GATET Workshop on
"High Density (JP 10) High Energy (Boron Based) Slurry Fuel for Gas Turbine Engines" GTRE, Bangalore

Progress on Boron Synthesis & Combustion Studies

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Background

- It was brought to our attention by Prof. H. S. Mukunda that there is need to produce Boron in order to capitalize on the in-house capability in chemistry and combustion.
- This work was taken up in 2014 in a stop-start mode since there was inadequate perception of the demand.
- It was uncovered that procurement of Boron from overseas was both very expensive and somewhat uncertain.
- And a perception at that time in which even local availability was somewhat uncertain, it was decided to maintain an in-house activity to understand the nuances of boron synthesis from first principles and progress the production of boron.
- Based on the systematic activity in small scale without necessarily having high quality mechanized equipment development took place.
- The holding of the workshop at GTRE gave additional motivation to accelerate the activity. What will therefore be presented are:

- **Experimental Studies on engineered synthesis of fine particle size boron**
- **Experimental Studies on the combustion of boron in an open LPG flame**
- **A screw +fluidization based transport of particles to combustion zone**
- **A possible injector system in which primary atomization is “mechanically” controlled**

Boron Synthesis - Stoichiometry

Heating

$$2\ H_3BO_3 \xrightarrow{> 350\ °C} B_2O_3 + 3\ H_2O$$

123.2 g — 69.6 g, 0.565 g/g

Pelletized Combustion

$$B_2O_3 + 3\ Mg \longrightarrow 2B + 3\ MgO$$

69.6g 72.9 g

Mg: 1.047 g/g

Leaching Removal of MgO

$$MgO + 2HCl \longrightarrow MgCl_2 + H_2O$$

40.3 g 72.8 g

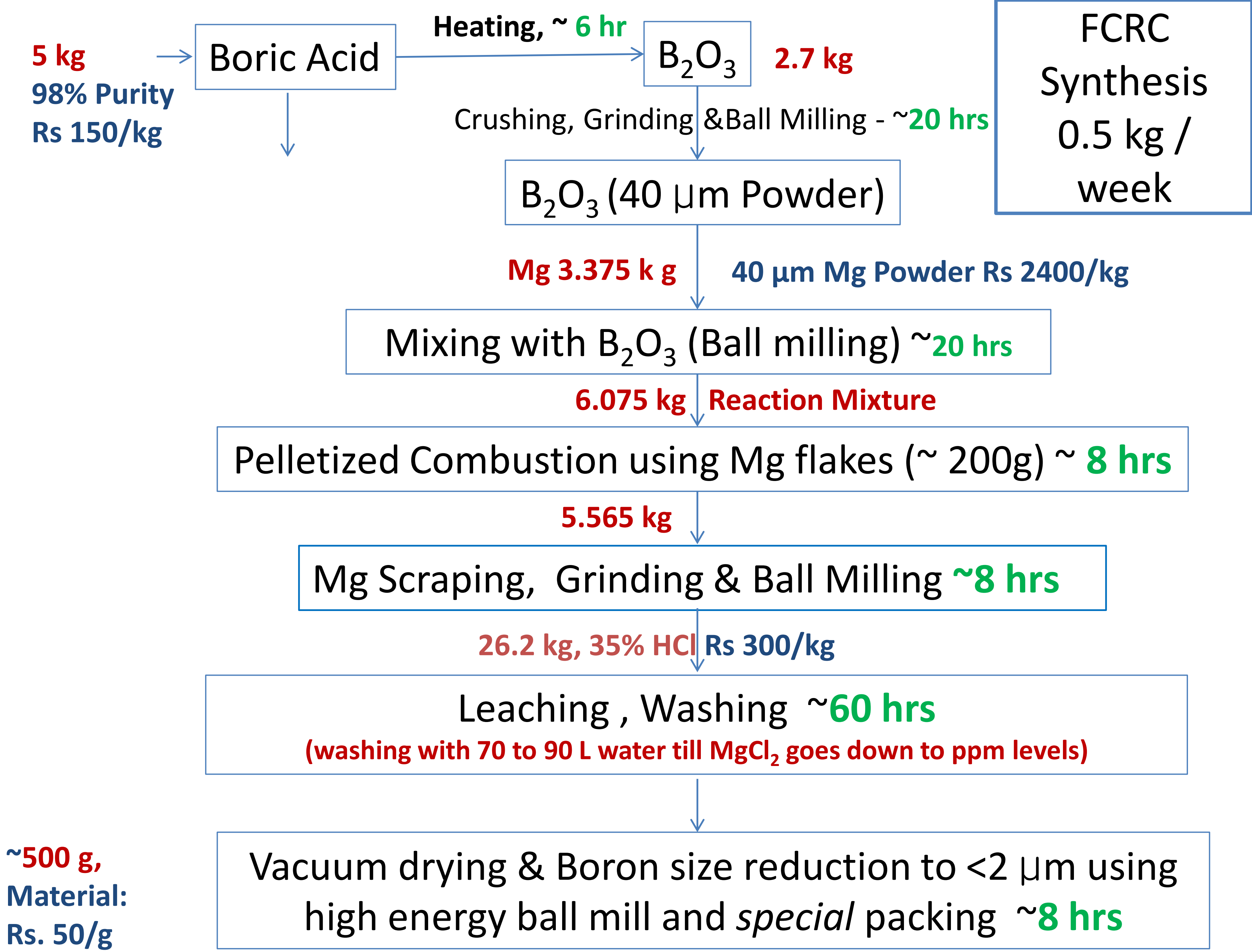
HCl: 1.8 g/g

Reactants per kg Boric Acid

Step	**Reactant**	Quantity kg
Combustion	Mg	0.591
Leaching	HCl	1.539

Products per kg Boric Acid

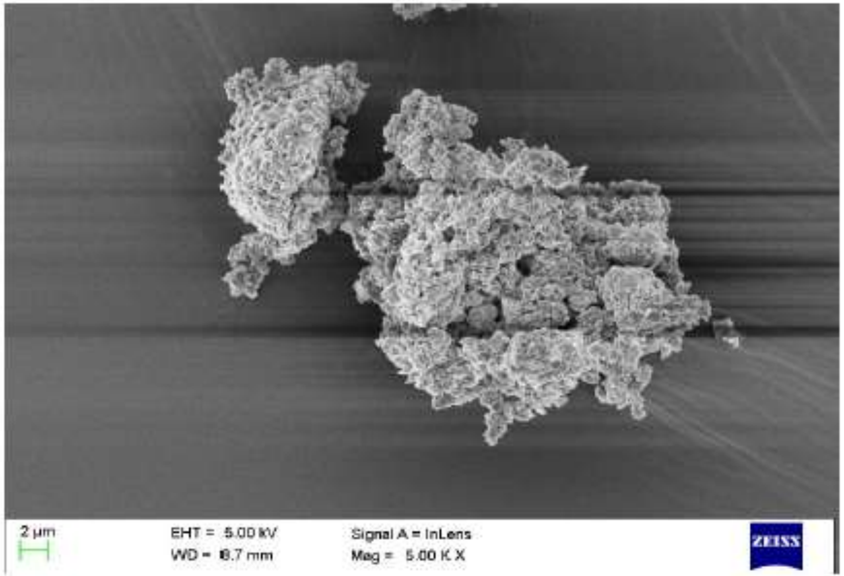
Step	**Products**	Quantity kg
Heating	B_2O_3	0. 565
Combustion	B + MgO	1. 156
Leaching	B	0. 174

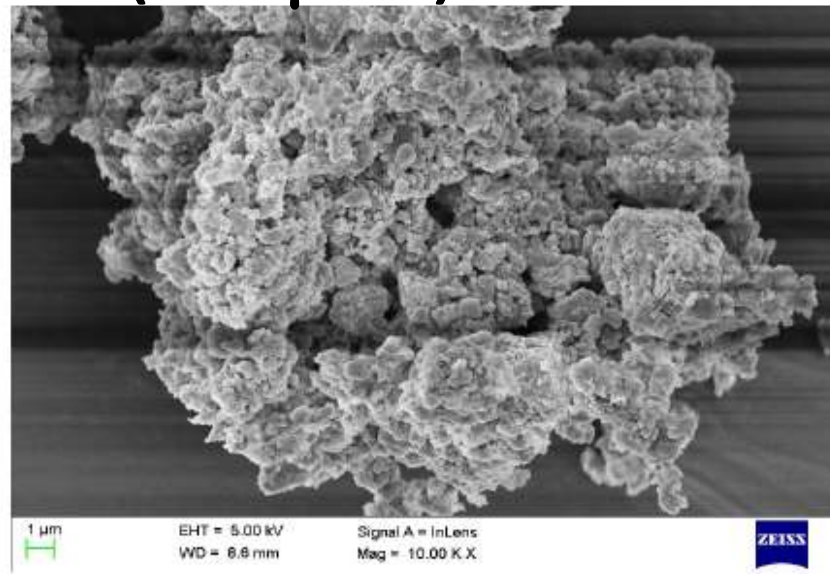

FCRC Synthesis 0.5 kg / week
5 kg
98% Purity
Rs 150/kg
Boric Acid
Heating, ~ 6 hr
B_2O_3
2.7 kg
Crushing, Grinding &Ball Milling - ~20 hrs
B_2O_3 (40 µm Powder)
Mg 3.375 k g
40 µm Mg Powder Rs 2400/kg
Mixing with B_2O_3 (Ball milling) ~20 hrs
6.075 kg
Reaction Mixture
Pelletized Combustion using Mg flakes (~ 200g) ~ 8 hrs
5.565 kg
Mg Scraping, Grinding & Ball Milling ~8 hrs
26.2 kg, 35% HCl
Rs 300/kg
Leaching , Washing ~60 hrs
(washing with 70 to 90 L water till $MgCl_2$ goes down to ppm levels)
~500 g,
Material:
Rs. 50/g
Vacuum drying & Boron size reduction to <2 µm using high energy ball mill and *special* packing ~8 hrs

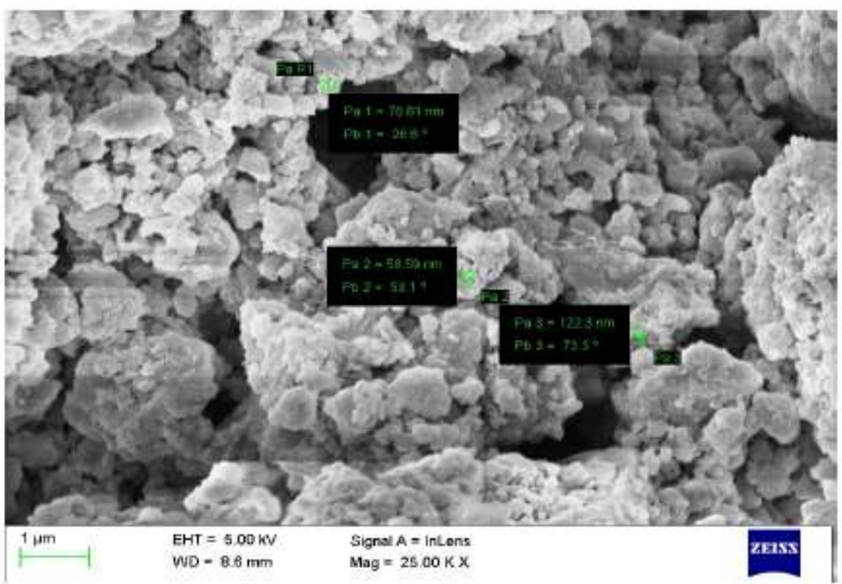
Activity Chart : Boron Synthesis @ 0.5 kg / week

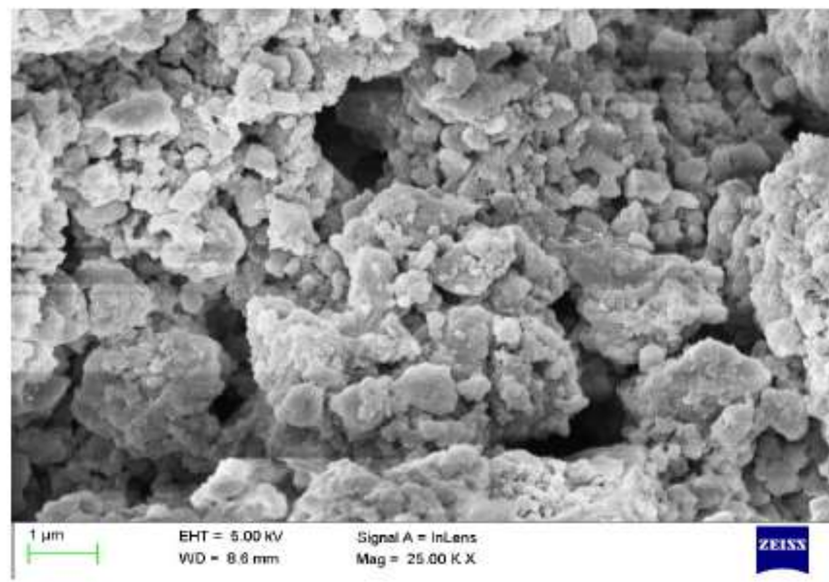
S. No.	Activity	Duration (hr)	Batch Quantity (kg)		No.of Persons	Week 1					Week 2					Week 3				
			I/P	Estimated O/P		D1	D2	D3	D4	D5	D1	D2	D3	D4	D5	D1	D2	D3	D4	D5
1	Boric acid to B_2O_3 by dehydration	6	5	2.7	1	B #1					B #2					B #3				
2	Crushing, Grinding, Milling of B_2O_3 to 40 µ	20	2.7	2.6	2		Batch-1					Batch-2					Batch-3			
3	Mixing of B_2O_3 with Magnesium at 1:1.25 ratio	20	5.85	5.8	1		Batch-1					Batch-2					Batch-3			
4	Pelletisation & Combustion; MgO scrapping	16	5.8	5.39	2			Batch-1					Batch-2					Batch-3		
5	Leaching, Washing	60	5.3	0.53	1				Batch-1						Batch-2					
6	Vacuum Drying, High energy ball milling & Packing	8	0.53	0.5	1									B #1						B #2
Note:	Finished product expected to be ready from week 2 onwards with an weekly o/p rate of 0.5 kg / week																			
	D6 is for maintenance and D7 is weekly holiday; Leaching process will be continuing 24 x7																			

SEM IMAGES (< 2μm)

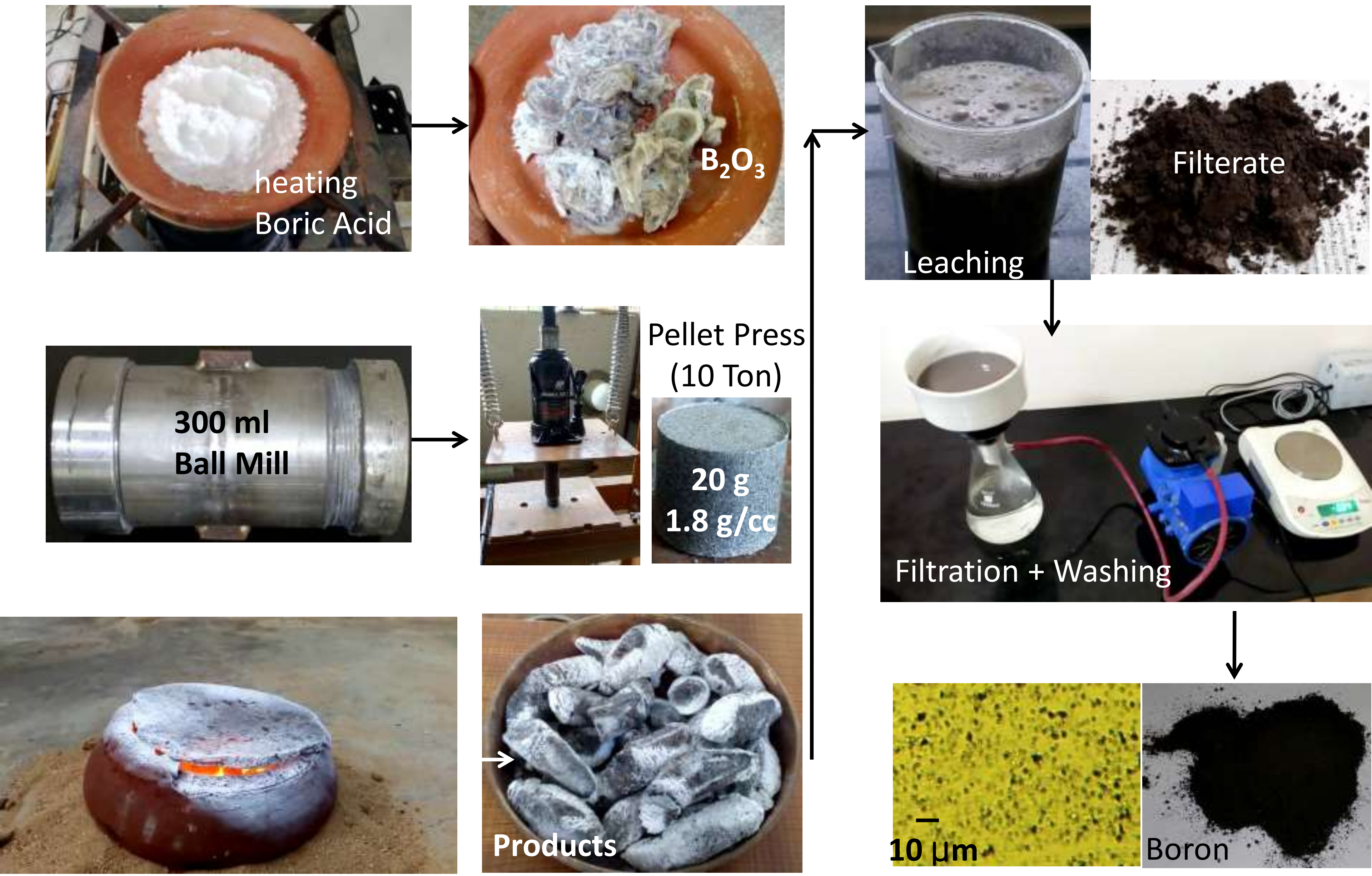








FCRC Process: Pictorial Depiction



Boron Recovery

- Process stoichiometry indicates Boric acid has about 17% of Boron.

- From reactant size reduction and pelletized combustion route, we are able to recover about 11% at the batch size (1 kg Boric acid) operated.

- This represents 65% recovery of finer particle size (< 5 µm, > 90% purity) is achieved

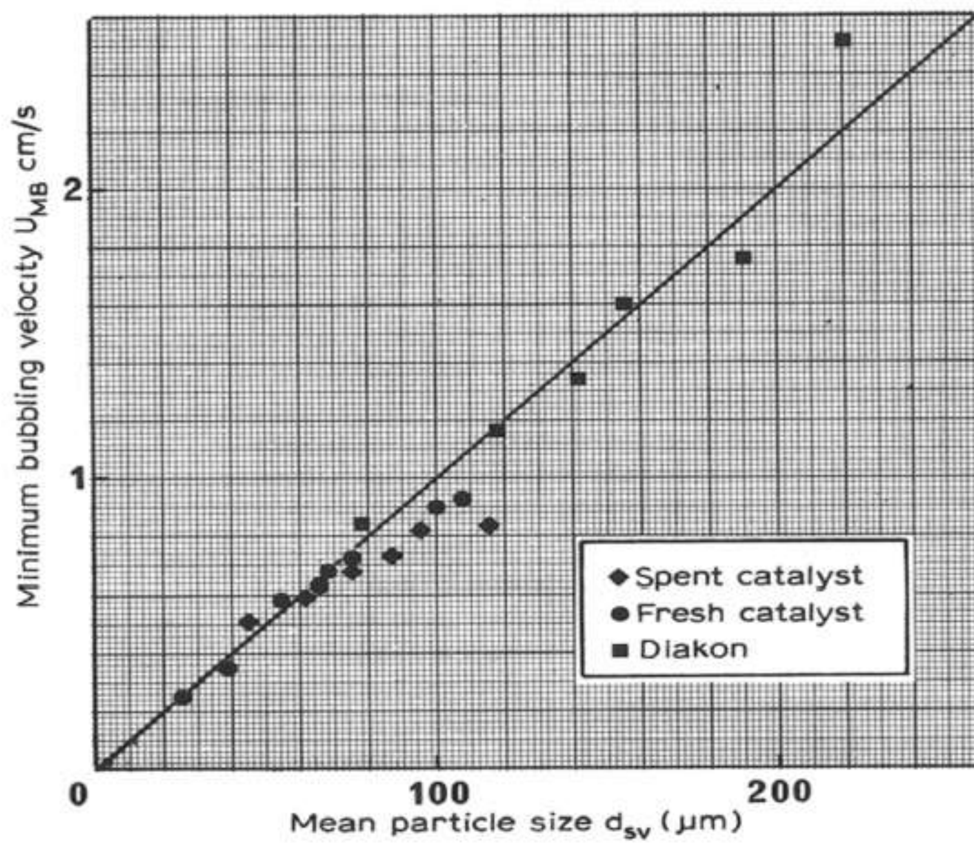
- If needed, - **scaling up** of the production process will be addressed

Boron Combustion - Approach

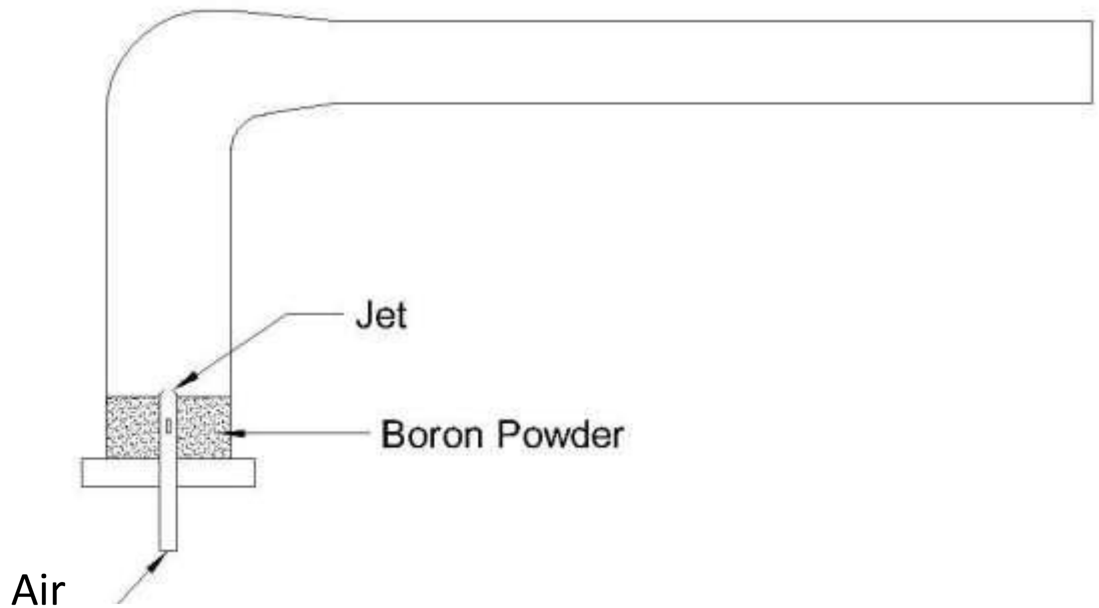
- Finer particle Boron (< 2 μm) - injected directly into Hydrocarbon stoichiometric combustion zone with recirculation has highest availability of ignition Temperature source & residence time
- Transport of powders was studied fluidized transport appears to be very convenient
- Free flowing nature of particles is essential for fluidization, Teflon coating enables this.
- Coating supports ignition

Fluidization Transport

- Classical studies on Fluidized transport indicate ~ 1 cm/s fluidize 100 µm particles and scales linearly with particle size.
- Gravity based powder transport devises can have solid loading ~500 times the transport air



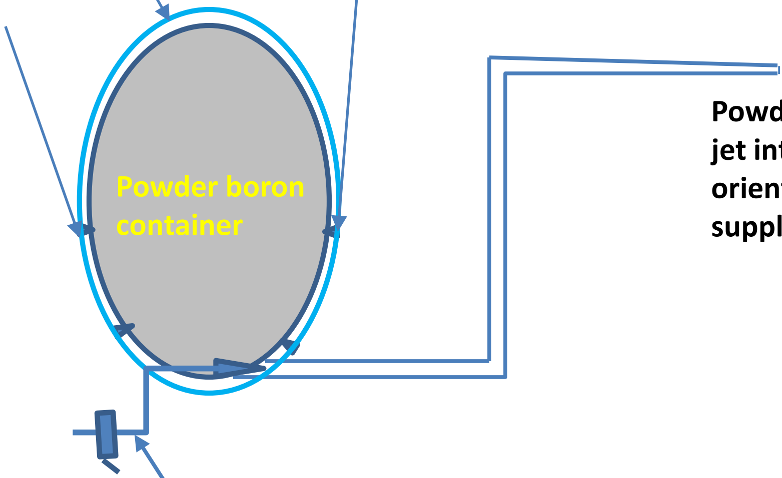
Power Feed System



- Trials were conducted using dry chemical power, used for fire extinguishment to characterize feed system
- Aluminum and Mg fine powders were also tried
- Air jet, 1.2 mm size, with powder in 10 mm plenum around it can eject < 20 µm powder at about 1.2 g/min, at air pressure of few cm water column.

Powder feed system for GT

Outer ring air supply at specific points to enable gentle fluidization of the powder inside to keep the entire mass in semifluid condition

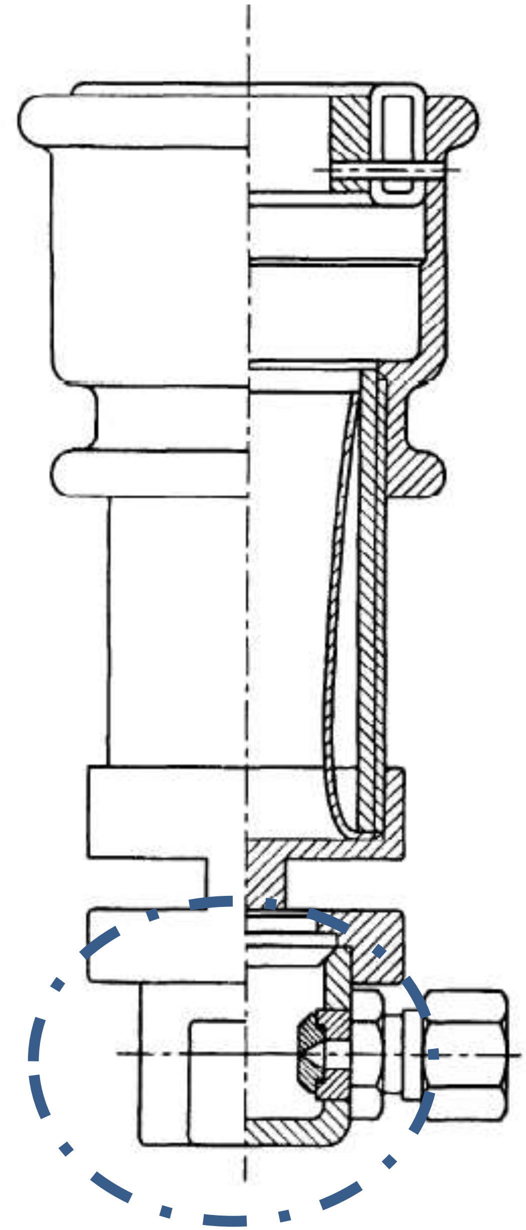


Powder-air mix delivered through a jet into the combustion chamber orientation does not affect the supply of the boron powder.

Ejector air supply that controls the feed rate of powder boron.

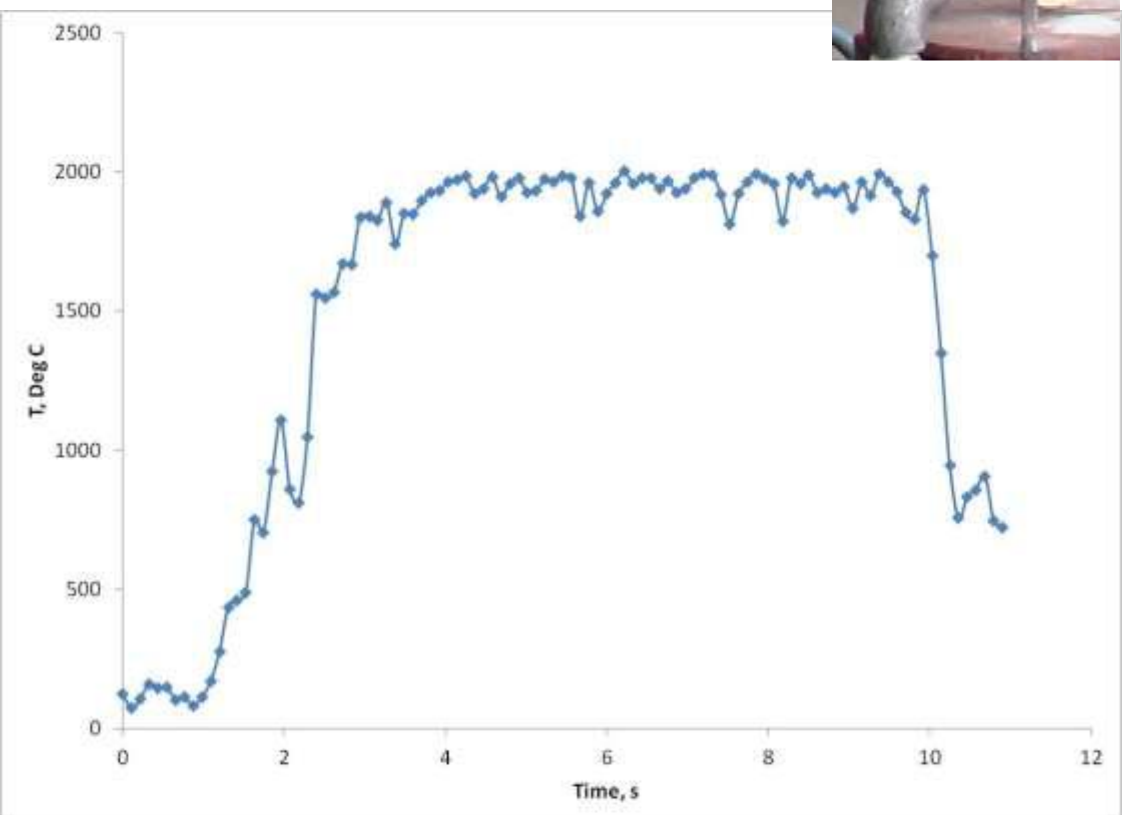
Trial Combustion System

- A standard T type LPG canteen burner was selected for studies
- Burner design power was ~1.8 kg/h at a supply LPG pressure of 0.3 bar with naturally aspirated air
- Powder was injected into aspiration zone of burner
- Trials were conducted on aluminum and Mg powders



Boron Combustion

R Type 50 μm TC



Considerations – design related

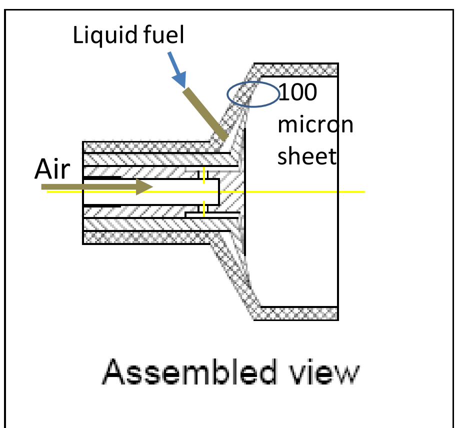
- We must take it that we must burn both the liquid/gaseous fuel and the solid fuel (B)
- Gas phase residence time decreases with pressure significantly (~ $p^{-1.7}$)
- The solid phase residence time decreases weakly as we noted earlier.
- For ambient pressure design if we complete the combustion in a residence time of about 10 ms, it should be adequate. At higher pressures, the demand on residence time comes down to about 6 ms and this should be reasonable for most medium class gas turbines.
- The average stream speed inside the combustor is taken as 20 m/s for the current design (it varies up to 50 m/s). This means that the length of the combustor is 20 m/s x 10 ms = 200 mm.
- If we now take that 30 g/s is flowing at 20 m/s at 1500 K, we get the cross sectional area of the combustor as (30 x1000/0.2 cm^3/s)/2000 cm/s = 75 cm^2 . This corresponds to about 100 mm dia.

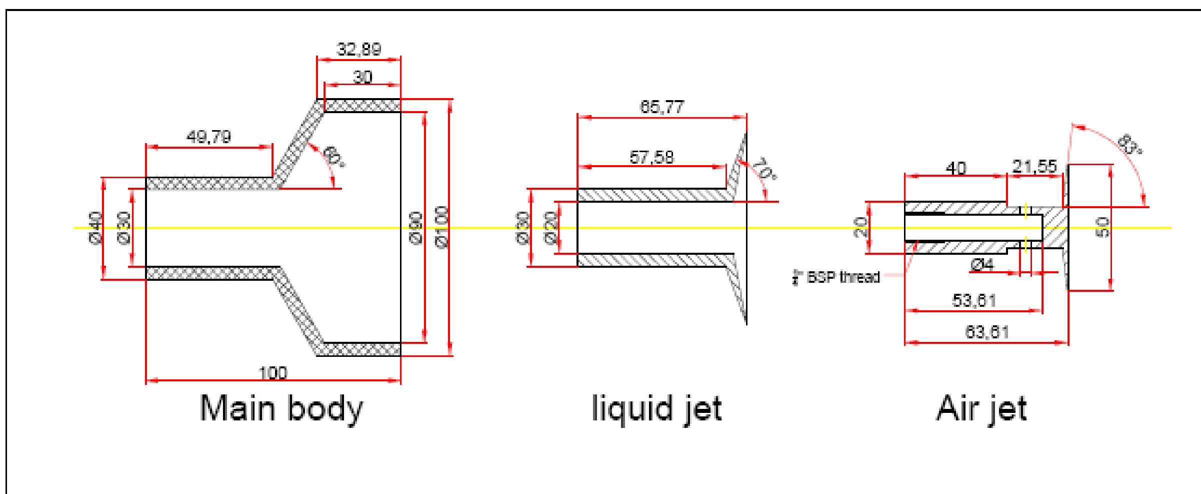
A new injector design

All injectors use swirl air and either pressure or air blast for atomization with primary atomization process being not too well defined. It needs extensive exploration.

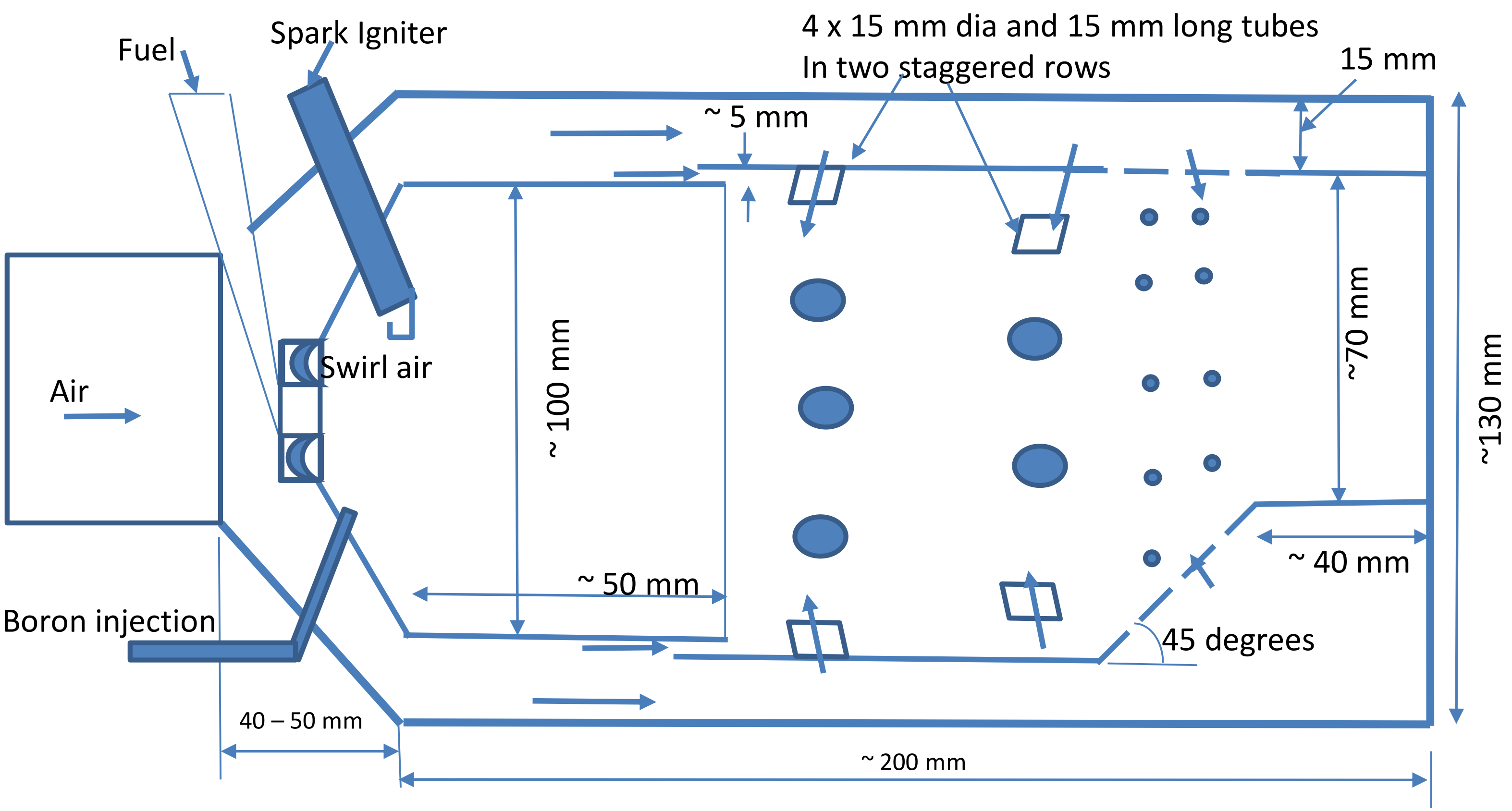
The question posed was: Can we not mechanically limit the size of the sheet to very low levels and disrupt the sheet with air at available high speeds in a manner that satisfactory atomization occurs?

It was intended to pursue this idea without compromise to the project progress that would get enabled by GTRE produced combustion system.





Test Combustor configuration



It is suggested that two options be tried out during the project period.

1. A standard gas turbine design based hardware by GTRE with liquid fuel and separate boron injection
2. A new design of liquid injector designed by FCRC preliminary tests conducted at FCRC to be produced for precision by GTRE for combustor tests at FCRC.

Suggested test scheme

- There should be an exit temperature rake with about 5 to 6 points of measurement with Pt – 10 or 13 % Rh thermocouple of 100 micron dia.
- This should be a control on the fuel flow rate. Measurement of fuel flow rate with prior calibration will be done. Similarly, air flow will be measured.
- Initial tests can be on fuel-air alone. Ignition system hardware will be put together and ignition system will be tested for functionality and robustness.
- Measured exit temperature profiles will be set around 750 to 800 C.
- Boron injection scheme will be worked out and calibrations of boron injection rate will be conducted – knowing that small changes can cause larger changes in the combustion process.
- The exit temperature profile will be maintained same by controlling the fuel flow rate when duel fuel operations are being handled.
- These will be conducted at nominal and other conditions as the hardware permits.

Summary

- Studies have indicated synthesis of pulverized and pelletized combustion leads to fine particle size Boron with high purity
- If needed, process can be scaled up
- Fine particle Boron combustion has been achieved with direct powder transport to combustion zone

Thank You