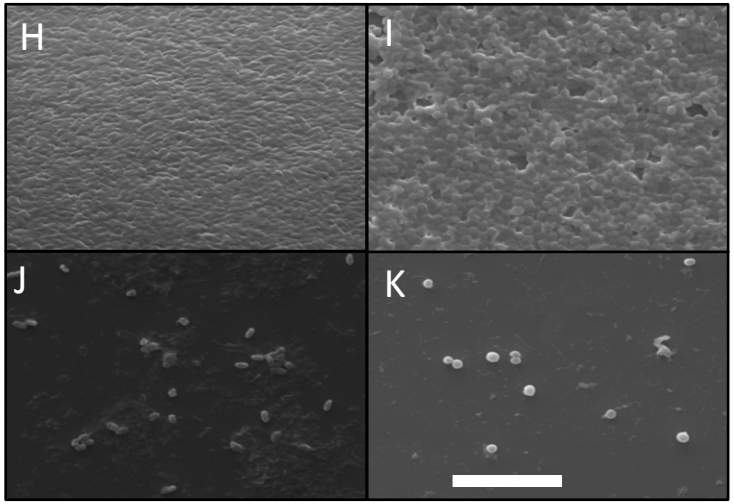
Diaphragmless shock tube for *in vivo* experiments

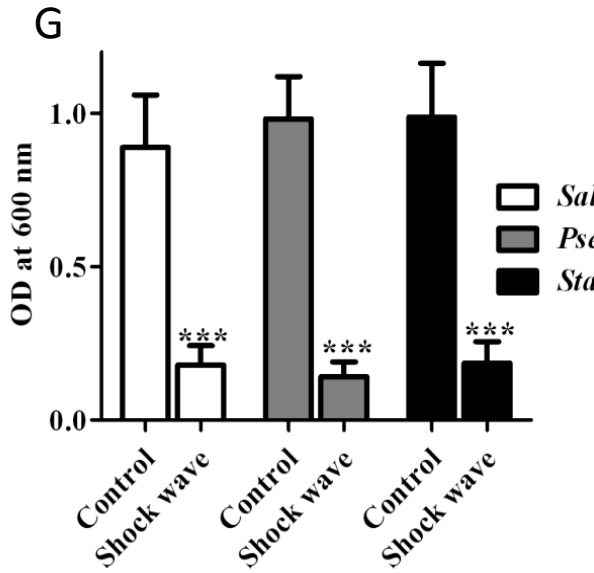
Effects of shock waves in infection

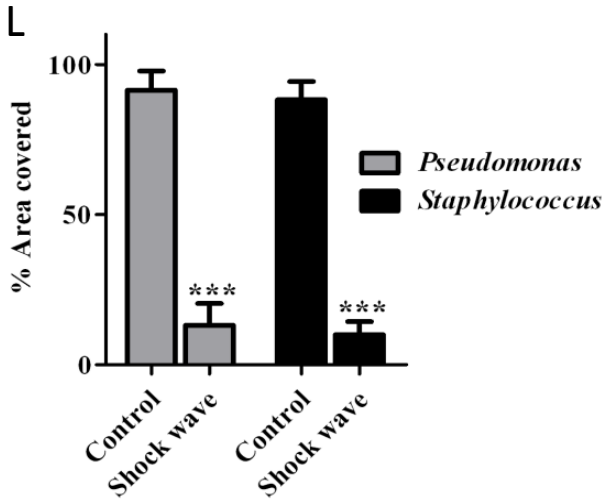
Decreased infection - when the mice were exposed to shock waves
Shock wave appear to induce some sort of immune responses in the body







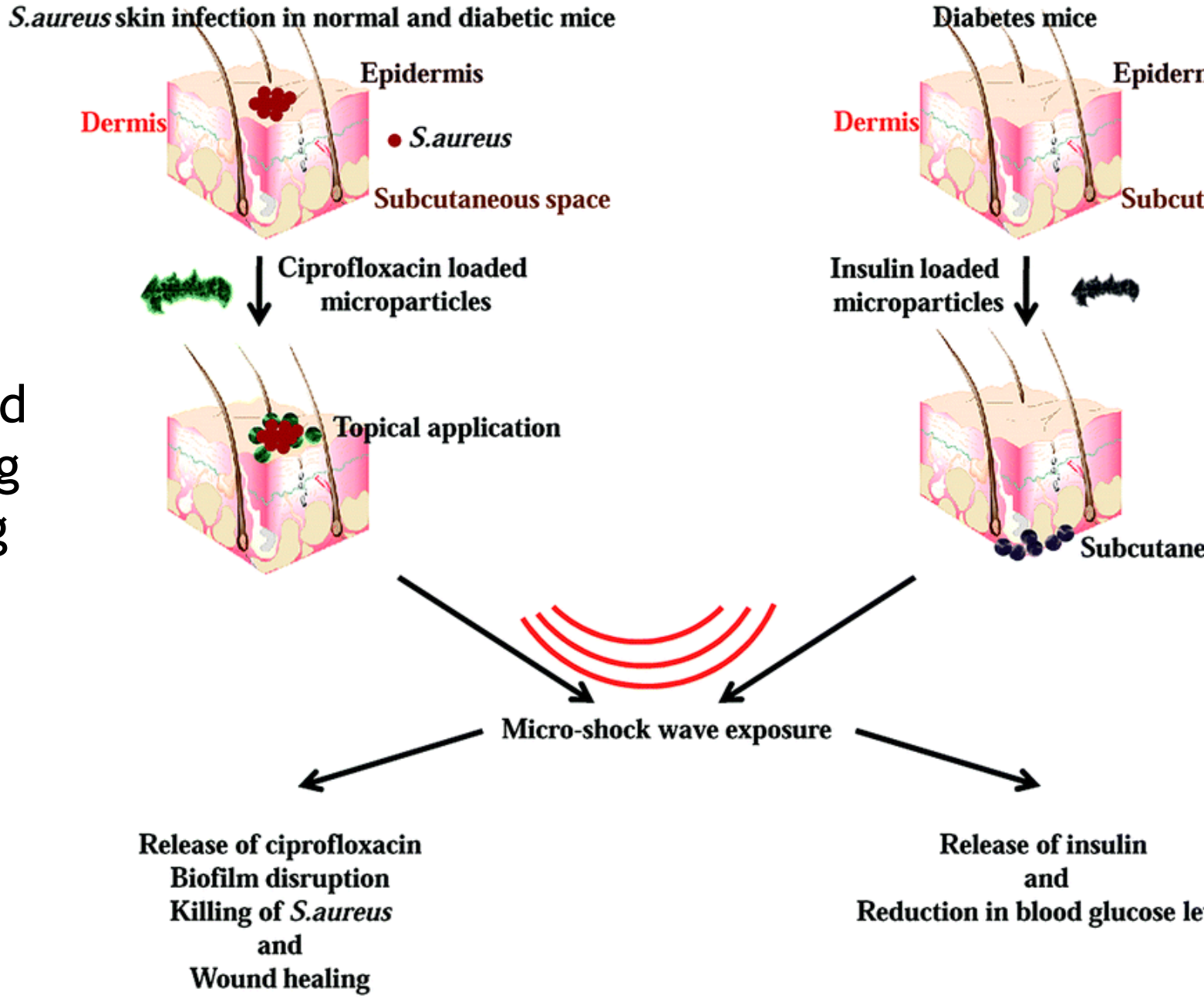


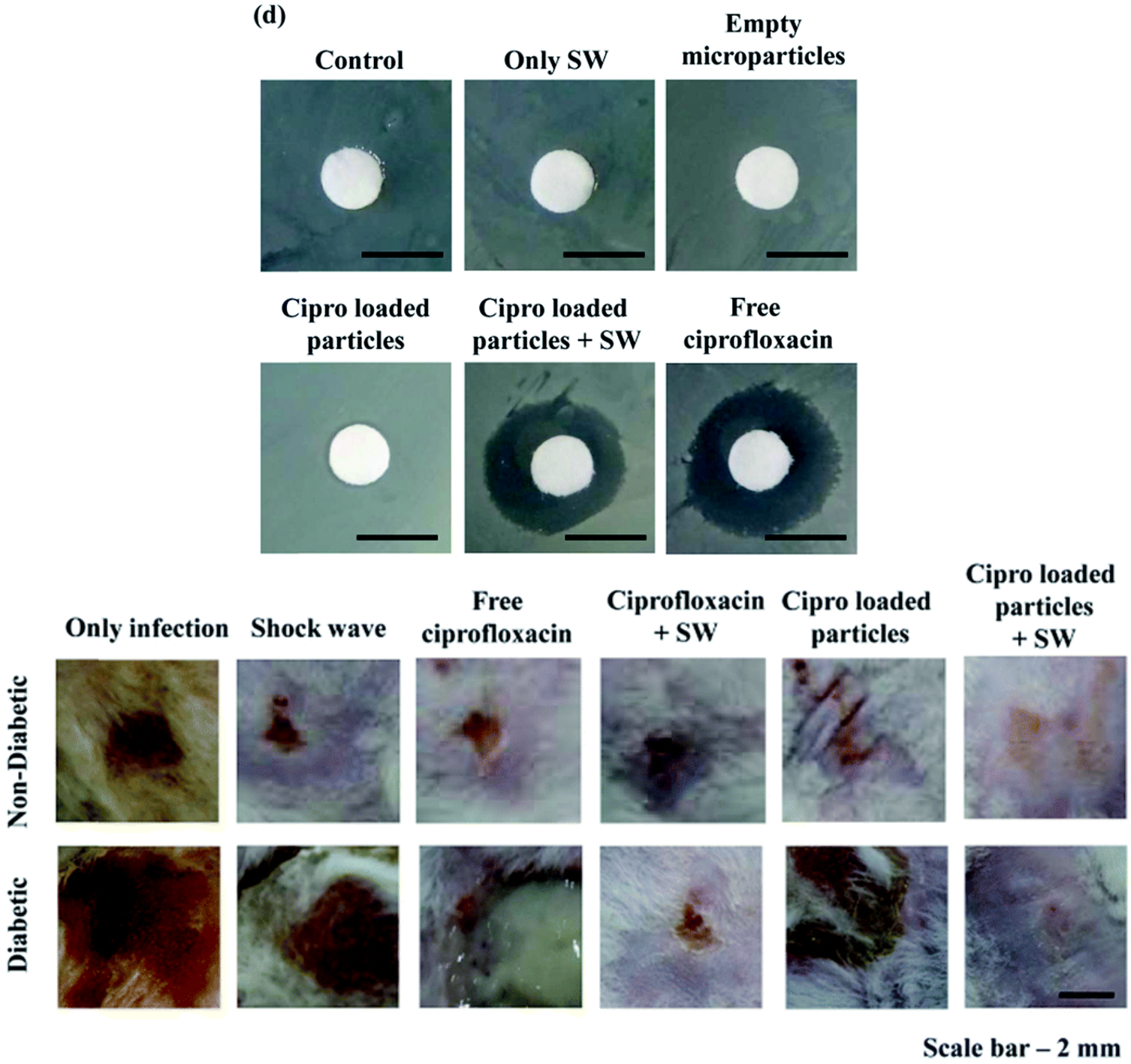


***In vitro studies* - Effect of shock waves on biofilm**

(2A-2F) SEM of bacterial biofilms grown on plastic microfuge tubes. (2A) *S.* Typhimurium biofilm. (2B) *P. aeruginosa* biofilm. (2C) *S. aureus* biofilm. (2D) *S.*Typhimurium biofilm after shock wave. (2E) *P.aeruginosa* biofilm after shock wave. (2F) *S.aureus* biofilm after shock wave. (2G) crystal violet staining of biofilms before and after shockwave treatment. (2H-2K) SEM of biofilms on urinary catheters before and after shock waves. (2H) *P.aeruginosa* biofilm. (2I) *S.aureus* biofilm. (2J) *P.aeruginosa* biofilm after shock wave. (2K) *S.aureus* biofilm after shock wave. (2L) The area covered by the biofilm estimated from examining 50 SEM fields. Scale bar in 3F & 2K 10µm.

ving diabetic wound
tion and controlling
d sugar levels using
shock waves



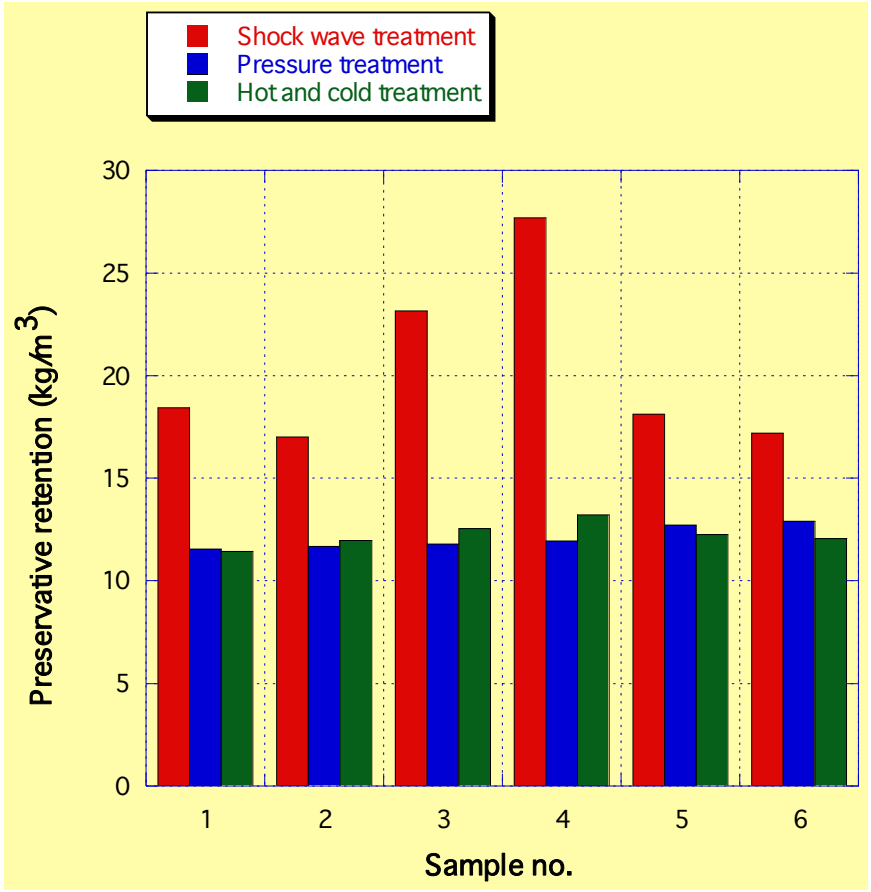

(d)
Control
Only SW
Empty microparticles
Cipro loaded particles
Cipro loaded particles + SW
Free ciprofloxacin
Only infection
Shock wave
Free ciprofloxacin
Ciprofloxacin + SW
Cipro loaded particles
Cipro loaded particles + SW
Non-Diabetic
Diabetic
Scale bar – 2 mm

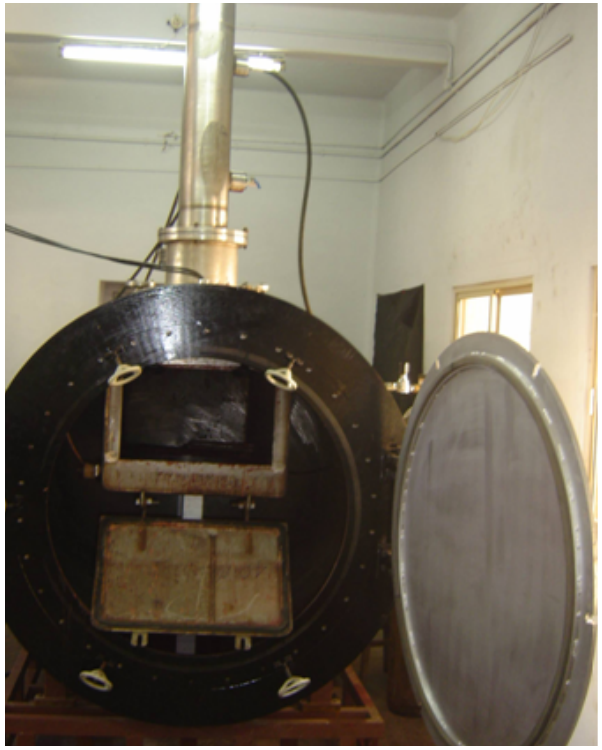
Shock wave assisted preservative impregnation in Bamboo

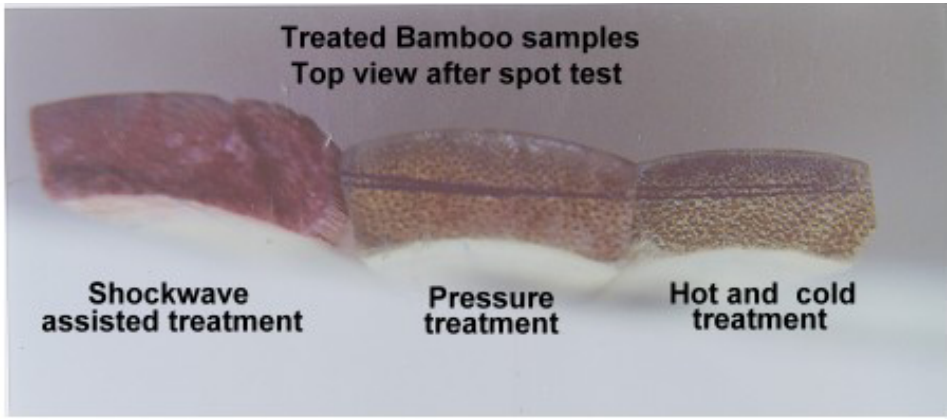
mboo can grow in most places, it's nutritious, it checks soil erosion, conserves moisture, repairs de
questers carbon and is useful against global warming.
ently bamboo's contribution to Indian economy is ~ US $ 2000million and is expected to grow in the

mboo is not made up in a way that facilitates preservative treatment. The outer skin, with its hig
forms a good raincoat and resists insects but also prevents preservative from entering the culms.

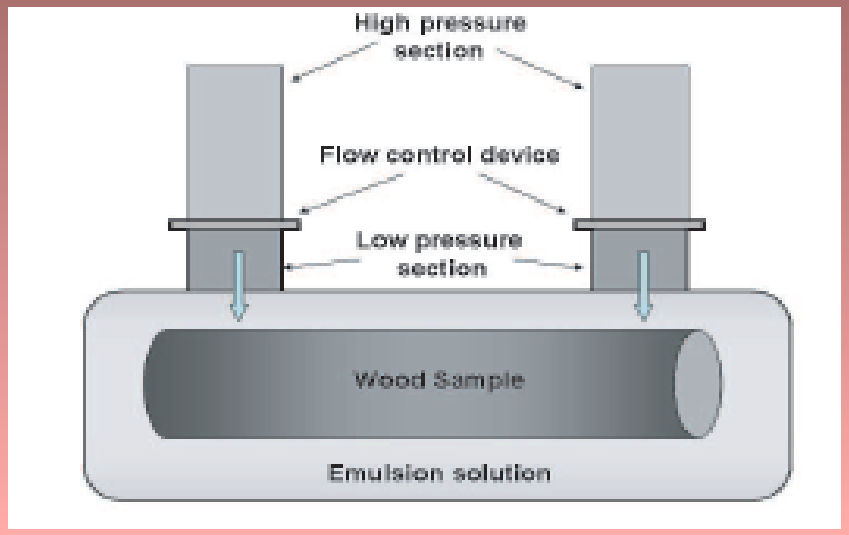
nside is covered with a waxy layer that is impermeable as well. So, a preservative can enter only thro
ing vessels, which are not more than ten percent of the cross-section. **Bamboo however is suscep
and destruction by biological agents like fungi, insects, marine borers etc... This re
erable monetary and material losses.**


Shock wave treatment
Pressure treatment
Hot and cold treatment
Preservative retention (kg/m3)
30
25
20
15
10
5
0
1
2
3
4
5
6
Sample no.



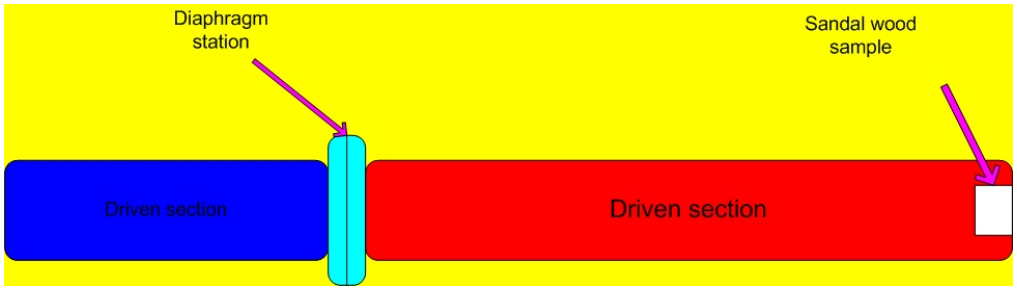

Treated Bamboo samples
Top view after spot test
Shockwave assisted treatment
Pressure treatment
Hot and cold treatment

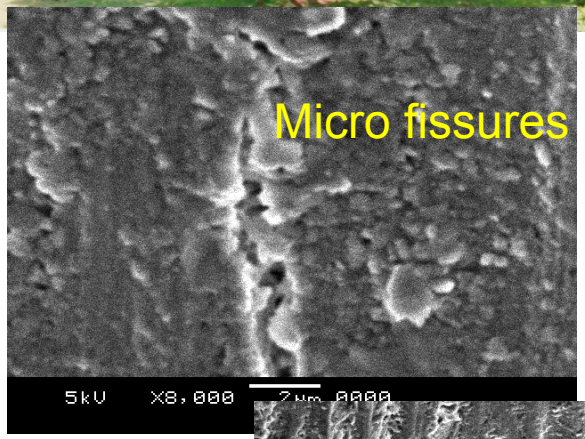
Shock wave assisted preservative impregnation system for pencil industry



Shock Wave Assisted Oil Extraction

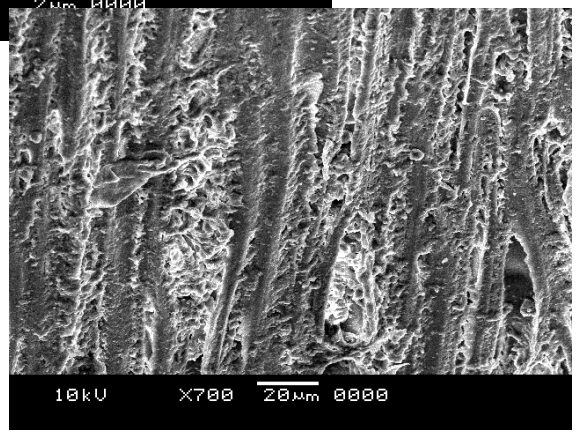
Shock Wave loading of natural products before extracting a pre-treatment process. After treatment oil can be extr conventional techniques like solvent extraction or distillati technology drastically reduces the time of extraction.

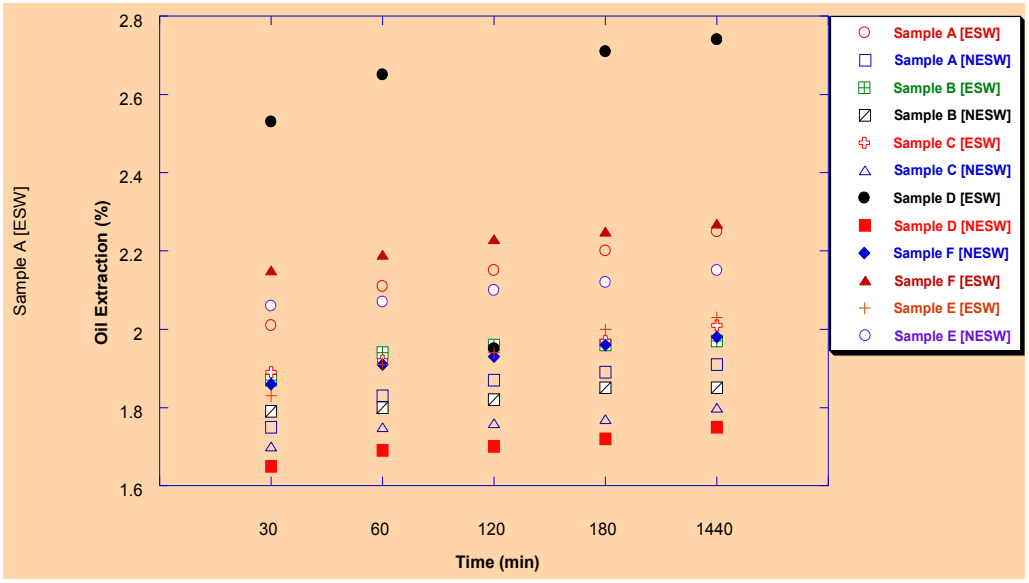




After exposure to shock waves

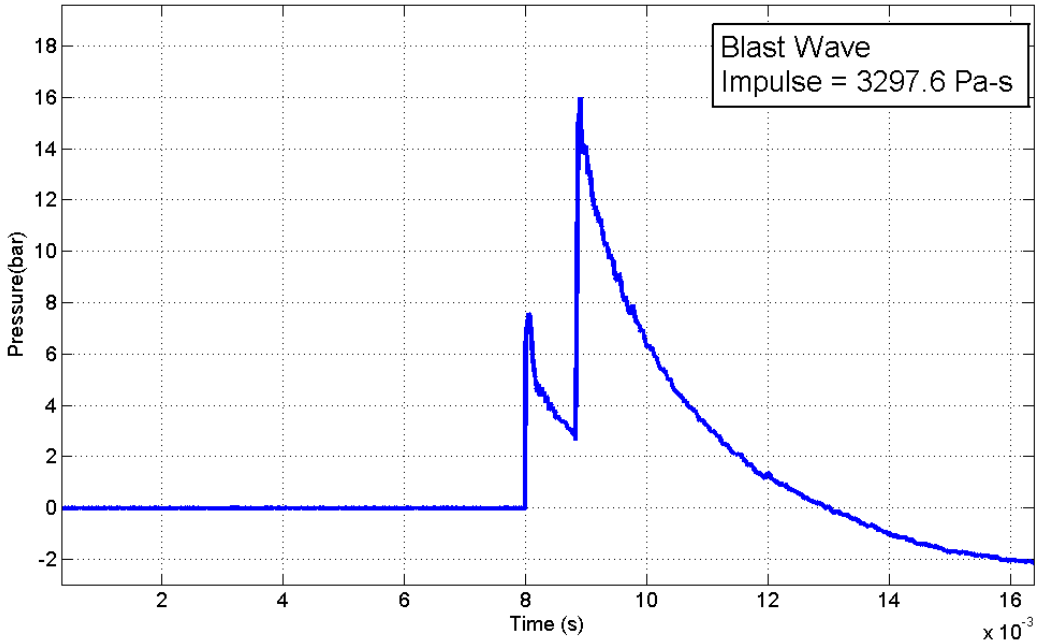
Before exposure To shock waves





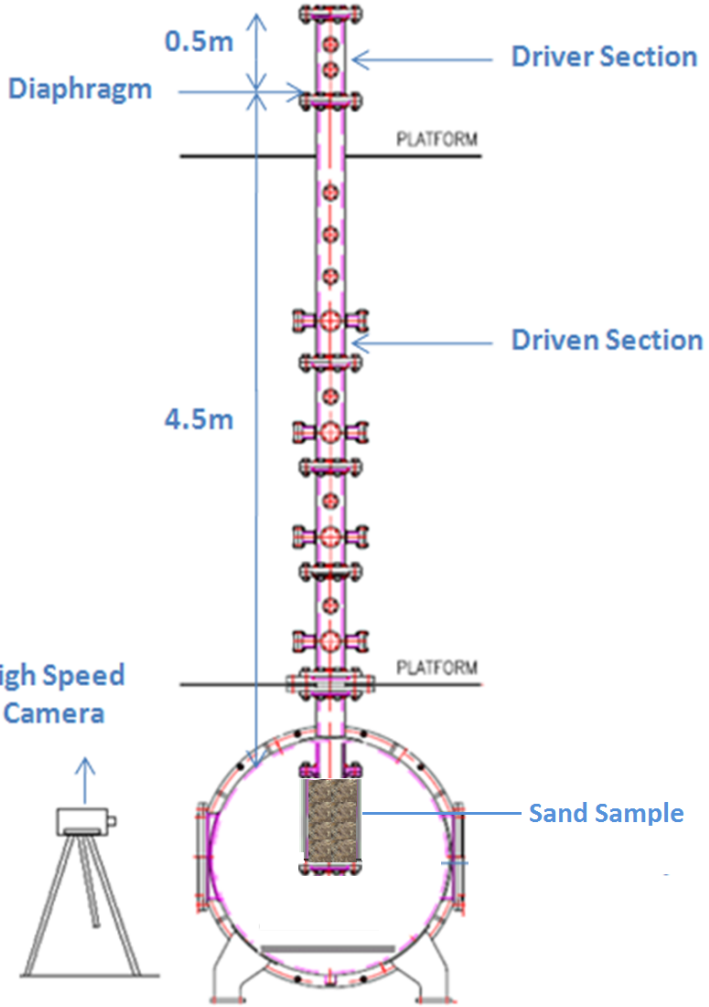
Blast Wave Induced Stress Wave Propagation and Attenuation in Sand

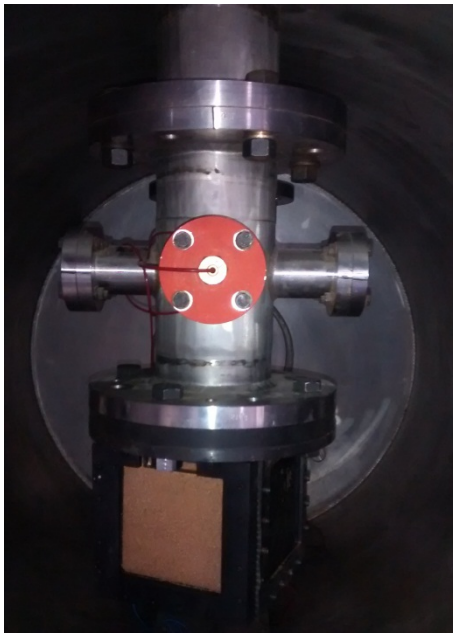
Shock Tube ID= 135mm
Driver section = 0.5m
Driven section = 4.5m
Driver gas : Helium



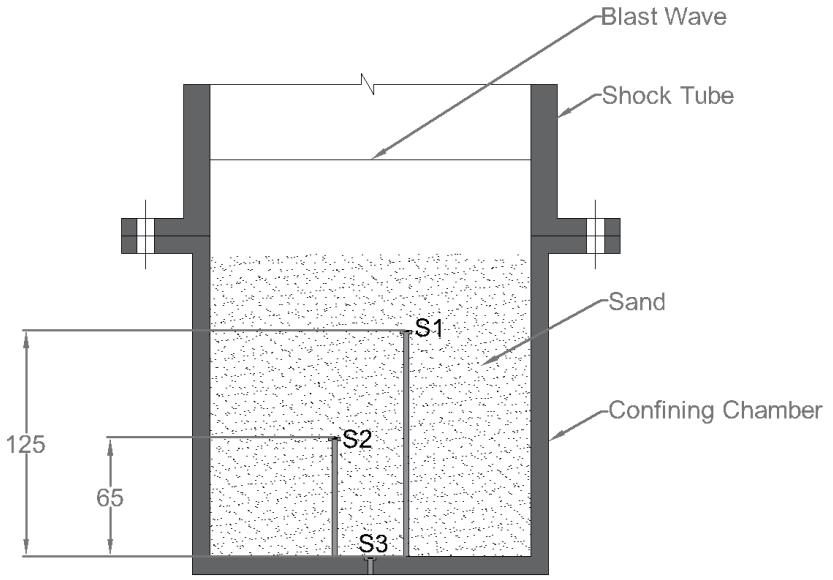
Blast Wave Incident Mach = 1.94
Peak over pressure = 16 bar
Positive time period = 4.12 ms
Blast Impulse = 3297.6 Pa-s

Blast Wave Induced Stress Wave Propagation and Attenuation in Sand





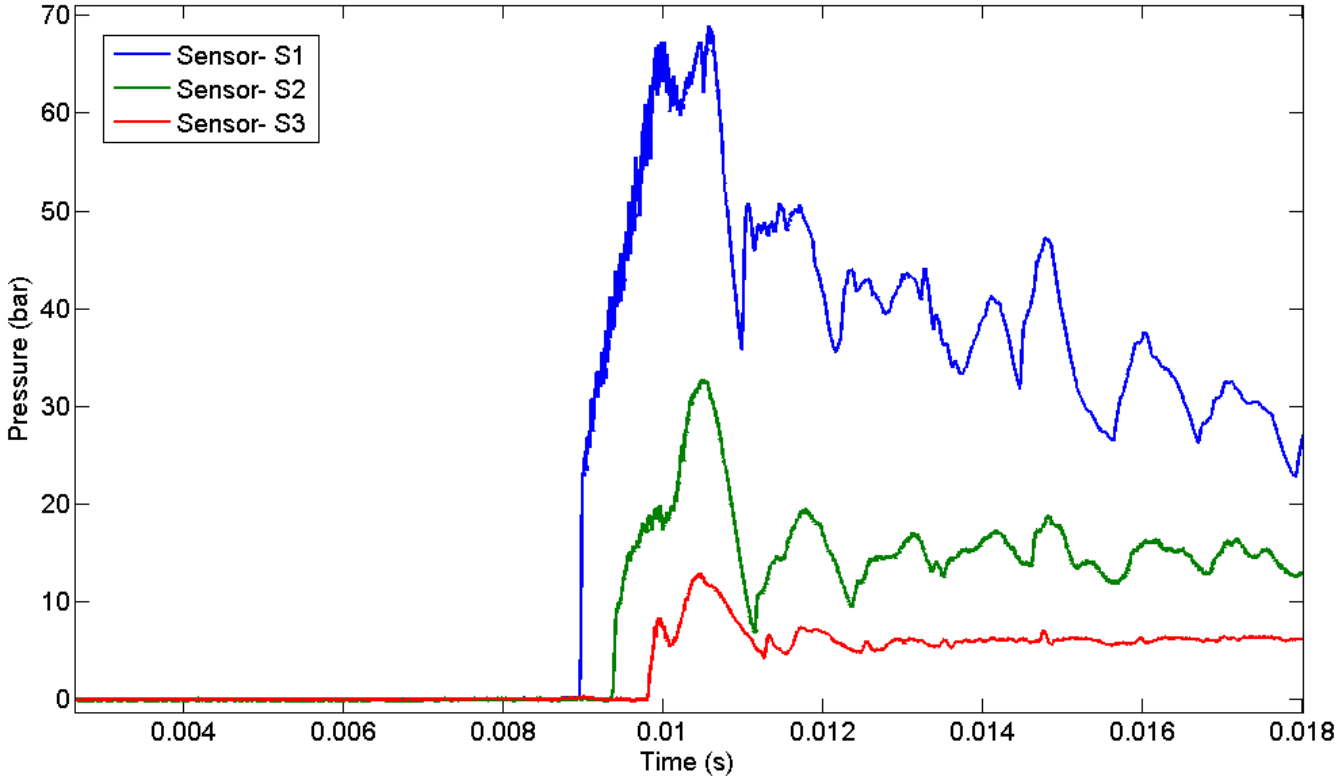
S1= PCB sensor at 125mm
S2= PCB sensor at 65mm
S3= PCB sensor at 0mm



- Sand is well graded with uniform size - varying from 75 micron to 4.75mm
- Relative density of 70% is maintained for the Sand Bed

Blast Wave Induced Stress Wave Propagation and Attenuation in Sand

Peak Pressure
S1= 67.2 bar
S2= 32.8 bar
S3 = 12.5 bar



Observation

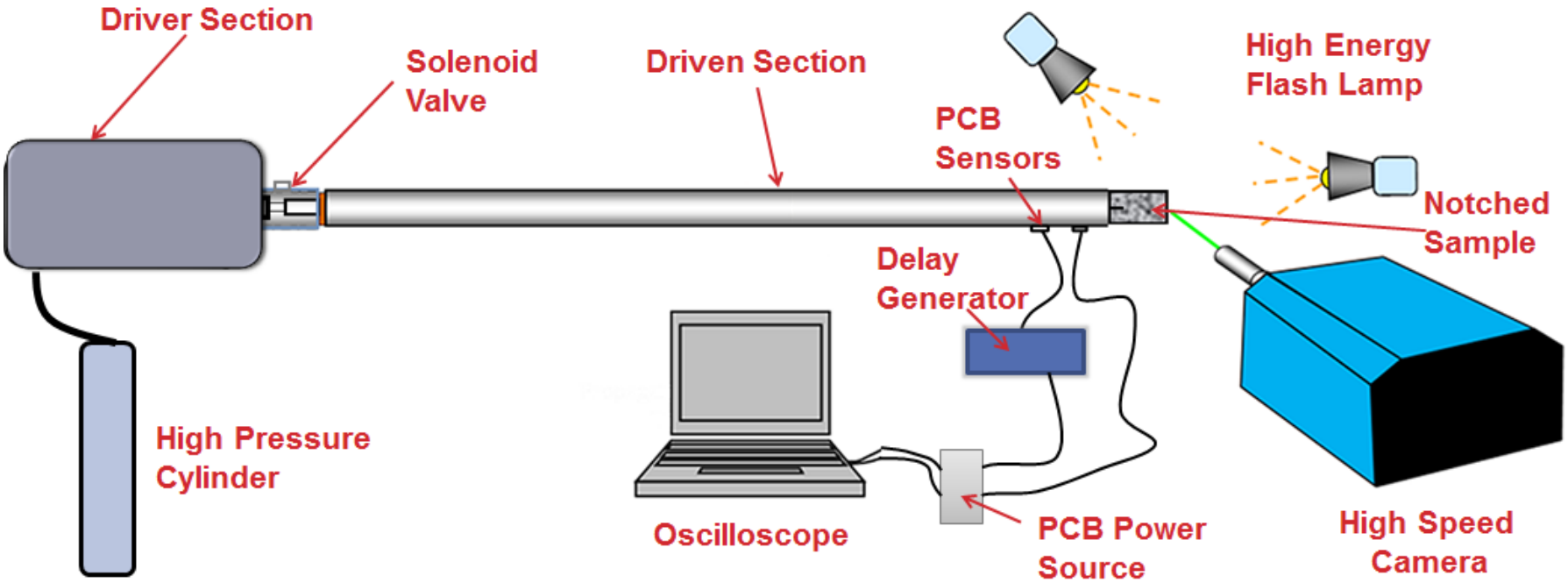
- 48.7% of attenuation from S1 to S2, 38.4% of attenuation from S2 to S3
- Stress wave propagation from S1 to S2 is found to be 149.63m/s and from S2 to S3 is 142.54 m/s

CRACK PROPAGATION IN ROCKS

Rocks Blast Parameters : Fracture Energy
Crack Velocity
Fracture Propagation toughness
Fracture initiation conditions

- Plaster of Paris and Mortar is used initially as model material for soft rocks like sandstone, Mudstone and Hard rock like Granite

- Crack velocity measurement using high speed photography

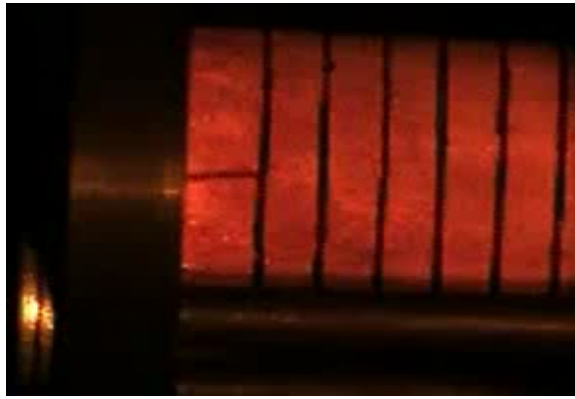


CRACK PROPAGATION IN ROCKS

DIAPHRAGMLESS SHOCK TUBE

Experimental setup

A pre-determined notch
made on the sample to ini
the crack and



Images were captured at 90
with a resolution of 256X128

Nature inspired Model for INNOVATION

Synergy between
Science
Engineering
Technology

- **People**
- **Leadership**
- **Vision**
- **Networking**
- **Money**

\+ Intensity

\+ Focus

INNOVATION

New Product
OR Technology

Genesis of a New Entity and Vision

Intellectual capital
(~ 25 patents)
R & D Laboratory
(US $ 25 Million)

Oil and Petroleum Industry

Bio-medical Engineering

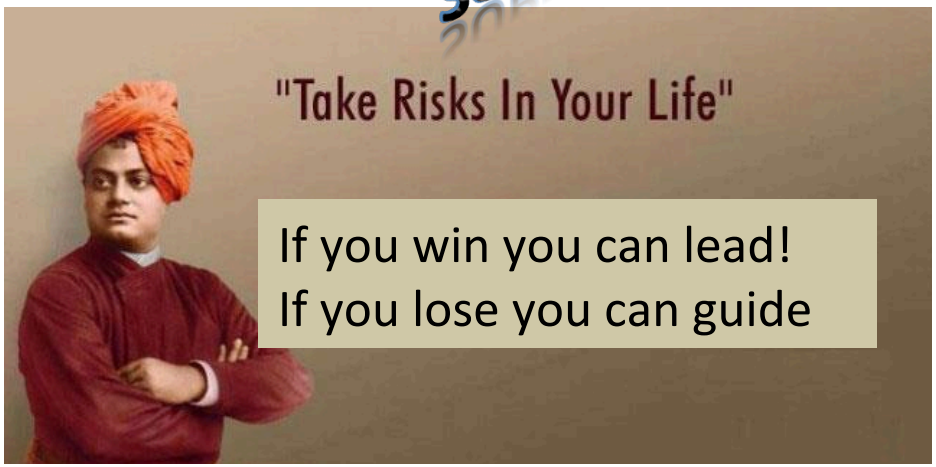
Wood processing

Extraction from natural products

Shock Waves

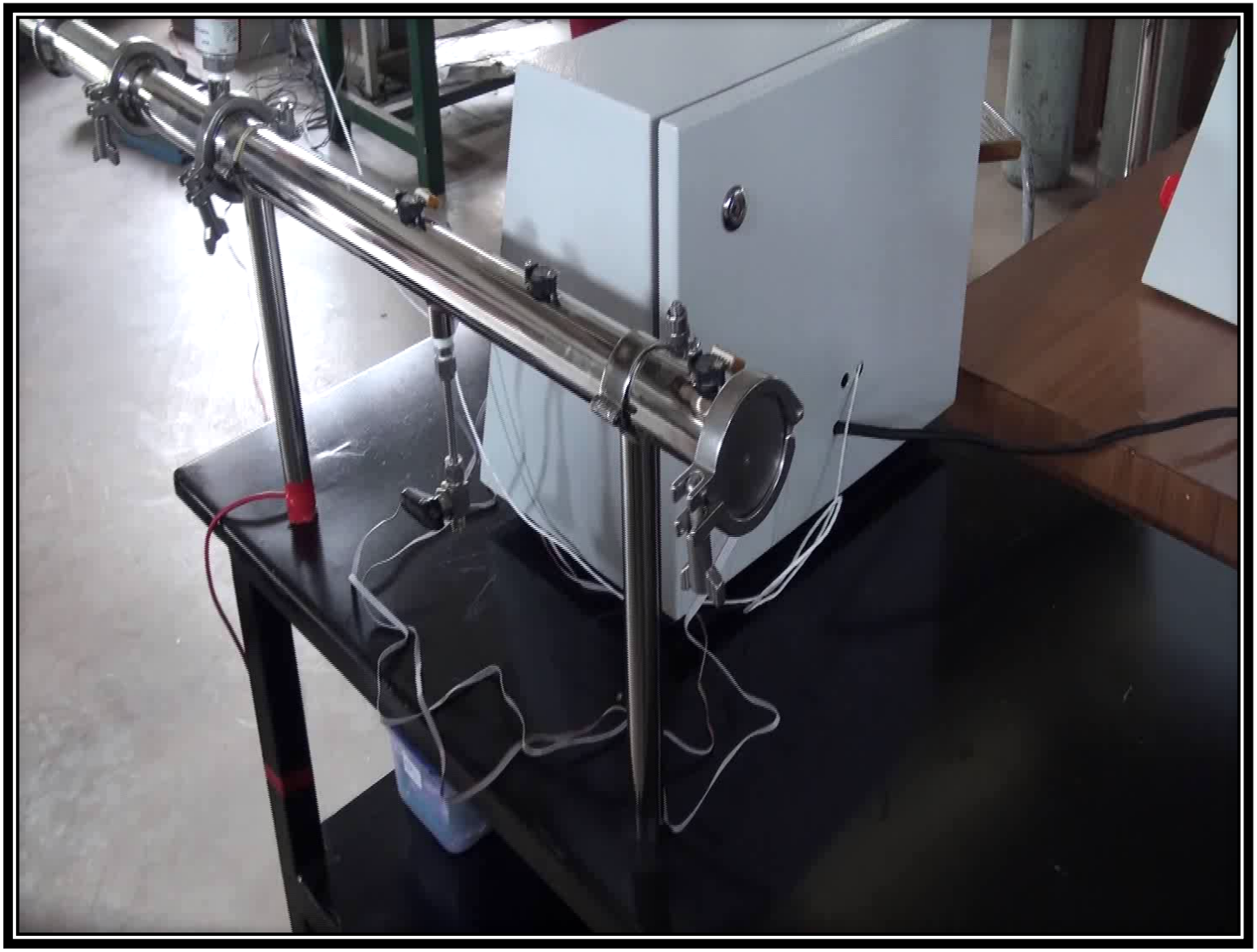
Tea Industry

SUPER-WAVE TECHNOLOGY PVT LTD.



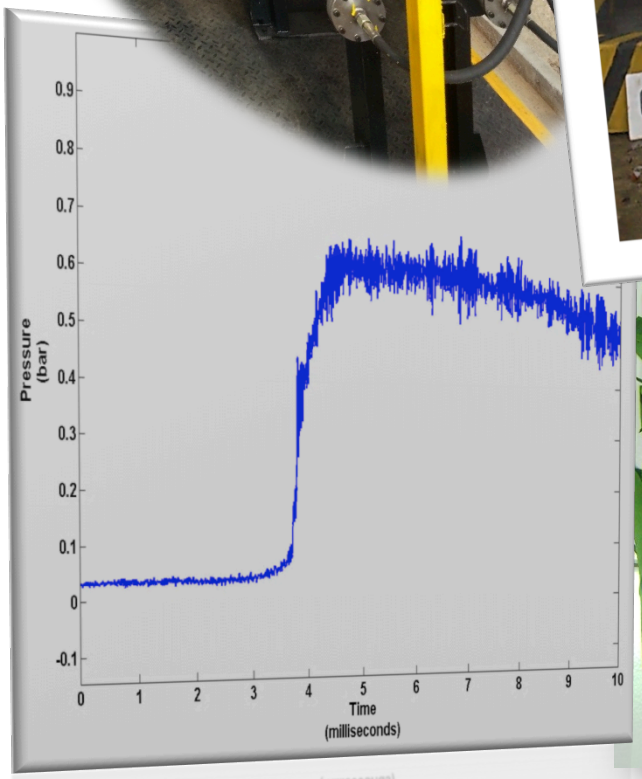
Hand Operated REDDY TUBE

First Product from LHSR
Out in the market

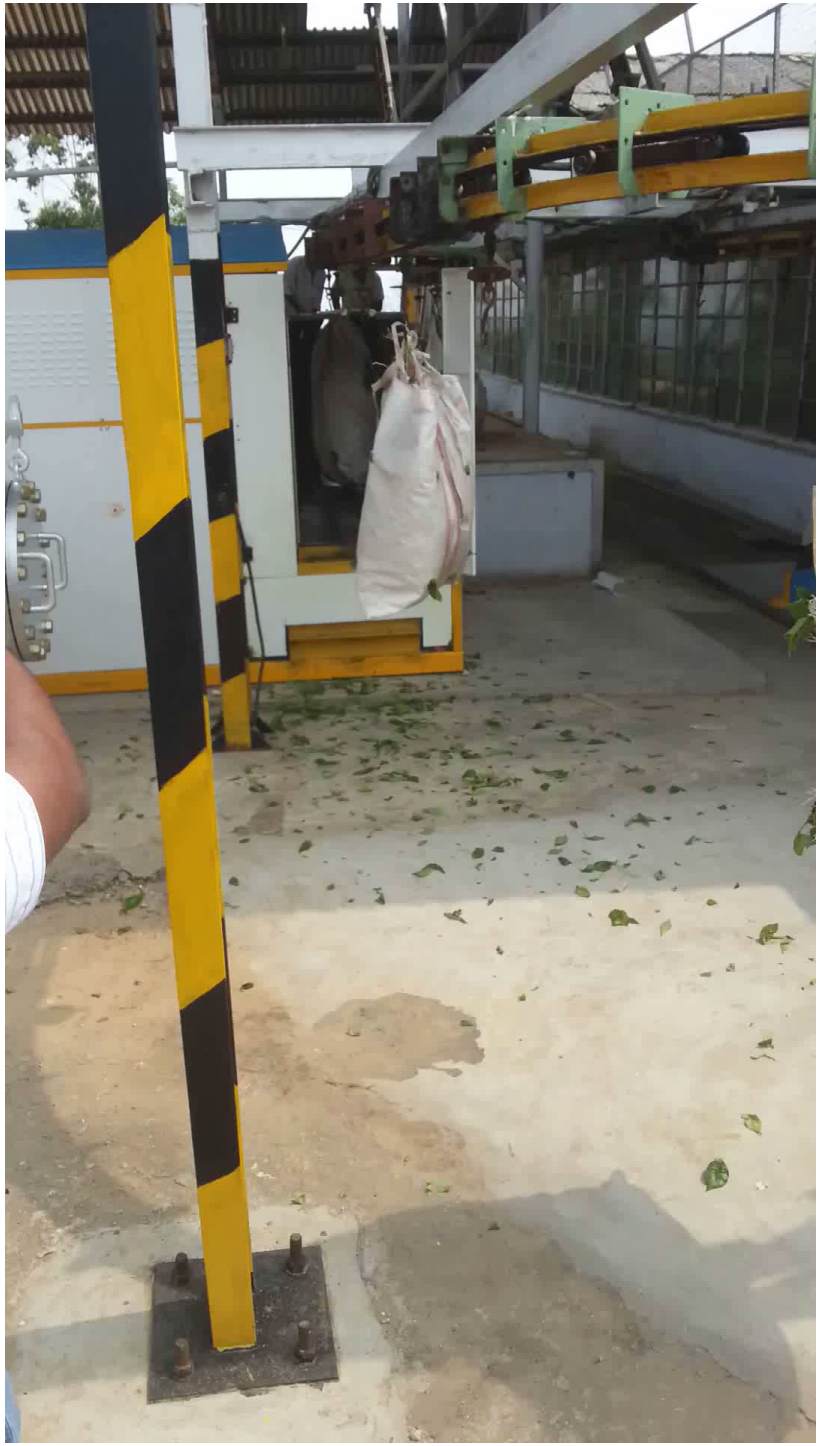


Indian Patent Filed

A new Anti-Cancer Tea produced using Shock Waves

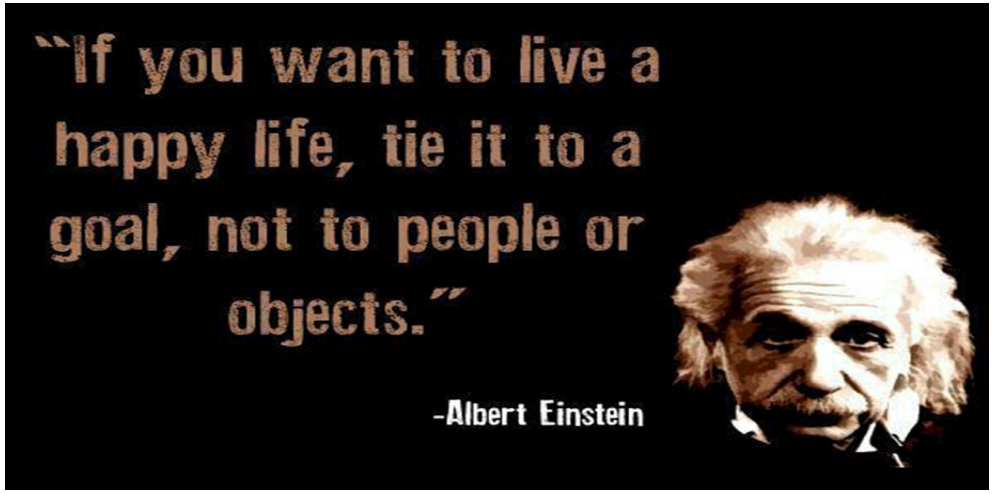


From LAB to LAND
in 8 Months time!



Indian Patent Filed

The Road ahead…….



From projects to produ

Thank you