Tryst with Missile propulsion
Some Lateral view points

- Contacts and reminiscences
- Productive interactions – erosive burning and combustion instability in liquid rockets
- CFD and RCFD – some personal experiences
- Future for propulsion in DRDL
  - Opportunities that may be lost and consolidation yet to be completed

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Contacts and reminiscences

- Way back in 1969 – Nayyar and a few others in DRDL – Bhooth bangla (as it was called) and another laboratory with GI sheet roofing come to my memory.

- Much enthusiasm with little infrastructure, physical or intellectual ; more dominated by thinking from services on research and development.

Some productive interactions

- Dr. A. R Vaidya (or AVM) who was in charge of solid propulsion at DRDL gave a project in 1972 – 1974 on measuring erosive burning data of some DB propellants.
- This started my interest in the subject of erosive burning. Led to my deeper love for the subject.
- In one paper I had argued about the relevance of kinetics on erosive burning (1978). In a paper written a decade later, I and my colleague Paul argued for the universality of erosive burning behavior.
- Two papers both accepted and published with opposing view points! …strange…why so?

Later insights different…why?

- Large number of data were published only later than 1978 including a review paper by Kenneth Kuo
- This appeared quite insipid as a large number of correlating parameters were chosen, plotted against each other creating more confusion than clarity.
- A review of all the work cited by him and some at a later time allowed the possibility of thinking along the lines of choosing non-dimensional correlations – something trivial on hind-sight.

L & R Theory

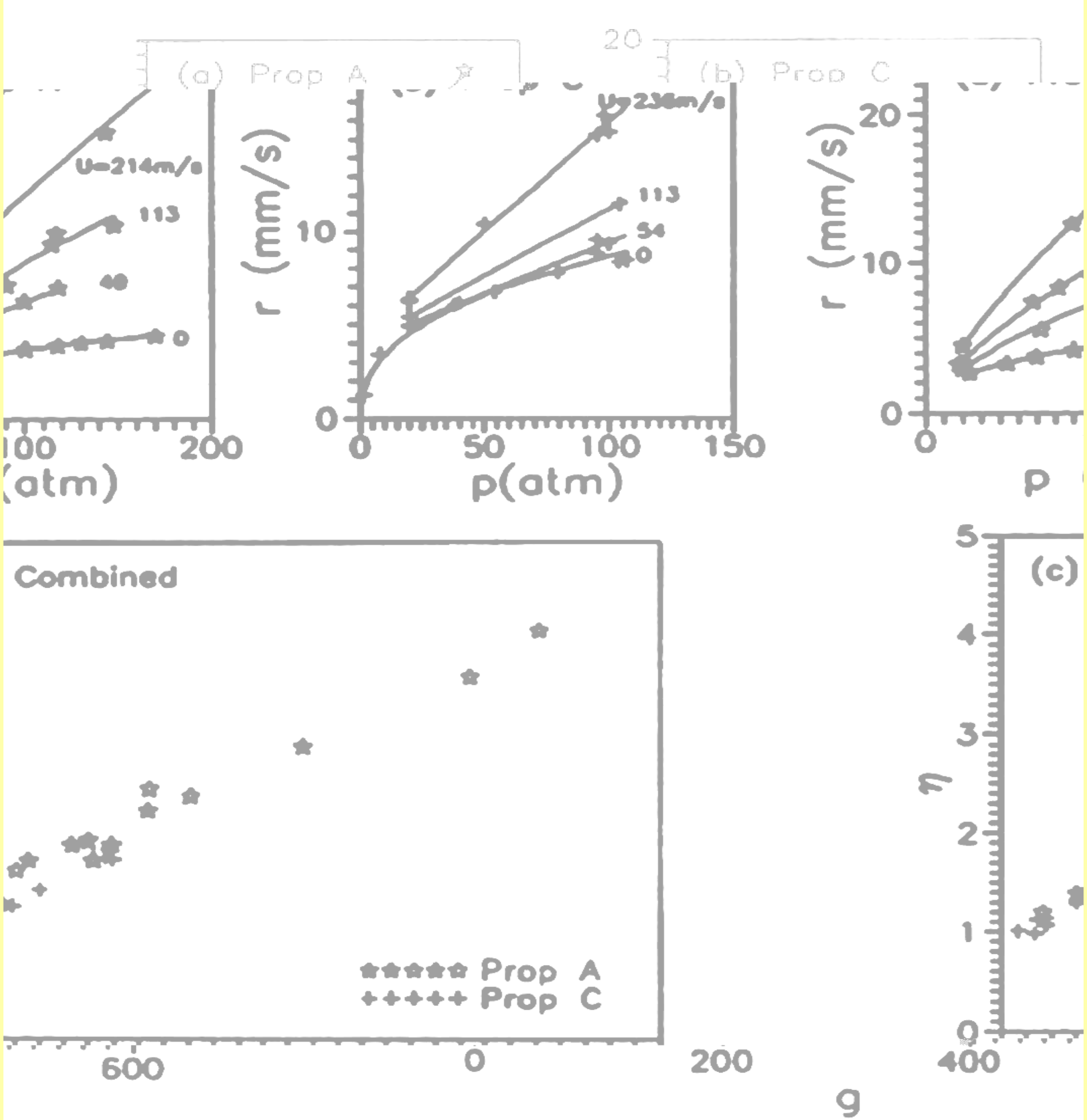
$$r = ap^n + \frac{\alpha G^{0.8}}{L^{0.2}} \exp\left(\frac{-\beta \rho_p r}{G} \right),$$

The present non-dimensional expression

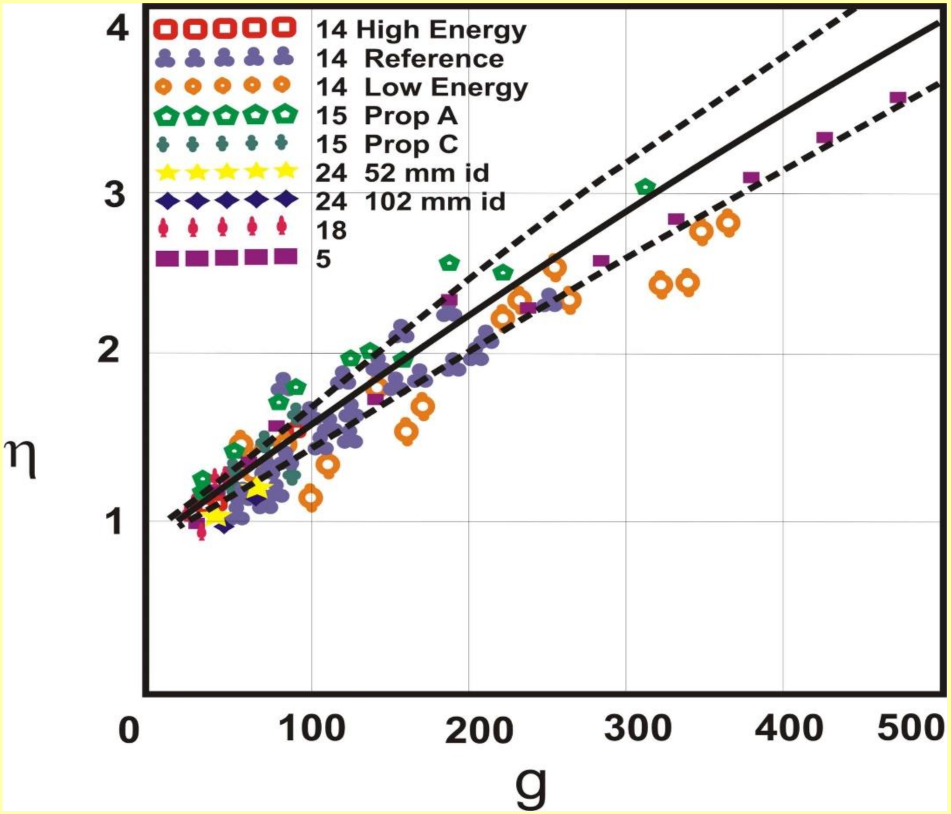
$$\eta = 1 + K_1 (g^{0.8} - g_{th}{}^{0.8}) \mathrm{H} \quad (g - g_{th})$$

with

$$g = K_2 g_0 \operatorname{Re}_0^m, \;\; \eta = r / ap^n$$



Mukunda and Paul, Combustion and Flame, 1997

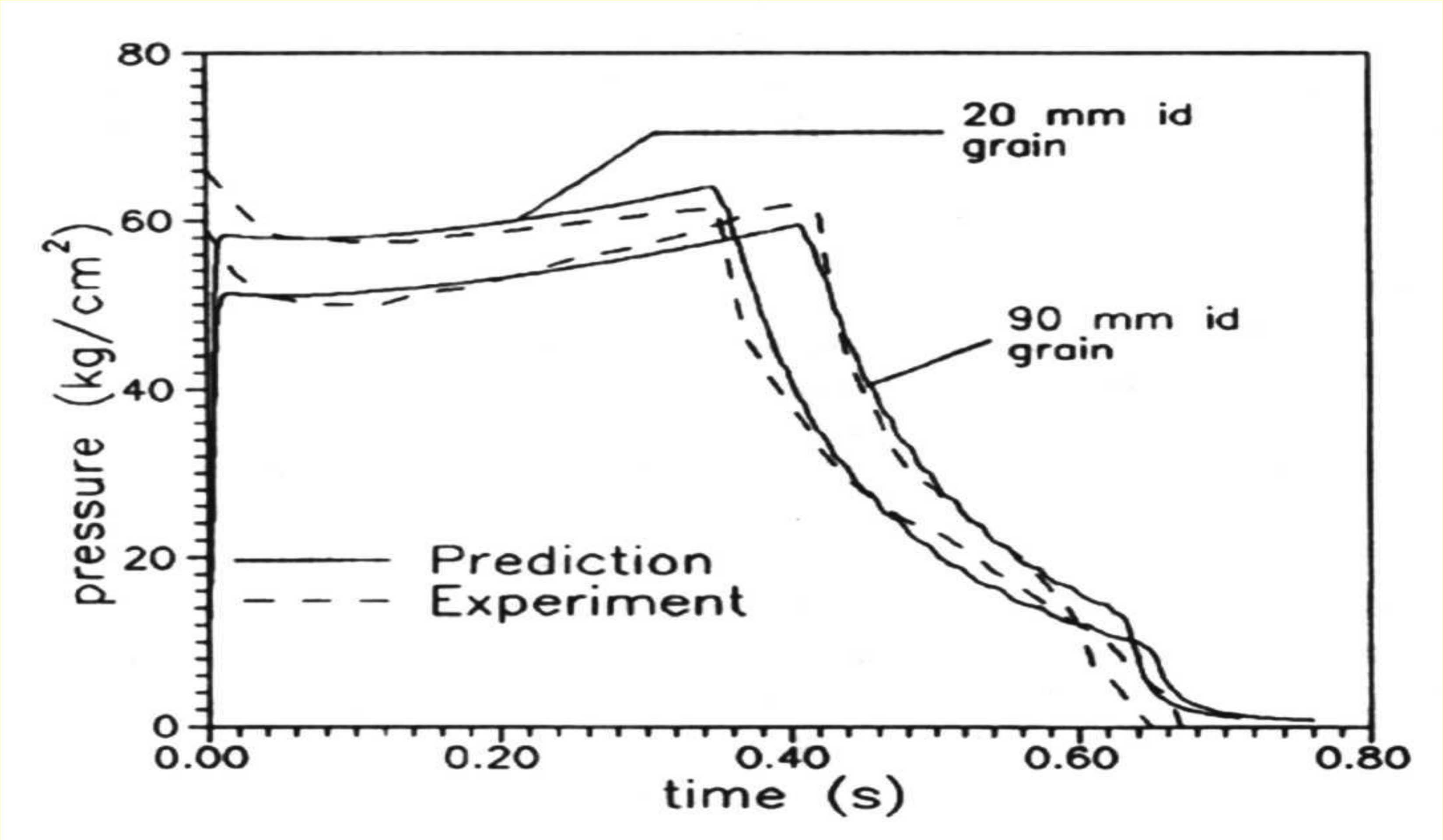


With experimental data from over twenty investigators over 6 countries and over thirty years on a dozen different propellants all the data fitting into, the curve is universal including one set studied by two investigators.

An important conclusion: We may have said the last word on the subject!

Why?: Any more experiments will add into this data and cannot be out of it.

(Mukunda and Paul, Combustion and Flame, 1997)



Proving the point: Predictions of pressure time curve of a highly loaded (implying significant erosive burning) solid motor and experimental data from a Japanese work.

Mukunda and Paul, Combustion and Flame, 1997

Some productive interactions

- The universal correlation can be used for design
- This contribution would not have happened were it not for the kick-starting by Dr. Vaidya.
- Wouldn't we have always be using some relationship of a "western scientist" (and many are tempted even now)

Conclusion: Think, find a committed person (from your perspective), and give money for research. You may not know the extent of benefit and even the investigator may not know; the pathways of academic research are sometimes inscrutable

On an instability saga……

Some productive interactions

- Venu (your present director, P Venugopalan) visited me once IISc (1978 – 80?) and told me they had done a test on Valient engine.
- He described the failure of the engine on the test bed with glee (!) and asked me a quiz question: what was my estimate of the root cause?
- I failed in answering the question!
- He then enlightened me on his assessment of the cause: high frequency combustion instability.
- This kick-started my life long interest in instabilities.

Conclusion: Listen to smart scientists, no matter where they are from!

Some productive interactions

- There was a problem of instability on the high altitude test facility hardware burning storable propellants in a liquid rocket combustion chamber and mixed with water to produce high pressure steam for operating an ejector.

- This was sporadic occurrence of pressure fluctuations argued by some as instability and others as heat transfer related problem

- With the previous knowledge, it did not take me more than a few seconds to realize that it is HFI. But proving it to somebody is far more difficult, as you can appreciate.

- I brought it to the attention of Prof. Dhawan and he constituted a committee from IISc, SHAR and VSSC to analyze and find solutions.

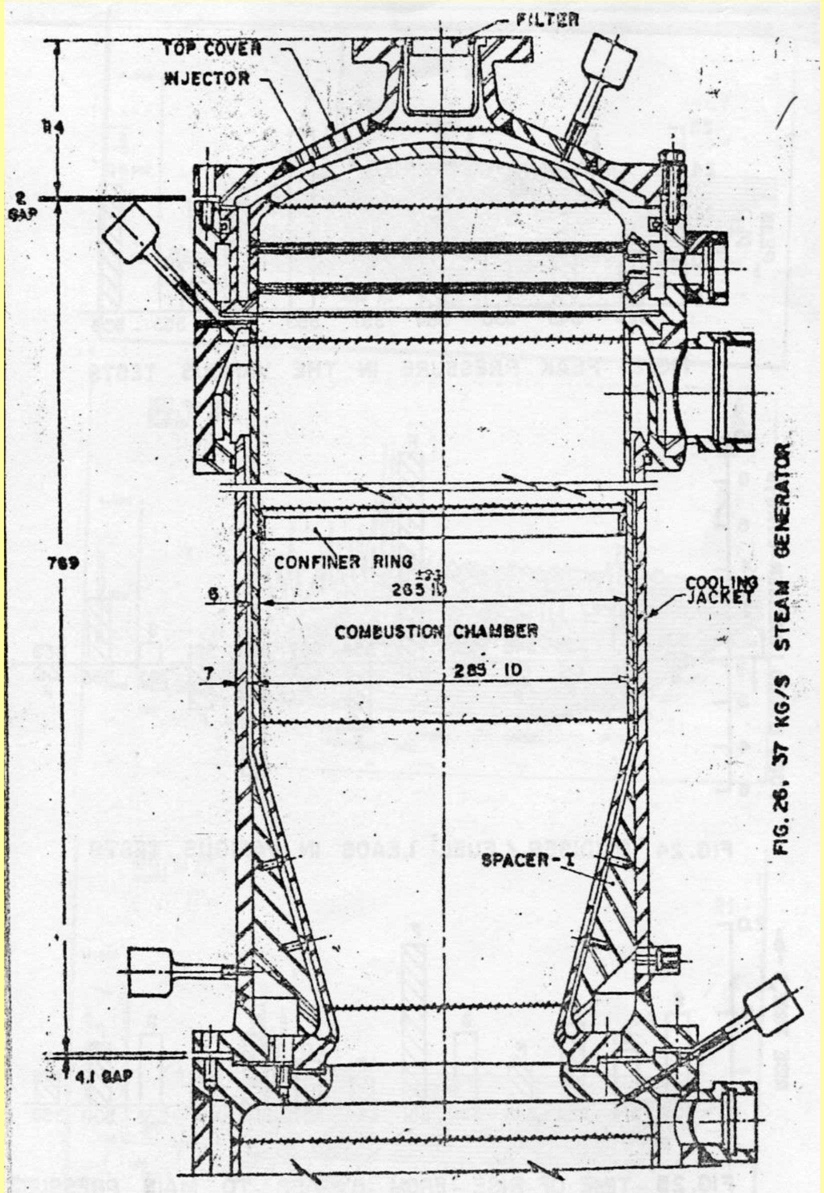
Some productive interactions

- Just for historical record, it had me as convener, Annamalai (SHAR) Ayyappan Pillai, K. Ramamurthy, Sivaramakrishnan Nair (VSSC), PJP, BNR, and N Balakrishnan (IISc) as members.

- Apparently, the subject had a record of earlier committees with apparently no great progress in understanding – confusion between thermal and instability problems continuing to persist

- Annamalai's grouse was that yet another committee had been hoisted on him! – he did not hesitate to state this at the beginning itself.

The combustion system of the HAT facility water as a regenerative coolant and injectant



This facility is of German design with radial injector

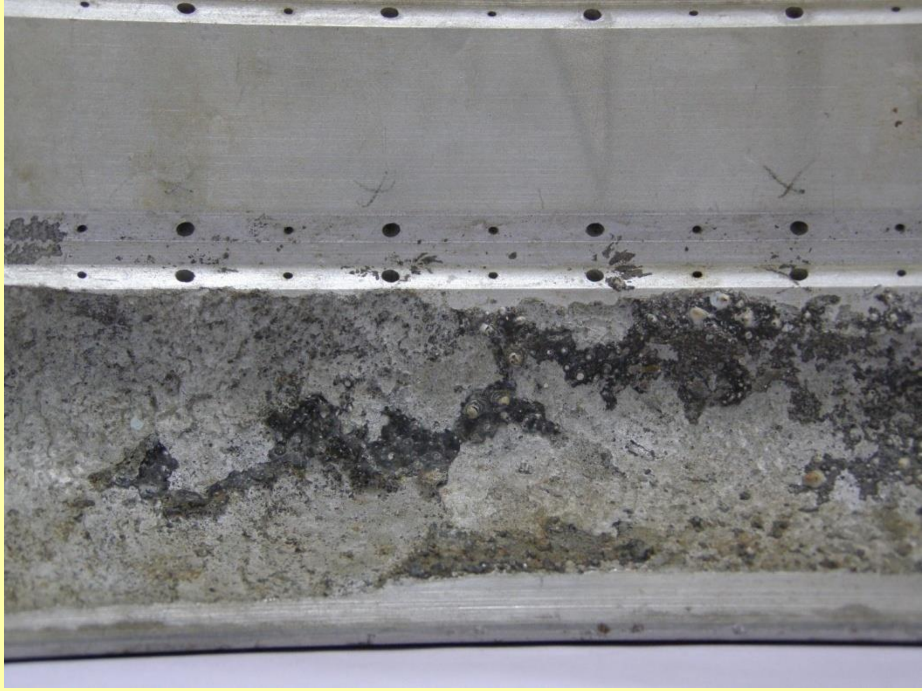
Fuel: (Turpentine + diesel) at 2 kg/s through 152 orifices of 0.95 mm dia

Ox: RFNA – 11 kg/s through 152 orifices of 1.9 mm dia

Water: 24 kg/s; Total: 37 kg/s

Start-up: Furfural alcohol slug
Operation: steady state 12 s+ and runs for ~200 s

Nominal p_c = 21 atm.
Down-rated p_c = 19 atm.



Notice the damage on the injector head. There is some room for doubt about HFI, though small

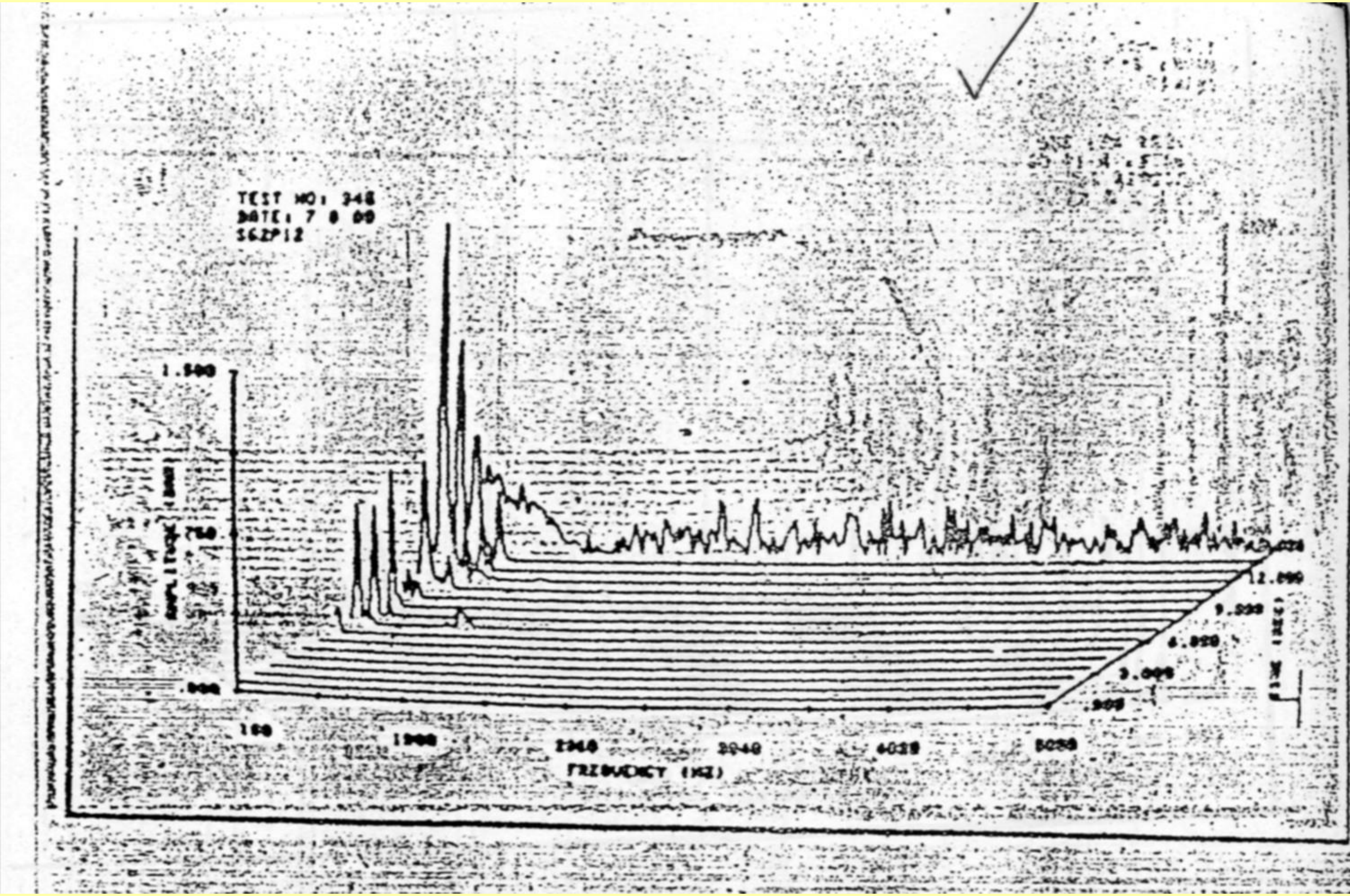
Probing the data - 1

Q: Is the failure correlated with HFI? Is thermal problem the cause?

A: There were 15 useful tests. HFI data was not known for 6 tests. HF transducers were introduced later, it appears.

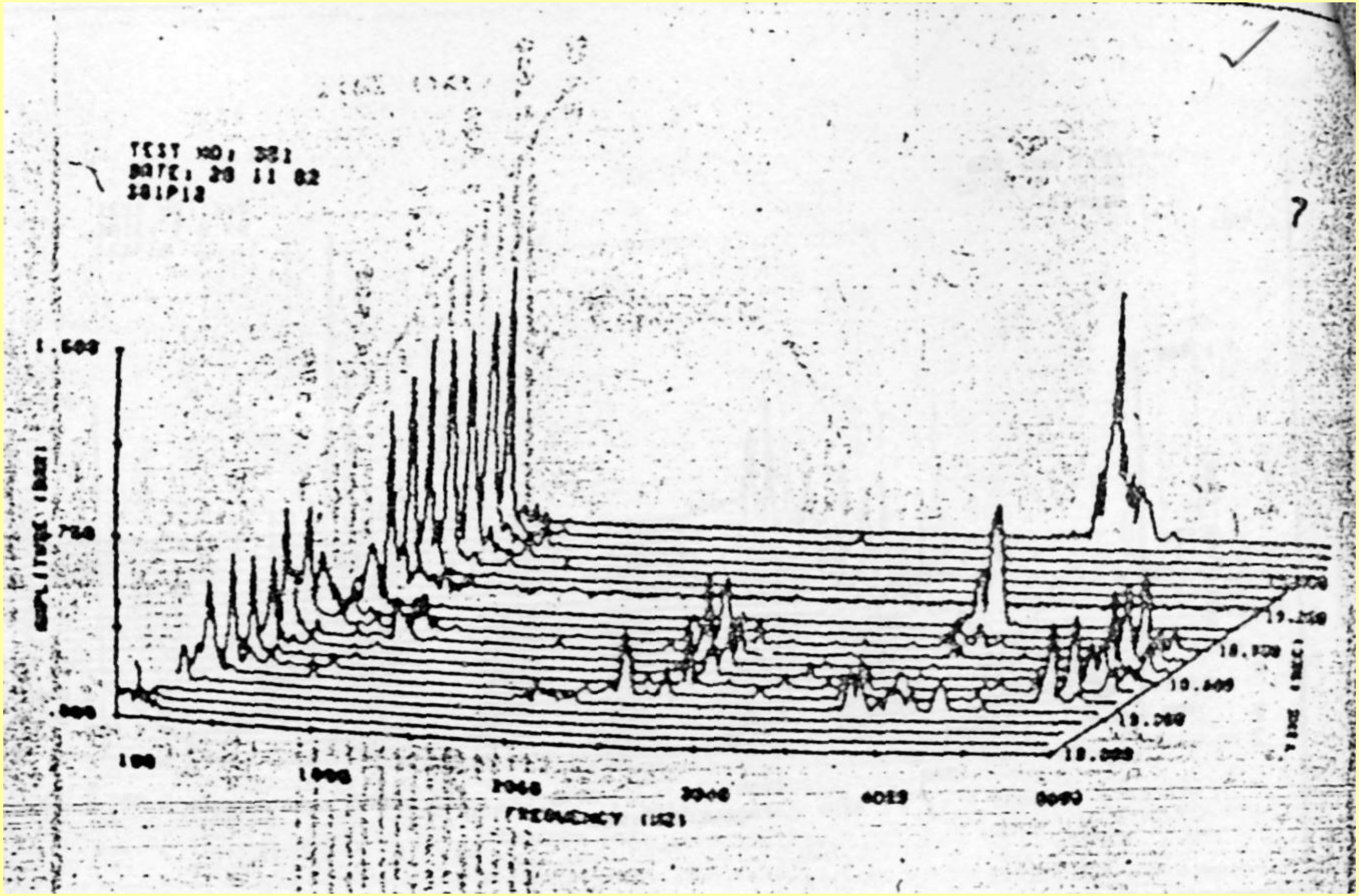
PJP and Ayyappan Pillai did a detailed and careful spectral analysis of p_c – t data at SHAR. Frequencies identified were 1T mode – 2.3 kHz, 2T mode - 3.6 kHz, 1R mode – 4.6 kHz.

These showed that whenever there was HFI there was failure in 7 tests. When it was clearly known that there was no HFI, there was no failure (2 tests). It was also inferred that when there was no failure, there was no HFI.



One of the cases with no instability

The fluctuations seen constitute white noise.



The case with HFI; Notice peaks at ~ 2.3, 3.6 and 4.6 kHz

Probing the data - 2

- Many questions were raised and answered.
- Some suggestions were made to overcome the instability – providing ablative liners inside the combustor to help attenuate the instability.
- Finally, change in O/F towards oxidizer side reduced the incidence of the instability to a low value and this appeared acceptable.
- The system is now moth-balled as most tests that needed input were completed.

Finally, Mr. Annamalai admitted that he did not imagine the degree of scrutiny undertaken in this effort would be so significant and specifically admitted that he wished to withdraw his original observation of this being another committee.
Later, he returned to the laboratory for inputs on his thesis on ejector systems for space simulation with enhanced impression of academic strength.

Origin of productive interactions…

Origin of productive interactions and so….

- Vigorous participation in review meetings

–involvement in PDR of all stages of PSLV including satellite propulsion systems and most propulsion systems of IGMDP.

- I thought I became effective as time went by.
- Things I learnt went back to students through lectures.

- I notice that not many young faculty are not found in reviews these days.
- Understandably, in-house capability has improved significantly making external inputs partly redundant.
- My plea is: Please try involving young faculty in reviews even if the inputs are inadequate. Some will flower and the multiple benefits of these will make wholesome contribution.

Computational fluid dynamics including reaction (RCFD)

- There has been interest in RCFD from early seventies
  – 0D, 1D, 2D, 3D
- Whenever flames in practical systems are looked at, one needs to deal with CFD itself – 2D and 3D
- Laminar flames are as practical as turbulent!

Example: Solid propellant combustion.

- Turbulence modeling is fashionable; usually presented as formidable; used as a defense when there are differences between predictions and experiments.

CFD, RCFD

- Really speaking, effects of turbulence are not as un-understood as painted except for detailed or complex effects.

There is one serious issue – faith in CFD or RCFD.

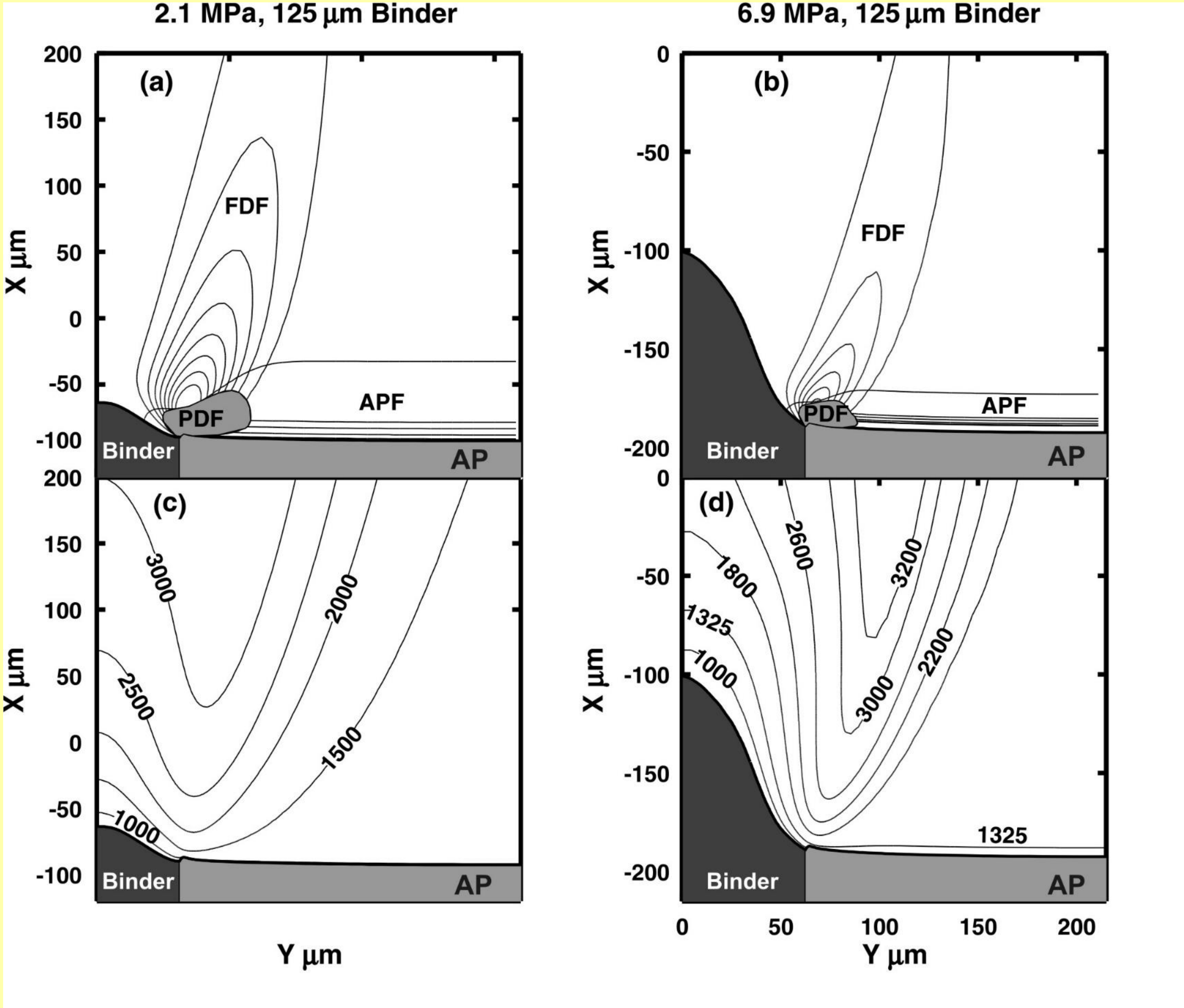
– It is <u>not often thought </u>that it is the conservation equations that are being solved and if attention is paid to solving them accurately, why should they not represent reality

Now from our own experience on this subject

- Sandwich propellants are thought as good analogues for understanding propellant combustion. Though this is a matter of debate, I have had no doubts. Extension to solid propellant combustion, I think is possible and is yet to be done.
- 2D AP-Binder sandwich problem – predicting computationally the burn rate of a sandwich system – 100 microns sheet of AP and 50 microns of CTPB sheet.
- It turns out that the key parameter is the activation energy of pyrolisis.

Sandwich propellant combustion - 1

- A 2 D reactive fluid dynamic code written by Prof. Paul was validated against stretch effects on a Bunsen flame and used on the AP – CTPB sandwich propellant combustion problem.
- The code is a special one written for tracking the burning surface and accounting for its movement while preserving the conservation of mass, momentum, energy and species
- Solving two momentum equations with energy and species conservation equations using 3-step chemistry with along with a pyrolysis law for AP surface decomposition and unsteady condensed phase were the substance of the problem.



Results from a calculation of sandwich propellant

Sandwich propellant combustion - 2

- This research forming Dr. Ramakrishna’s thesis had a test of confidence in CFD. Computer solutions with the known chemistry parameters from the literature always went chaotic. Code was suspected.
- It took nearly an year and half of struggle to examine the possibility of errors of a variety of kinds.
- Finally, the suspicion of error proved incorrect and the non-converging nature of the solution needed explanation.
- After much soul searching, the simplified problem of AP combustion was run in 2 D mode. Non-convergence of solution persisted even then.

Sandwich propellant combustion - 3

- It was clear that the non-convergence of the full problem must have been related to some instability.
- Linear stability solutions from literature were then examined; these clearly showed that for the chosen parameters that were standard in the literature for over thirty years and used by all stalwarts, the solution of the full unsteady problem was unstable.
- This feature had bypassed all the stalwarts because they never treated the problem fully and when a few treated the problem fully, did not analyze what they found clearly, and bent other features to somehow show a steady result – great science by stalwarts!.

Sandwich propellant combustion - 4

- Then onwards, the pathway for Ramakrishna was clear but not necessarily bright.
- The physically observed steady combustion process implied that the chosen parametric values for a crucial parameter, namely, the activation energy for pyrolysis was incorrect.
- Efforts were put in to determine this parameter consistent with other experiments and the observations of AP and AP-sandwich combustion.
- A paper was written and sent of to a journal. One reviewer, from what we deduced, as a stalwart was highly caustic arguing how a new study that departed in its choice of parameter from those of the stalwarts could be correct at all!.

Sandwich propellant combustion - 5

- It then took two years, spirited defense at an international conference by Ramakrishna, showing up the presence of this instability in others' calculations not adequately recognized, and arguments with several scientists to remove the blocks in the minds of a few scientists and the editor of a journal for the important finding to see the light of the day.
- The central message from this struggle is that it is important to have faith in CFD for oneself, that too of a substantive nature for ensuring that others respect what you have done.

What is the relevance?

After you have really acquired this faith (in what? fundamental conservation equations!), you discover that what is around is a fair amount of <u>pseudo-faith</u> in the subject.

Why do I say this? A major review was held at DRDL some years ago on the hypersonic missile with India’s “who is who” in CFD also being around.

Presentations of results of external flow, internal flow and air intakes were made.

Whither CFD?

- Comparisons of external flow calculations with wind tunnel measurements were shown. As usual, some were and some not so good allowing discussion and some general acceptance
- Similarly, comparisons of internal flow (supersonic combustion) with several results from literature were presented. These too were accepted (somewhat grudgingly by some).

Whither CFD?

- Wind tunnel results on some model specifically designed for testing were presented. There was no presentation of CFD results. I simply asked why is it so? It appeared as though I was asking a heretical question. The comments were (a) In the case of air intake it is not possible to account for all effects. (b) There are no adequate results to trust computations, and such other observations.

Most "appropriate" people making incredible arguments!

Whither CFD?

- Conservation equations are the same; it may be that viscous flow interactions in internal flows could be more severe.
- But then, so much progress has been achieved in the rest of the World in internal flows like in turbo-machinery that are even more complex. Why should one have even a trace of doubt regarding air intake flow calculations?
- Is it as though air intake computations have not been made at all? …. I was baffled!
- I stopped short because of being branded too “critical”

The message - it is useful to recognize the reality of the environment and continue to strive for establishing the truth with greater advocacy.

Why are CFD, RCFD so important?

- Truly speaking, most solid and liquid rocket development has been accomplished with simple computations.
- The benefits from computational work are far more substantive for aircraft applications – flow over the aircraft as well as gas turbines – where ever lift and drag issues are important (internal as well as external flows)
- The value addition in terms of getting a grip on the results without much testing and answering some tricky questions is better handled with CFD even with rocket like vehicles (with thrust to drag being very large – accelerating vehicles).

Why are CFD, RCFD so important?

- A hypersonic vehicle with a scramjet negotiates a very small corridor. It is nearly a cruise vehicle. It is more like an civil aircraft designed to fly autonomously 7 to 8 times faster after the boost.

- Any design strategy should treat the entire system together, generally a strategy alien to DRDL since most vehicles it deals with have a high thrust-to-drag ratio.

- For those religiously minded, the best way to describe it is that it is like ardha-nareeshwara, a shiva-shakti combine.

- The thought that one can accomplish its design without flying it on a computer much like a civil aircraft is a figment of imagination (why things are going this way is unclear; requires super-review. I some times wonder whether even this will be adequate)

Just when I had all the answers to the questions (in my mind)…

- I learn that the development of the long range missile has been successful (ref: India today). The characteristics of this rocket based missile are not far from those of scramjet based vehicle.

- I have some times wondered whether the inappropriate slow pace of the development of the more complex vehicle – HSTDV is indeed connected to the success of the rocket based vehicle

What about future work of DRDL in propulsion….
…..in the next 10 or 20 years?

I will not provide a list of opportunities. For they will present themselves. The essence is to capture the exciting and execute. However….

To attempt to answer this question
we ask a subsidiary question:

Notwithstanding all the good that has happened till now, does DRDL want always to be a follower? a 2nd nation, a 4th nation to get somewhere?

Or

Does DRDL want to do something unique others think they must do?
better, others are not even thinking they will accomplish?

If it is the first, “business is as usual”.

From what I have seen till now, only that much will be accomplished that makes people gently happy or mildly unhappy, both of which will be short-lived.

The people to be impressed may slowly move from one to the other.

Dependence on continued positive support from armed forces will become a question since seeking hardware from outside may become more attractive.

If DRDL wants to do something unique,

It must shed complacency and intended neglect of central issues:

1. Making efforts to loose interesting opportunities – like building a hypersonic vehicle. This was and perhaps is a very important project, but doomed not to take off the way things are.
2. Not consolidating what is accomplished - Can we hope to design new vehicles based on DRDO 001 or DRDO 010 report instead of NASA 194, etc. I have spoken on this at VSSC and DRDL to several directors over years and at least one SA in an open meeting with no result.

- You cannot get to where US/France/USSR are by strategies that fall much short – whether it is DRDO or ISRO the answer is the same
- Make your countryman gently happy/mildly unhappy or make him surely be proud of you. The choice is yours, wherever you want to be.

I am sure there are issues that I have stated on which you have something to say – Please go ahead and say what you want.

Before that:
Just let me thank you for the patience in listening to me.