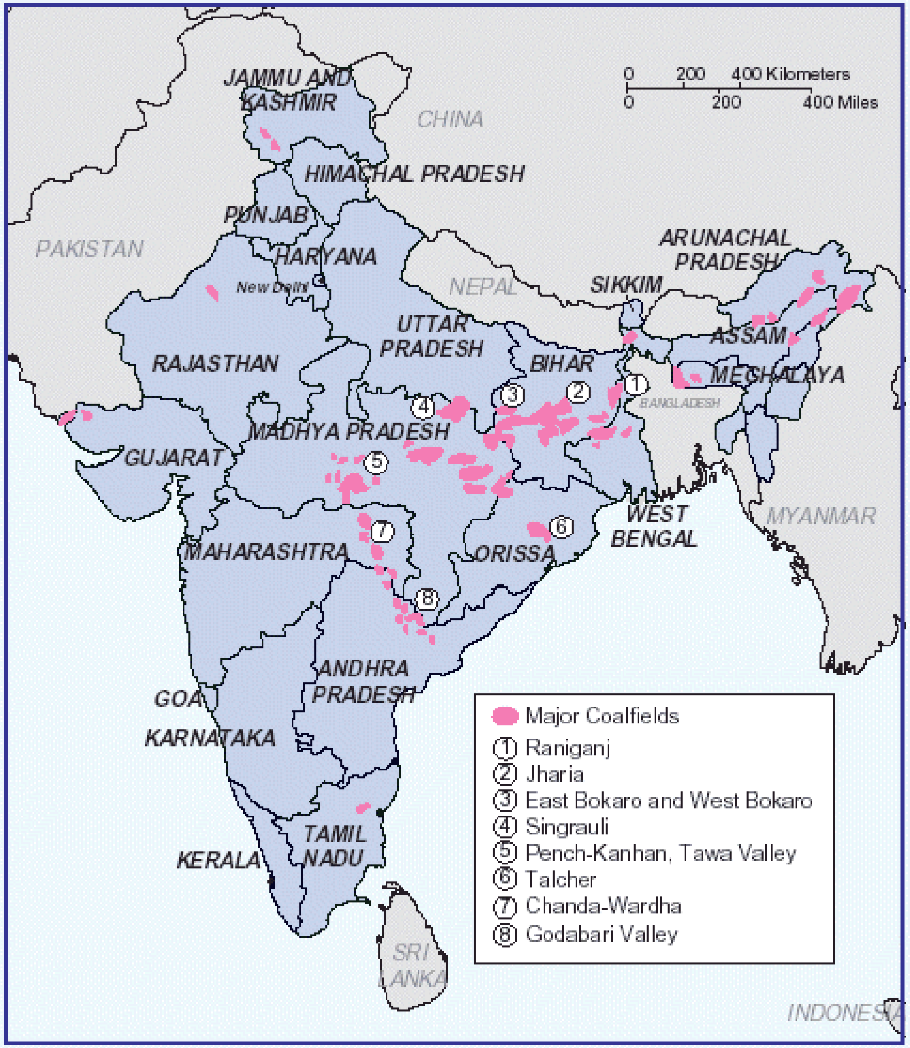
Clean coal technologies, some history and novel approaches Science – research, technology and outreach

- Background on coal –to– power in India
- What is clean coal technology? Why?
- How is it approached elsewhere in the World?
- How was it approached for the last fifteen years in India?
- How do we break the impasse?
- New ideas, Ideas pursued in China.
- What should done here? What is the science involved?
- Research, technology at small levels
- Approaches to reach out.



Grade	Gross cal value @ 6% moisture, MJ/kg
A	**> 27**
B	**24 - 27**
C	**23 - 24**
D	**21 - 23**
E	**19 - 21**
F	**16 - 19**
G	**13 - 16**

Major coal fields in India. Coal produced is 640 mmt in 2011-'12

(m tonnes)	FY07	Incremental demand by FY12	FY12	(%) increase
Power (Utility)	326.5	216.4	542.9	66.3
Power (Captive)	29.0	19.2	48.2	66.2
Cement	20.4	11.9	32.3	58.3
Others	82.2	20.2	102.4	24.6
Total non-coking	**458.1**	**267.7**	**725.8**	**58.4**
Steel (including imported coke)	38.8	29.7	68.5	76.5
Total	**496.9**	**297.4**	**794.3**	**59.9**

Characteristics of Indian Coal – E F and G types

• Low sulphur	Less of SO_2 problem in combustion mode, H_2S in gasification mode
• Low GCV & High ash	Expensive coal & ash handling system; Burden on coal transport Solid waste management problem
• Base to acid ratio < 0.3 & low S and alkali content	Low slagging and fouling potential

Moisture, % by wt	6 – 20
Ash, % by wt	25 – 45
Volatile matter, % by wt	17 – 30
Fixed carbon, % by wt	18 – 40
Sulphur , % by wt	< 0.7
Hardgrove Grindability Index (HGI)	45 - 60
Ash fusion temperature in reducing atmosphere, ^0C	
- Initial deformation temp, Softening temp	> 1150, > 1300
- Hemispherical temp/Fluid temp	> 1400

Coal Beneficiation – a solution for poor coal

- Clean Coal Technologies need Coal beneficiation – reducing ash in coal.
- Beneficiation of thermal coal is a relatively new development in India – 2001 +.
- Regulations promulgated in 2001 by the MoEF, GoI.
- These regulations mandate that raw coals be cleaned to less than 34% ash if transported more than 1,000 km or if burned in environmentally sensitive areas.
- It is a low-cost solution that can
  - (i) Cleaner combustion and less of unburnt carbon.
  - (ii) Reduced fly ash and associated hazardous air pollutant precursors,
  - (iii) Lower cost of transport, minimize capital, O & M costs,
  - (v) reduce the need to import higher-quality coals; and mitigates environmental degradation.
- This legislation does not apply to power plants located near mine sites, which can still burn raw coals without cleaning.

- **Washing plants are typically preceded by single or two-stage crushing to reduce the raw coal to a top size of 100, 75 or 50 mm. The smaller fraction of raw coal (-13, -10 or -6.5 mm) that typically contains low ash (20-30%) is usually not washed.**
- **The coarser fraction is washed by jig, heavy medium bath or heavy medium cyclone to the extent that the combined ash of the washed coarse coal and the unwashed small (<10 mm) and fine (<3 mm) coal is within the stipulated limit.**

- Message: When we need to deal with CCT must concentrate only on coal with < 30 % ash

An example of benefits of coal beneficiation – Satpura thermal power station (NTPC)

- Uses washed coal of 34% ash in 1 x 210 MWe unit.

- Plant Load Factor increased from 73% to 96%
- Coal consumption reduced by 29% (**from 0.8 to 0.6 kg coal/kWh**)
- Reduction in Auxiliary Power Consumption (~1.5%)
- Reduction in down time of mills
- **No fuel oil support**
- Boiler efficiency improvement by 3%
- Coal mill power consumption (kWh) reduced by 48% reduction
- Savings by using washed coal of Rs 43 million/yr (2.4 paise /kWh).

What is clean coal technology? Why?

1. Clean coal technology is the one in which emissions are minimal and efficiency is high.
2. This efficiency must go beyond the currently achieved values in thermal power systems (~36.5 %)
3. Both sulphur primarily and NO_x emissions must be reduced.
4. Fortunately, since Indian coals have small sulphur this will not be a serious issue. However, a wide range of coals – Malaysian, Indonesian and Australian may need to be dealt with.
5. Clean up before use is always more effective than post operations clean-up. This is also because the amount of matter to be dealt with is much more towards the tail end than in the beginning.
6. World-wise, it is understood that integrated gasification combined cycle is the answer. Better efficiencies (~ 40 %) and better emission control strategy.
7. India has also chased these ideas for over ten years without progress.

More on… why gasification if combustion is OK

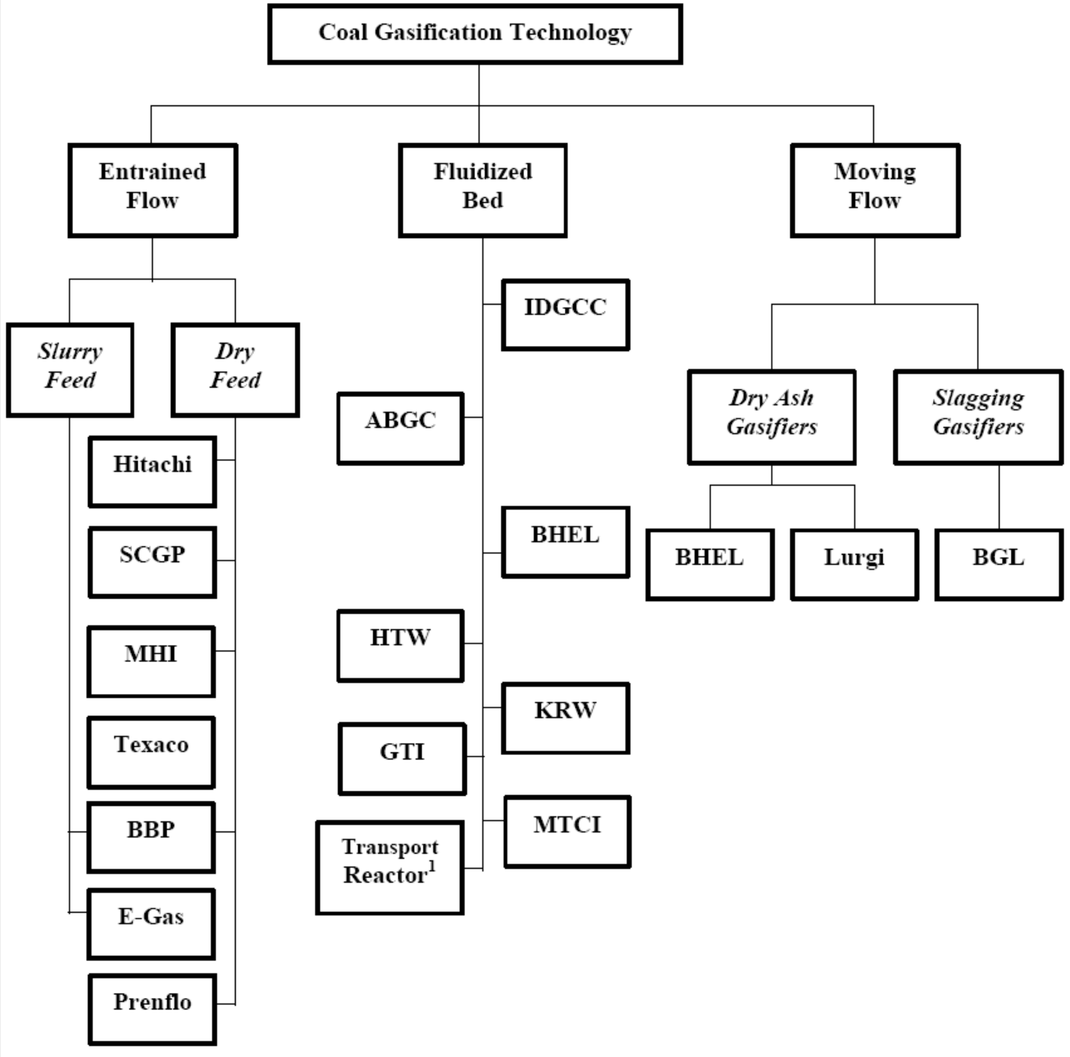
- **Combustion process** leads to products – CO_2, H_2O, NO_x, SO_x etc
- The best fuel-to-electricity efficiencies using high pressure steam turbine route are ~36.5 % in India. There is considerable interest to increase it to 37 % if possible. There are technical and engineering issues in this effort.

- **Gasification** produces a gaseous fuel from the solid fuel – CO (20 to 25%, H_2 (12 to 15 %), CH_4 (2 to 3 %), CO_2 (10 to 15 %), H_2O (2 % in cold gas), H_2S (depends on sulphur content in the coal, typically, 100 to 1000 ppm), rest N_2.
- If *high pressure gasification* is adopted, the gas is taken into a gas turbine and power is generated. The downstream hot gases are used to generate steam power (Heat Recovery Steam Turbine). This is called IGCC – integrated gasification combined cycle route. It promises 33 + 13 ~ 46 % efficiency. This technology is expensive as we will see.
- The technology becomes economical only at ~100 MWe +

- An alternate is to use ambient pressure gasification and use reciprocating engines. One can also integrate HRST into this strategy. This is new – not tried yet

Strategies in the rest of the World

The many routes….



1. Circulating Fluidized Bed

Plants operating world-wide

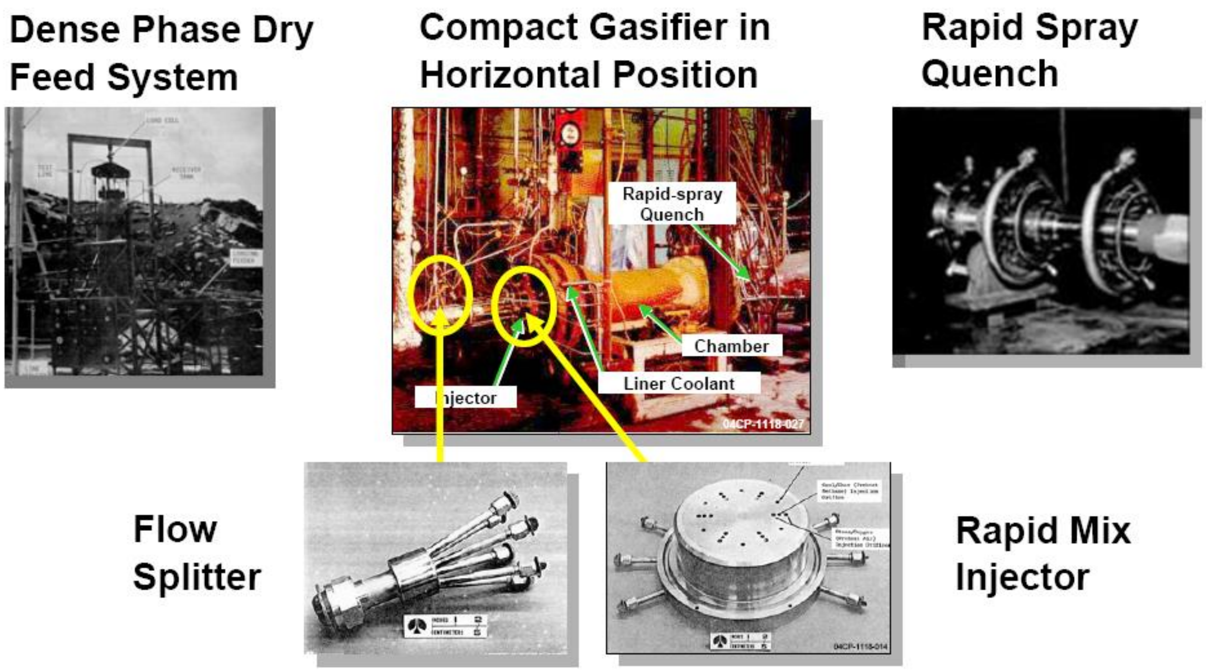
S.N.	Project, Comm. date, Country	Rating, MW(gross)	Design Fuel	Cost US $ mil.	Rs Cr/MW	Govt. Share
1	Buggenum, 1994 Holland	284	Low ash Coal	535	8.66	-
2	Wabash, 1995 USA	288	Low ash Coal	416	6.64 (Retrofit)	50 %
3	Tampa, 1996 USA	315	Low ash Coal	606	8.85	49 %
4	Puertollano, 1997 Spain	318	Coal+Pet Coke(low ash)	894	12.93	60 % in promoter ELCOGAS
5	Pinon Pine, 1998 USA	107	Low ash Coal	306	13.15	50 %
6	Auraiya, 2009 India	127 (as per DPR)	High ash Coal	192 (as per DPR)	6.96	37 % (Requested)

Yet to take-off

Most efforts in the world are for low ash coal. These coals have 15 % more calorific value compared to 30 % ash coal.

Aerospace Companies in gasification

1. The 400-ton per day prototype dry-solids feed pump system, developed by Pratt & Whitney Rocketdyne, will be used to test pet-coke, bituminous and sub-bituminous coals over the next 12 months (..news on …10 April 2012)
2. It has been at it from 1975!



- Gasified coal, petcoke, and biomass (20-40 TPD)
- Performed only short duration tests (< 1 hr)

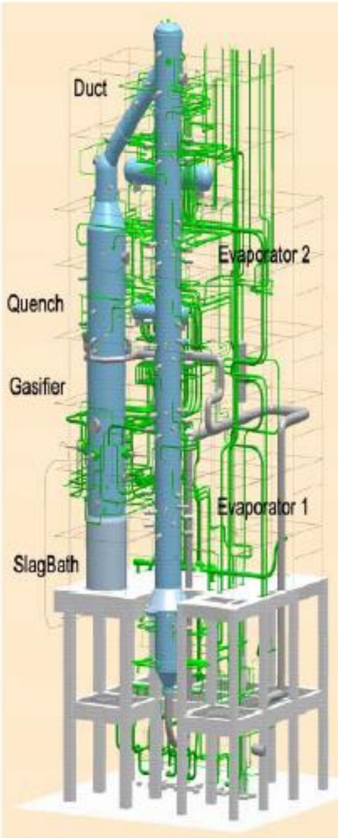
Rocket Engine Technologies

- Rapid Mix Injector
- Cooled Membrane Wall
- Rapid Spray Quench

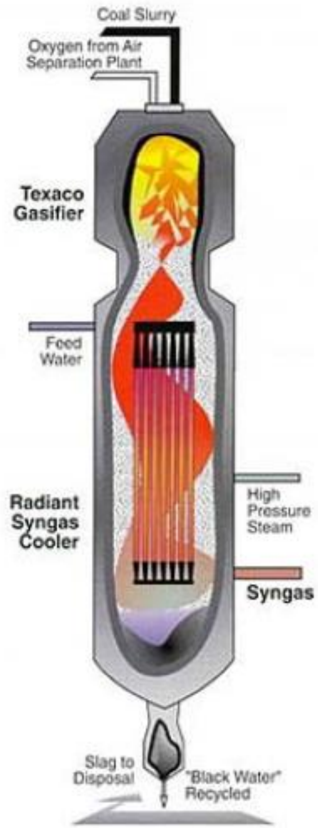
- 5000° F flame temperature gasifies most feedstock within 3 ft of injector
- Rocket engine cooling technology keeps metal temperatures below 800° F
- Plug flow provides uniform residence time for high carbon conversion
- High pressure and water quench enables low cost H_2 production and CO_2 sequestration
- Dry feed minimizes oxygen consumption and gasifies all ranks of coal

Rocket engine price < $10 per kW thermal (much less than current gasification systems)

Current Market Leaders



Source: Shell paper (2004)



Source: DOE paper (2006)

PWR Compact Gasifier

- 90% size reduction
- 50% lower cost (gasification system)
  - Factory fabrication
- 99% availability (gasification system)
  - Long life components
  - Rapid repair
  - Short scheduled outages
- 80% to 85% cold gas efficiency
  - Dry feed system
  - 99% carbon conversion
  - Low oxygen consumption
- Low cost gasification of all ranks of coal & petcoke

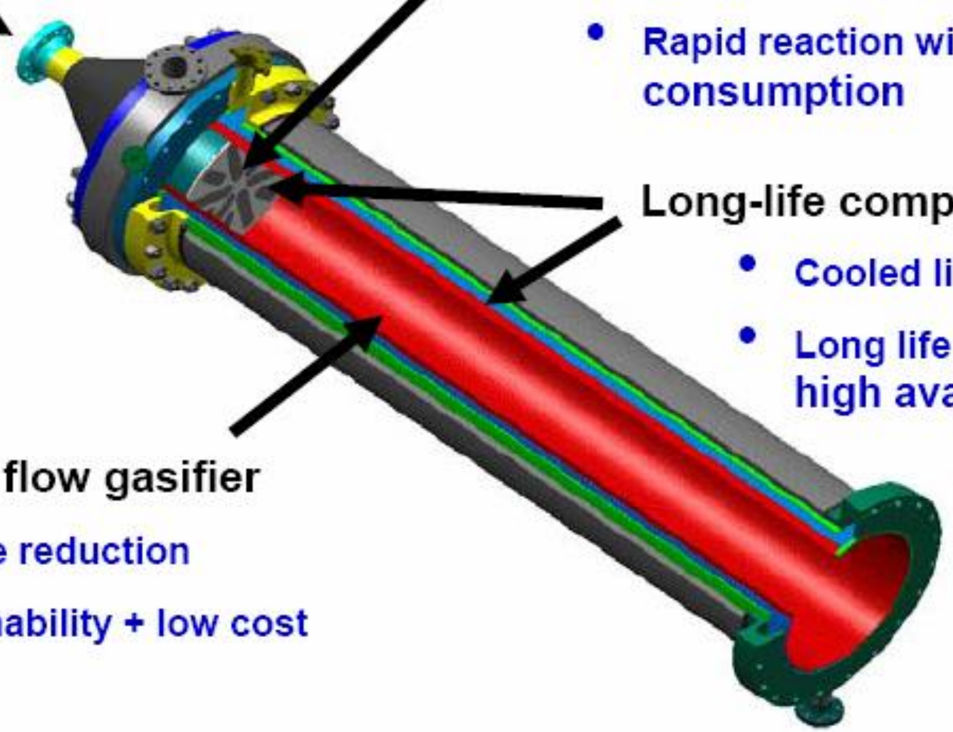
P & W Reactor

Fuel flexibility

- All ranks of coal
- Resid, stranded gas, etc.

Rapid-mix dry feed injector

- >95% carbon conversion
- Rapid reaction with low O_2 consumption

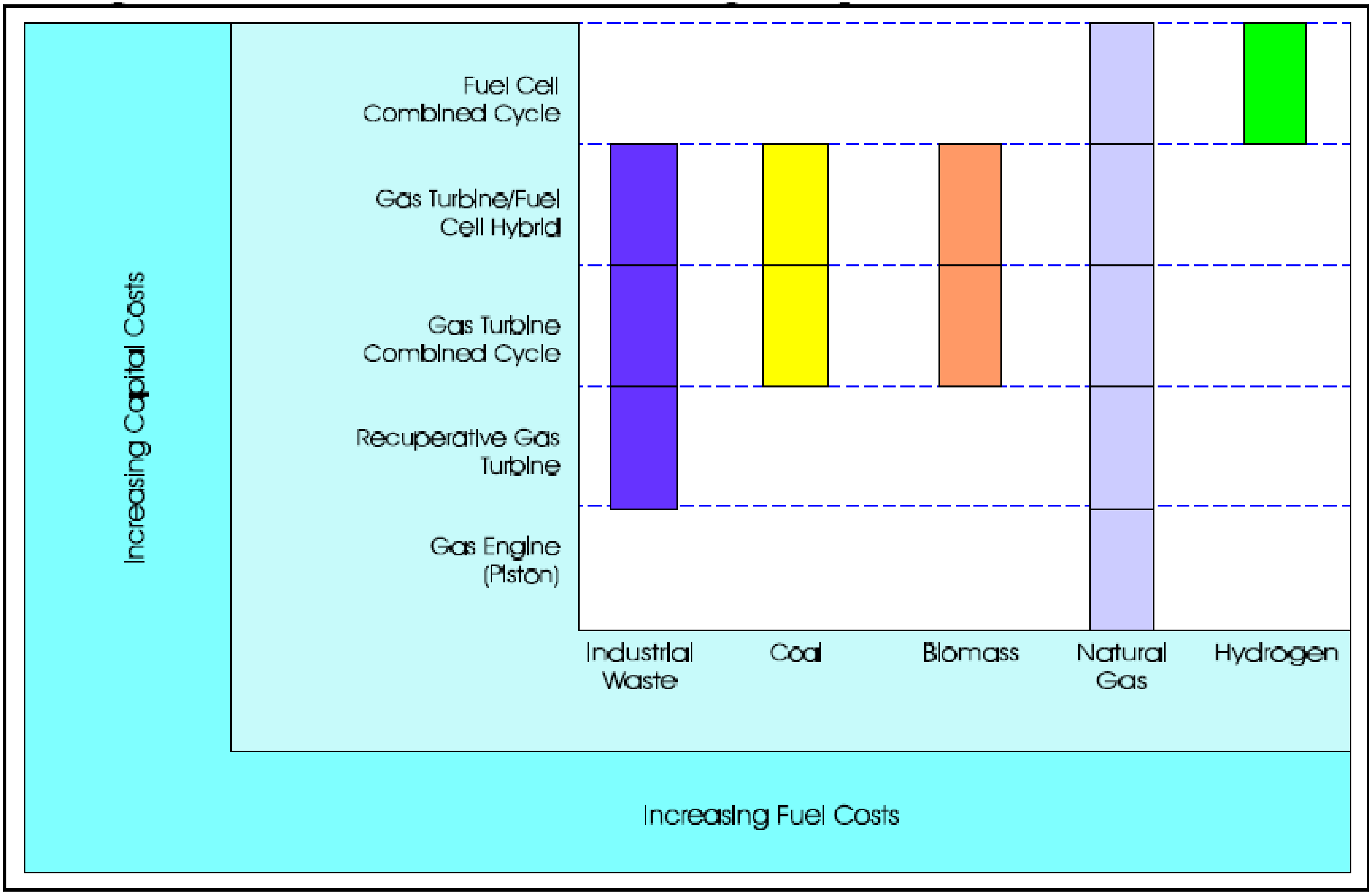


Long-life components

- Cooled liner and injector
- Long life + short MTTR = high availability

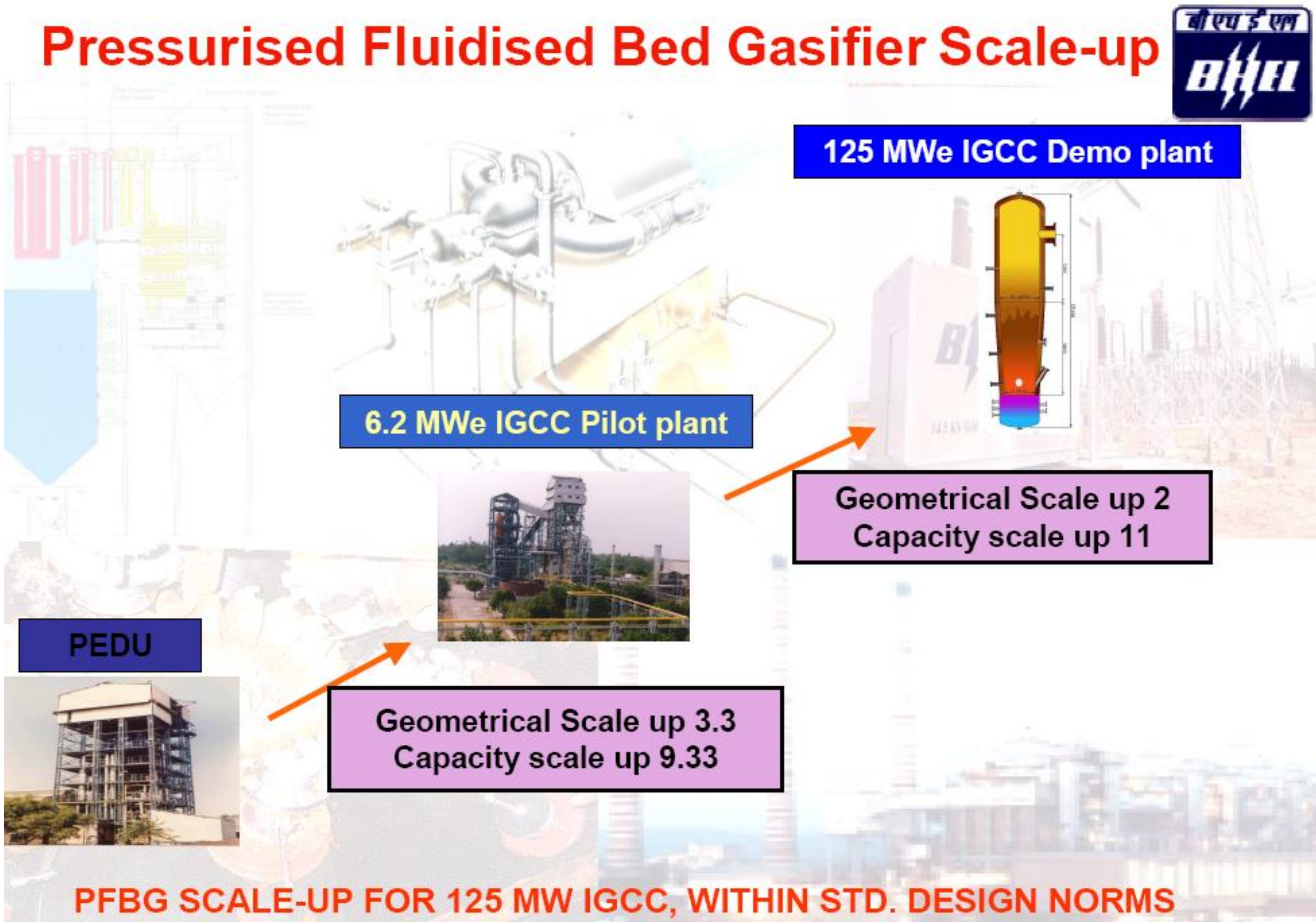
Compact plug flow gasifier

- 90% size reduction
- Maintainability + low cost



Fuel Cell Combined Cycle
Gas Turbine/Fuel Cell Hybrid
Gas Turbine Combined Cycle
Recuperative Gas Turbine
Gas Engine (Piston)
Industrial Waste
Coal
Biomass
Natural Gas
Hydrogen
Increasing Capital Costs
Increasing Fuel Costs

Efforts of BHEL




6.2 MW
IGCC Demo Plant
BHEL Tiruchi
Pressurized fluid bed design

Summary of the past

- Have visited (along with colleagues from CGPL) BHEL, Trichy and Hyderabad in 1998 – 99 and discussed with scientists on high pressure gasification system development and the updraft coal gasifiers
- After two major discussion meetings at Trichy and IISc, it appeared that the thermo-chemical basis of the high pr gasification system design <u>was highly inadequate </u>and needed major inputs
- The subject of 140 MWe IGCC plant has had a Checkered history

- Conclusion: The space for "smaller" coal power systems must be explored without blinkers of large-being-great idea that is ruling the Coal world

Why only one owner of 500 MWe at Rs. 3 – 3.5 billion? Why not also 50 owners of 10 MWe at 50 x Rs. 60 – 70 million?

- Big money is too difficult to come by. At roughly same investment cost of Rs. 6 – 7 crores per MWe, it would be possible to enthuse very large number of investors to build these plants and stabilize the grid – this is why?
- What about efficiencies, one might ask?

On efficiencies and…

- Large steam power systems enjoy a coal-to-electricity efficiency of 36.5 – 37 % in India (systems in Europe get around 40 % for the same class of parameters)
- 1 to 3 MWe class reciprocating engines (say Jenbacher, MWM, Deutz) allow natural fuel to electricity of 40 % and producer gas-to-electricity efficiencies of 37 %.

- Conclusion: Small reciprocating engines are more than reasonable in terms of efficiencies. They aspirate the fuel gas at ambient pressure unlike gas turbines that need the fuel gas to be compressed
- Therefore, we can make do with ambient pressure systems that are far simpler (reasonable first costs also) than high pressure variety.

Therefore….

- One idea would be to combine ambient pressure fixed bed downdraft gasifiers with r/c engines to get solid fuel to electricity at efficiencies of say 37 % x 0.85 (gasification efficiency) = 32 % in the open cycle.
- We still have exhaust at 300 °C + other heat in the system available for use. These can be used along with heat from additional coal combustion if needed to run HRST to enable IGCC strategy

- For 3 MWe with the steam cycle, we need to operate the gasifier-engine system at around 6 MWe. The total cycle efficiency should touch 39 to 40 %.
- There are other ideas….

Current ideas

- Biomass systems have had field experience up to 1 t/hr. Perhaps, these can be scaled to 2 to 2.5 t/hr.
- There is no interest to scale them to levels beyond this value because biomass acquisition radius limits the sustainable operations.
- Can ideas of biomass be directly used for coal as well? What are the differences?
- Biomass has 75 % volatiles and 25 % fixed carbon, Ash content of biomass is typically 1 %. Some agro-residues have higher ash content with rice husk and straw having 16 to 20 % ash.
- They are also well structured internally because that is how biomass grows. Its density is 150 to 500 kg/m^3.
- Tar and particulate problems in biomass gasifiers are to be dealt with seriously.
- Coal is a product of biomass with natural cataclysmic events creating high pressure and higher temperatures within the earth. It loses volatiles within and becomes denser material (1200 to 1500 kg/m^3); gets integrated into inorganic matter more. Thus, ash content of coal varies from 5 to 45 %.
- Volatile content in coal is about 30 % and rest is dense carbon integrated with ash. Tar problems are much less than in biomass. However, After the loss of volatiles, the effective ash content goes up (~ 50 %). This is the principal difficulty in terms of reduced coal char reactivity compared to biomass char.

Current ideas

- It may be appropriate from conversion demands that fine particles are dealt with since the size reduction exposes reactive material (just as well as inactive material, though)
- We can treat the fine particles (70 to 100 microns) with intensely fluid dynamically dominated high temperature environment like the P & W systems. Perhaps, greater compactness of design may result. Such ideas gel well with the strengths of AeS department to undertake such projects.
- The origin goes to the work of Sudarshan Kumar (currently a Professor at IIT Bombay) when he was a student at CGPL. He studied gaseous fuel combustion in Moderately Intense Low-oxygen Dilution (MILD) systems. This approach has received increasing attention in the last several years.
- It is intended to be combined with some early Chinese work on MILD combustors with pulverized coal. The current suggestion is to deal with atmospheric pressure ***MILD reactors for gasification of coal*** with ~ 30 % ash (This is entirely new and nobody has even thought along these lines and hence a time lead is guaranteed)

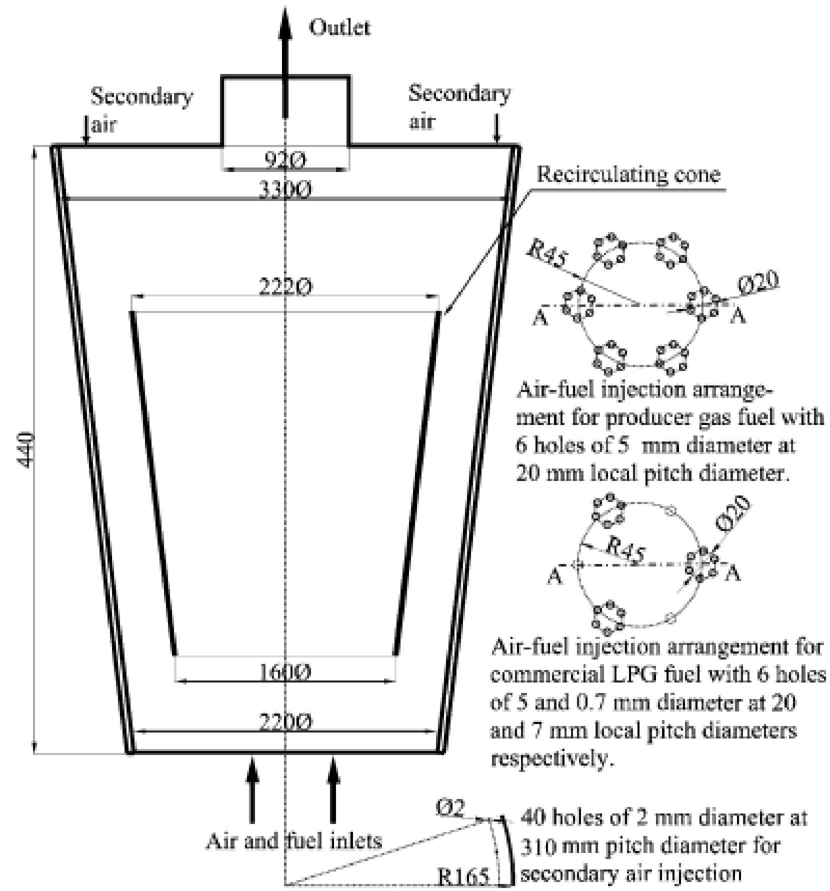


Fig. 3. Details of optimized configuration for 150 kW burner with alternate peripheral injection schemes for both LPG and producer gas fuels.

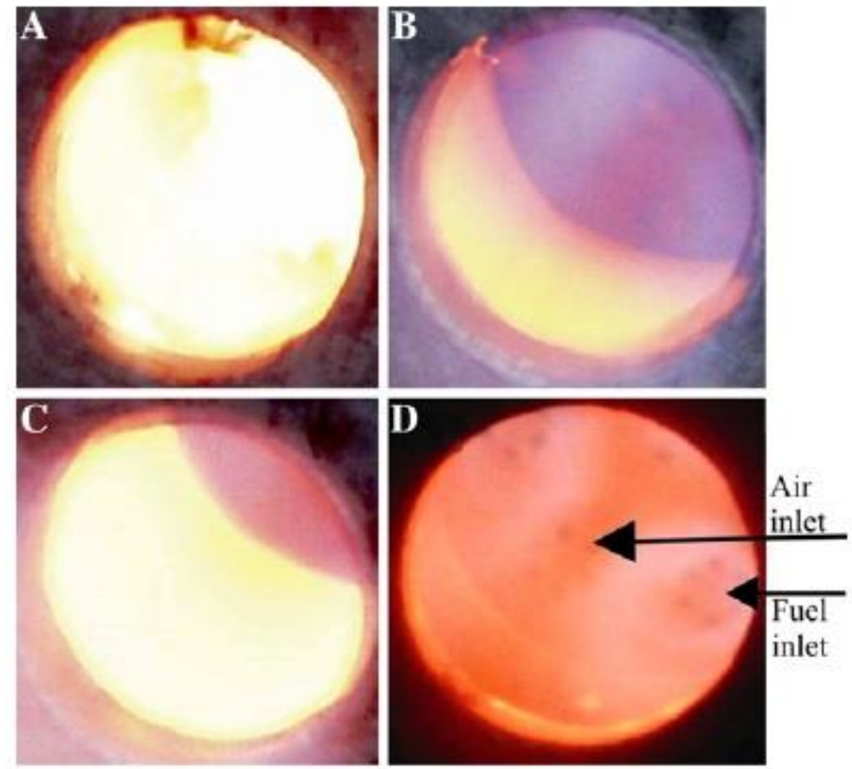
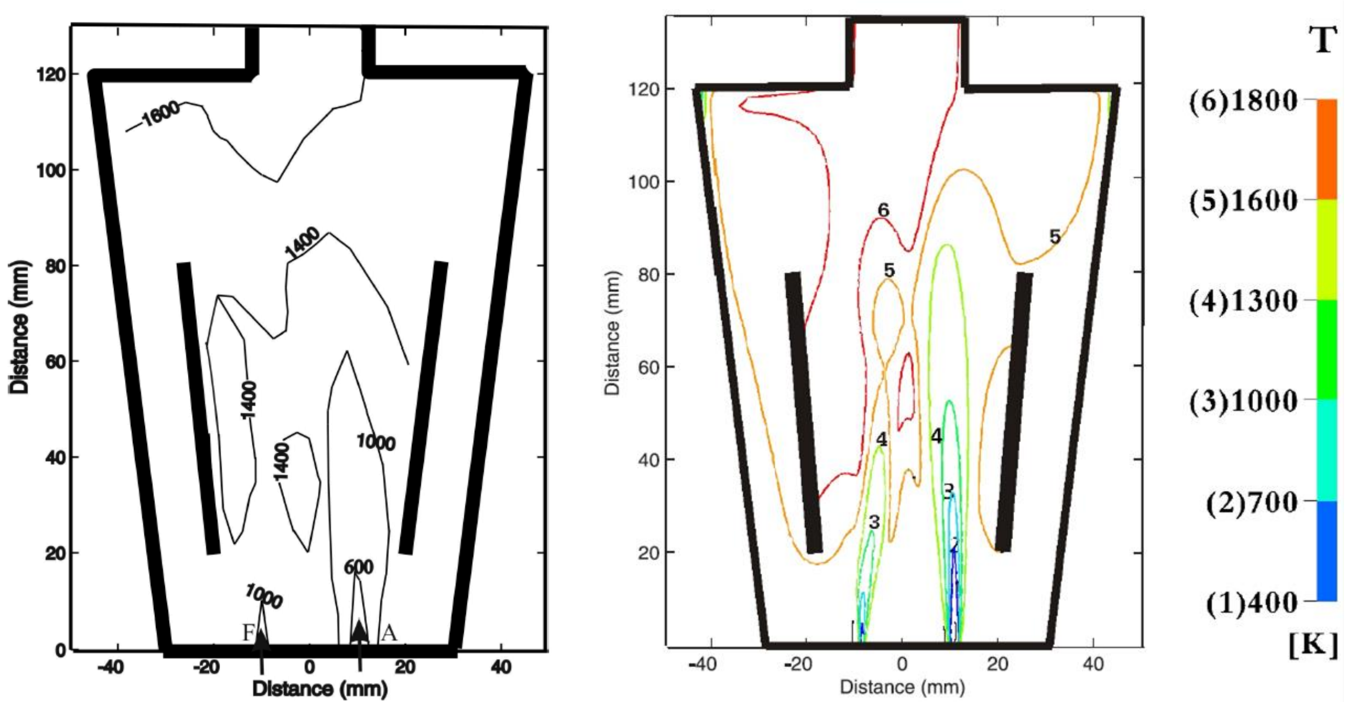


Fig. 7. Comparison between conventional and mild combustion. (A) Conventional turbulent combustion with low recirculation rates. (B,C) Mild combustion mode with LPG fuel. (D) Mild combustion mode with producer gas fuel.

From Proc. Comb Institute, 30 (2005), pp 2613 – 2621, S Kumar, PJP and HSM

Modeling of Flameless (MILD) Combustion Burners



(a) Experimentally measured **(b) Predictions with EDC model combined with local extinction model**

Measured and predicted temperature in a 3 kW flameless (MILD) combustion burner

Table 2
Summary of the previous work in mild combustion and residence times used in these experiments

Ref.	U_f (m/s)	τ_f (μs)	U_a (m/s)	τ_a (μs)	$\dot{Q}'''$ $(MW/m3)$	Q (kW)
[12]	20	250	73.7	74.6	0.32	10
[13]	9.34	503.2	33	151.51	0.18	6
[14]	12.57	318.21	28.9	162.58	0.18	6
[18]	100	100	70	1771	0.023	580
[20]	7.9–70.7	114–4.2	—	—	—	—
[15]	20–100	25–5	26–130	77–15.5	5.6	1–5
Present	243	3	95	52	5.6	150

Comment: The heat release rates of these systems can be large – smaller combustor volume for the same thermal output. Much of the physics of gaseous systems has been understood. It is only two-phase flows that need to be deal with. Of course, there are several issues that need to be understood and such a problem is both challenging and doable.

Notice that the stream speeds are about 240 m/s. In fact, the key feature of these systems is the use of very high speed jets – near the acoustic speed by introducing the streams at pressures of 2 atm or above into the ambient pressure reactor.

From Chinese studies….

The use of coflowing jets with large velocity differences for the stabilization of low grade coal flames – 21st symposium, 1986, pp 567 - 574

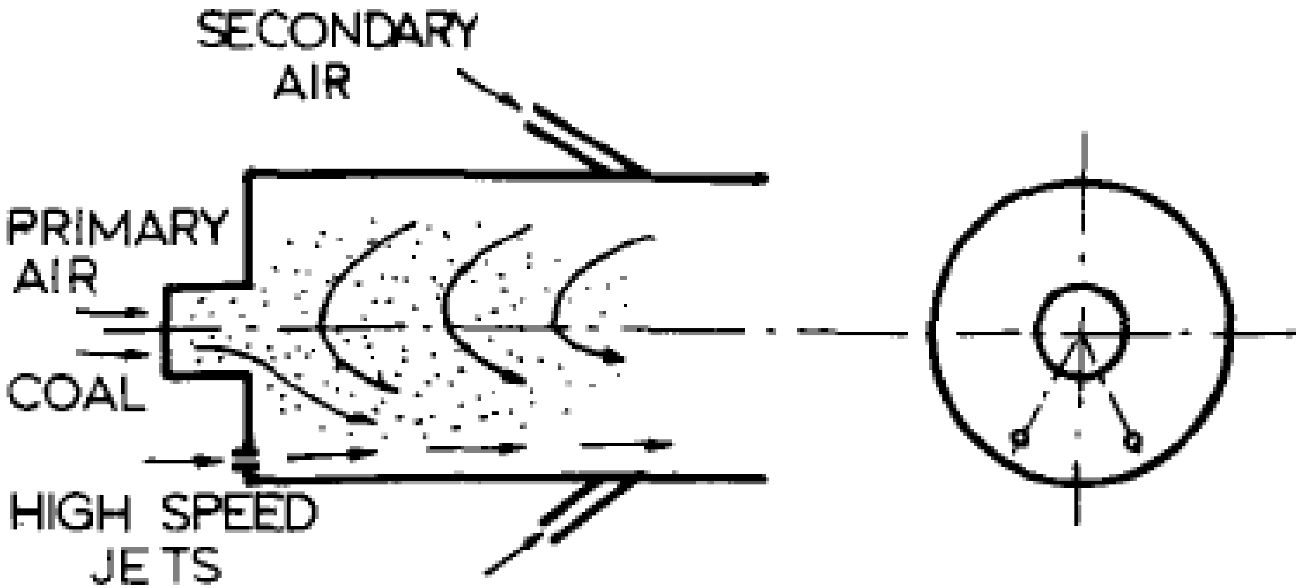


Fig. 2. Schematic diagram of the "coflowing jets with large velocity differences" principle

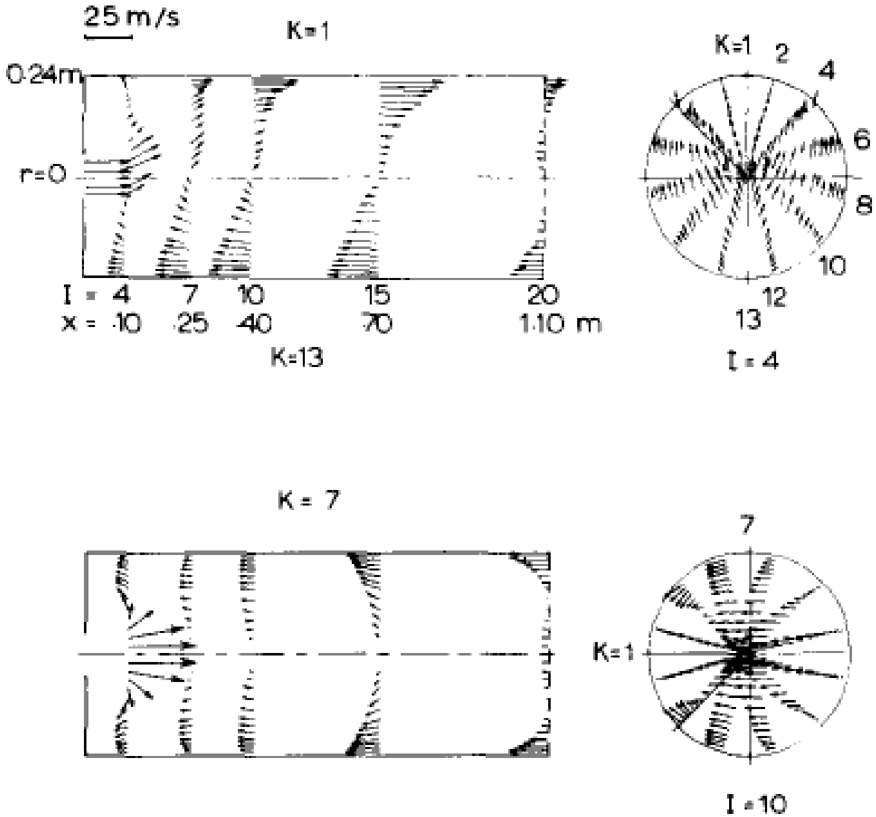


FIG. 3. Computed flowfield of a combustor using the coflowing jets (cold flow)
2 high speed jets located at $r = 0.21$m, at 45° from the vertical line (K = 4), high speed jet, velocity = 248 m/s, flow rate = 0.00486 kg/s (each hole)
primary air velocity = 25.6 m/s, flow rate = 0.238 kg/s

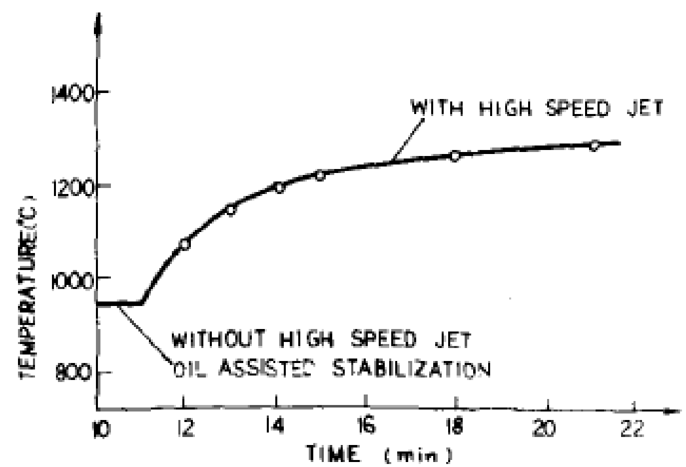
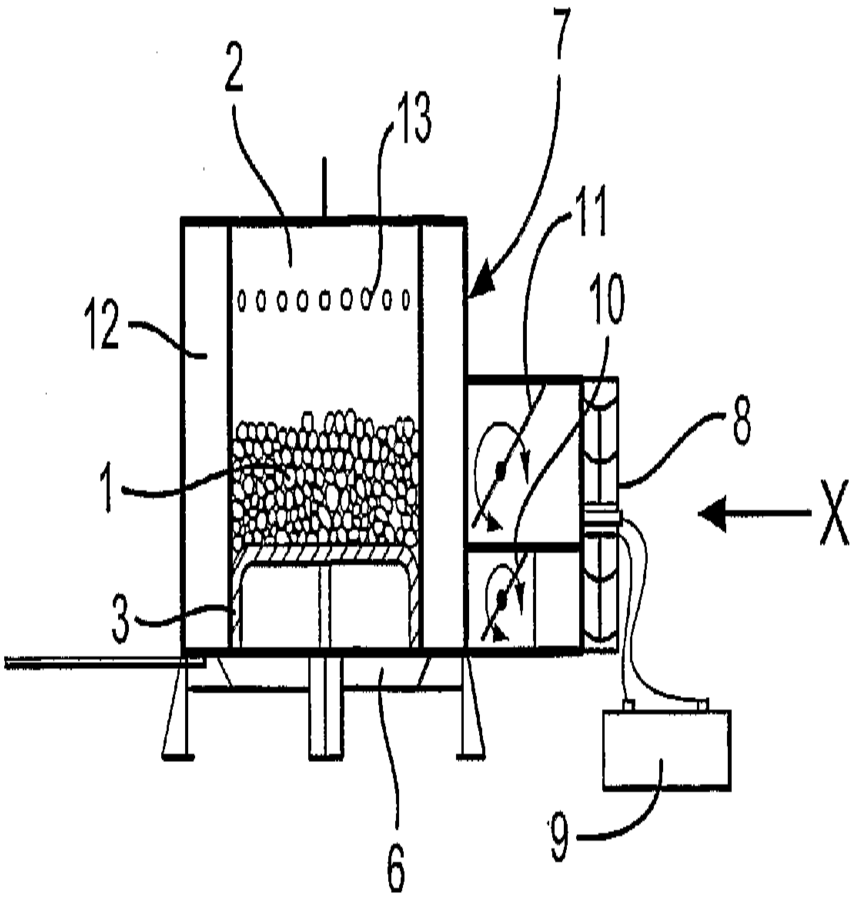


FIG. 6. Temperature rise after turning on the high speed jets, low volatile bituminous

Comment: It is clear that aerodynamics is playing an important role in the two-phase flow and heterogeneous reaction. These are studies aimed at burning poor coals. There are so many other partly symmetric geometries one can think of for the reactor. RCFD studies will be valuable.

Just an aside - Simple experiments on coal in “biomass systems” To show how 28 % ash coal behaves during combustion.



Coal pieces ~ 3 – 10 mm, 28 % ash content

The reverse downdraft gasifier stove – air for gasification from the bottom and the air for combustion from the top holes. Flame in phase II (coal char combustion) right

Summary

1. Smaller size systems (~5 MWe class) with 30 % ash coal should be a good alternative to work towards.
2. Experiments at 300 to 500 kWth (6 to 8 kg/h) could be the starting effort. Pulverized coal with high density transport should be the aim. High pressure jets at near-acoustic speeds should be used.
3. Starting with combustion and slowly shifting to gasification should be the aim. The reactor output goes into a standard cyclone to separate the dense carbonaceous ash from the gas. Measurements of gas composition temperature profiles are standard tools to be deployed.
4. Cooling, cleaning train can depend on what has happened at CGPL.
5. CFD and RCFD simulations should be the bed rock of development.
6. Once the gasifiers are working satisfactorily, scale up can be attempted.
7. Comparisons with experiments can be used to calibrate the models and use them for scale-up to larger size systems.
8. At this stage, time is ripe for bringing in industrial partners.

.......................*Thanks*