

Fluidization: Yesterday, Today and Tomorrow

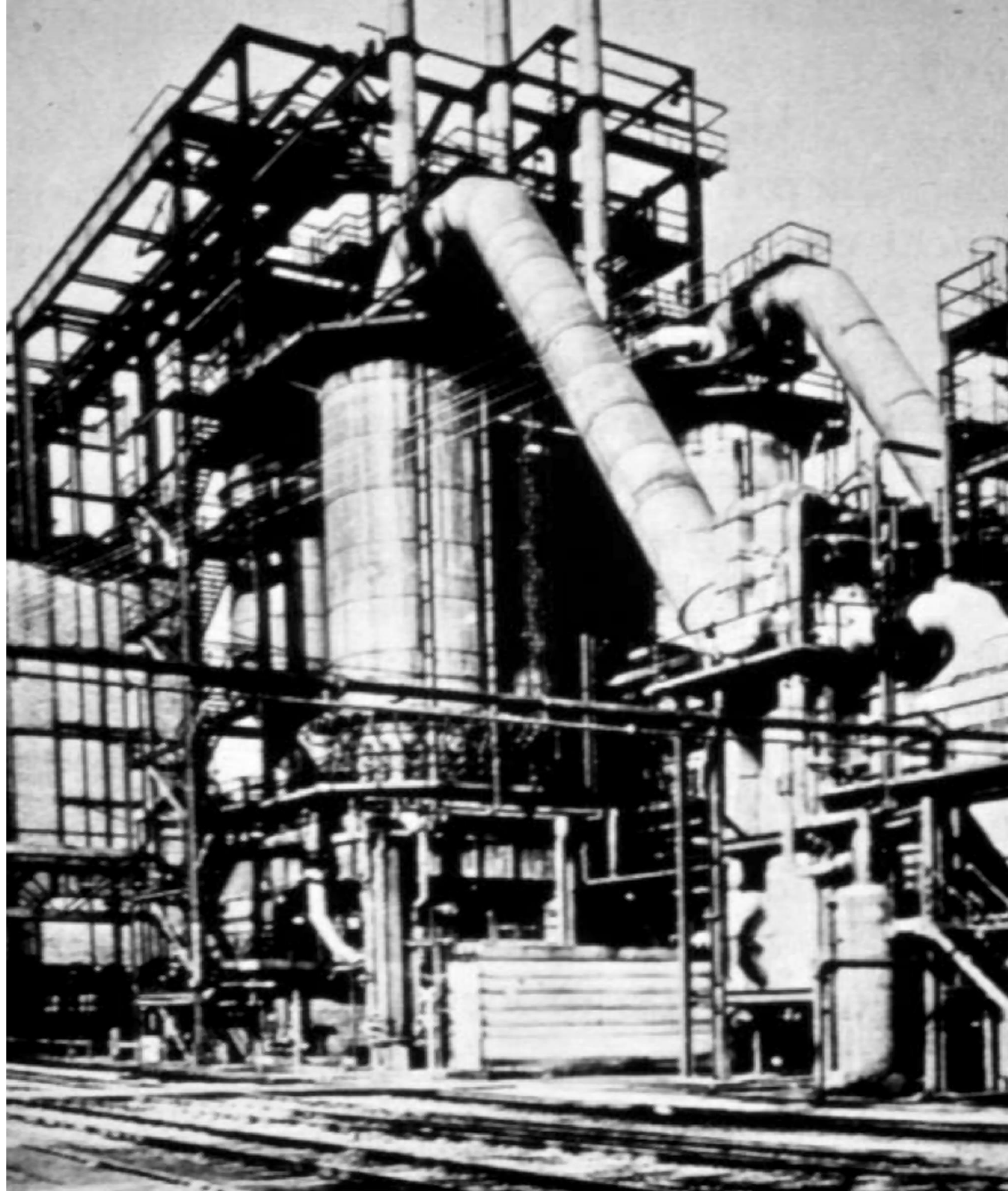
T. M. Knowlton and S. B. R. Karri
Particulate Solid Research, Inc.
Chicago, Illinois, USA

**Presented at the CPFD-Software 2026 Barracuda Virtual
Reactor Users' Conference**
The Wade Hotel
Chicago, Illinois

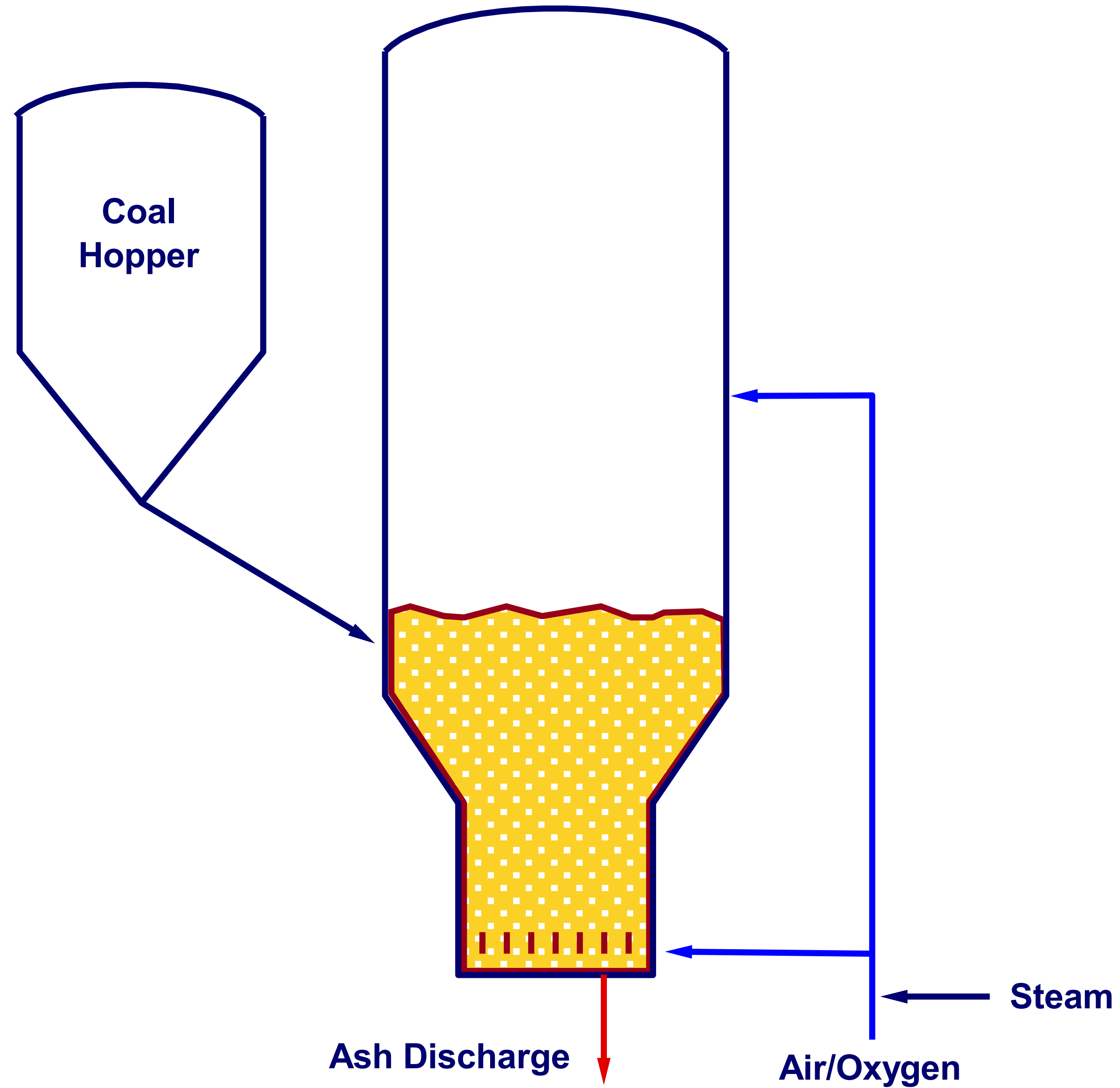
June 25, 2026

Early History of Fluidization

- **Fluidization is 100 years old this year**
- **The Winkler Coal Gasifier was the first commercial fluidization process, and it was commercialized in Germany in 1926. It was developed by Dr. Fritz Winkler who worked for the BASF Corporation.**
- **A photograph of the unit is shown in the next slide, and a diagram of the simple process reactor is shown in the slide after that**
- **The solids used in the process were large with an average size of approximately 3 mm.**



WINKLER GASIFIER - GERMANY 1926



WINKLER GAS GENERATOR (1926)

Early History of Fluidization

- **Fluidization was being explored in both the US and Europe in the 1920's using Geldart Group B and D particles**
- **Research was conducted by the US Bureau of Mines in the US and by companies such as BASF in Germany (Dr. F. Winkler)**
- **From about 1936, the research was still on large particles (>500 microns) in Europe, while fluidization in the US began focusing on smaller particles (<100 microns because of the development of the FCC process)**

Early History of Fluidization

- **The history of the development of fluidization essentially parallels the development of the Fluidized Catalytic Cracking (FCC) process. This process was important in producing high-octane aviation gasoline and Buta-S rubber for WW II.**
- **A French inventor, Eugene Houdry, invented modern catalytic cracking when he discovered that burning coke off of silica-alumina catalyst would restore its activity (1928).**
- **Houdry was a French engineer and playboy who was interested in improving the quality of gasoline to improve motor operation. He would test his new gasoline products in his Bugatti car on a “calibrated” hill to determine which gasolines would allow his car to proceed the longest distance up the hill.**



Eugene Houdry, Inventor of Catalytic Cracking



Houdry's Bugatti automobile which he used to evaluate different grades of gasolines

Early History of Fluidization

- **Houdry's patents were adopted by Sun Oil Co. and Socony Vacuum (which became Mobil) to produce the first commercial catalytic cracking unit (a packed bed) in 1936.**
- **Other oil companies eventually felt that Houdry's licensing fees were excessive and Standard Oil of New Jersey (called "Jersey", which is now Exxon) was the leader in forming the 8-Company, **Catalyst Research Association (CRA)** to develop a catalytic cracking process outside of Houdry's patents.**
- **Up to this point, work on the FCC process utilized Geldart Groups B and D particles with fixed beds and then moving-packed beds.**

**Catalytic Crackers
In the Houdry
Fixed-Bed Catalytic
Cracking Process**

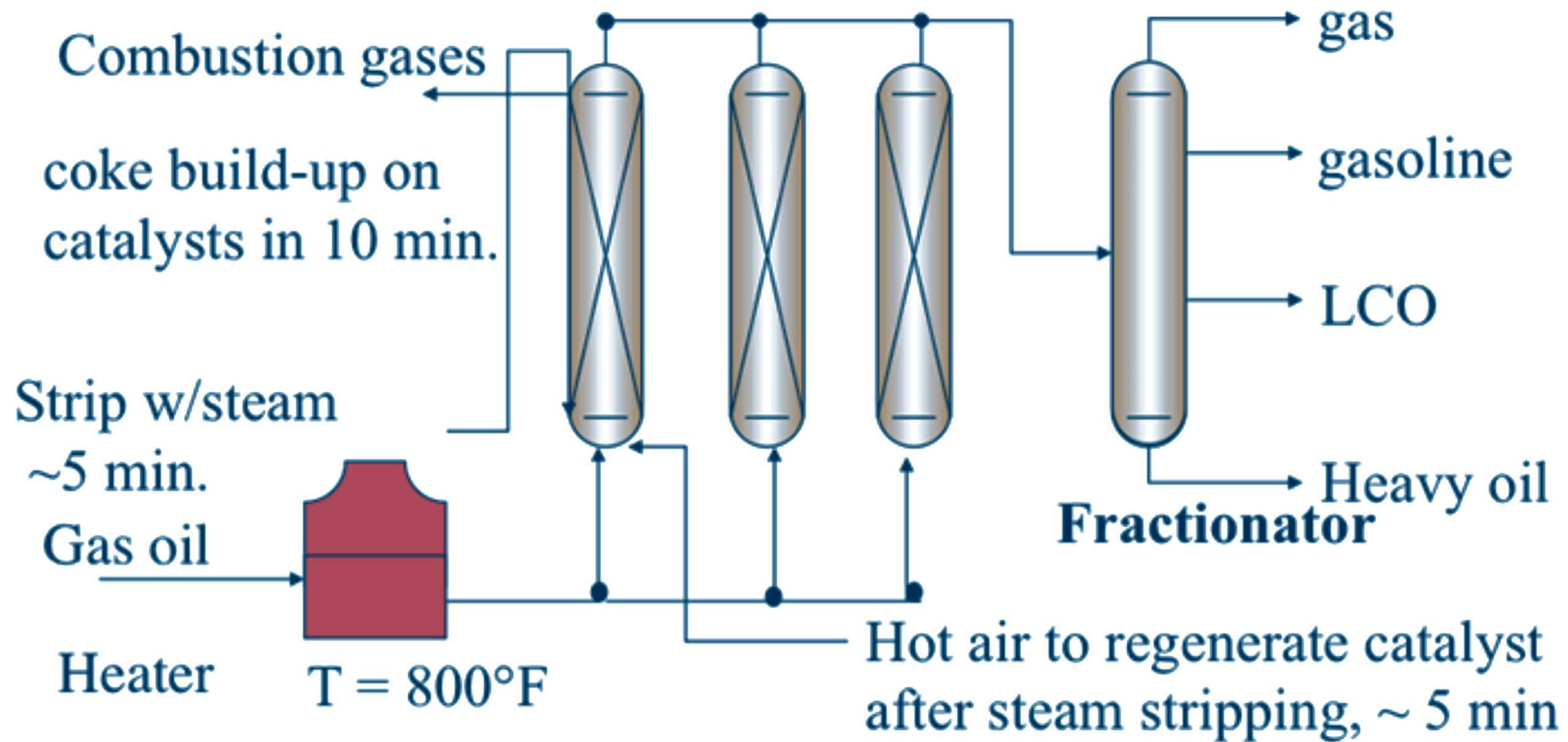


FIXED BED CATALYTIC CRACKERS

Houdry Catalytic Cracking

Introduced by Houdry in 1936 – first commercial, continuous process

Reactors: Fixed-bed natural alumina/silica pellets as catalysts



Early History of Fluidization

- **In 1934, before the formation of the CRA, it was discovered (accidentally) at Imperial Oil that a small (Geldart Group A) “powdered” catalyst could rapidly and catalytically crack oil. The CRA used this discovery to develop their cracking process using fine particles. At this time, the US began diverging from using large particles. However, large particle work on fluidization persisted in Europe for several more years.**
- **Early FCC units using fine particles employed horizontal tubes or coils. However, this concept had problems with plugging in the pipes and coils.**
- **Professor Warren Lewis and his colleague Edwin Gilliland from MIT, were consultants for Jersey and had attended a meeting describing the tube plugging problems. They proposed operating in a vertical tube and were given permission and funding by Jersey to test this concept at MIT.**

Early History of Fluidization

- **The tests at MIT were successful, and eventually this vertical fluidization concept was quickly adopted by Jersey and the CRA. Interestingly, Lewis and Gilliland said that they were not aware of the vertical fluidized bed used by Winker in Germany. Jersey was aware of the Winkler work but claimed that it did not influence the development of their FCC process because it used larger particles.**
- **The first modern FCC Process began operating in Baton Rouge, La in May 25, 1942 with the Jersey/Exxon Model I unit. The original name of the process was Powdered Experimental Catalyst Louisiana (PECLa). The Jersey/Exxon Model II unit was started in 1944.**
- **Both refineries have been designated as National Historic Chemical Landmarks, and you can go and view them in Baton Rouge.**



**EXXON BATON ROUGE MODEL I AND II FCC'S
MODEL I IS ON THE LEFT MODEL II UNITS ARE ON THE RIGHT**

Early History of Fluidization

- **Because of these developments, FCC has been called the “Grandfather” of the fluidization field. It originally got its impetus from World War II to develop high-octane aviation gasoline and butylenes to develop Buta-S rubber (both products important in the war effort). The development of the FCC process was a large factor in influencing the outcome of the war.**
- **After the war, the FCC area grew in parallel with the development of the automobile, trucking and commercial aviation industries – all which used its petroleum products.**
- **The FCC process is still the most important commercial application of fluidized beds today.**

History of Fluidization

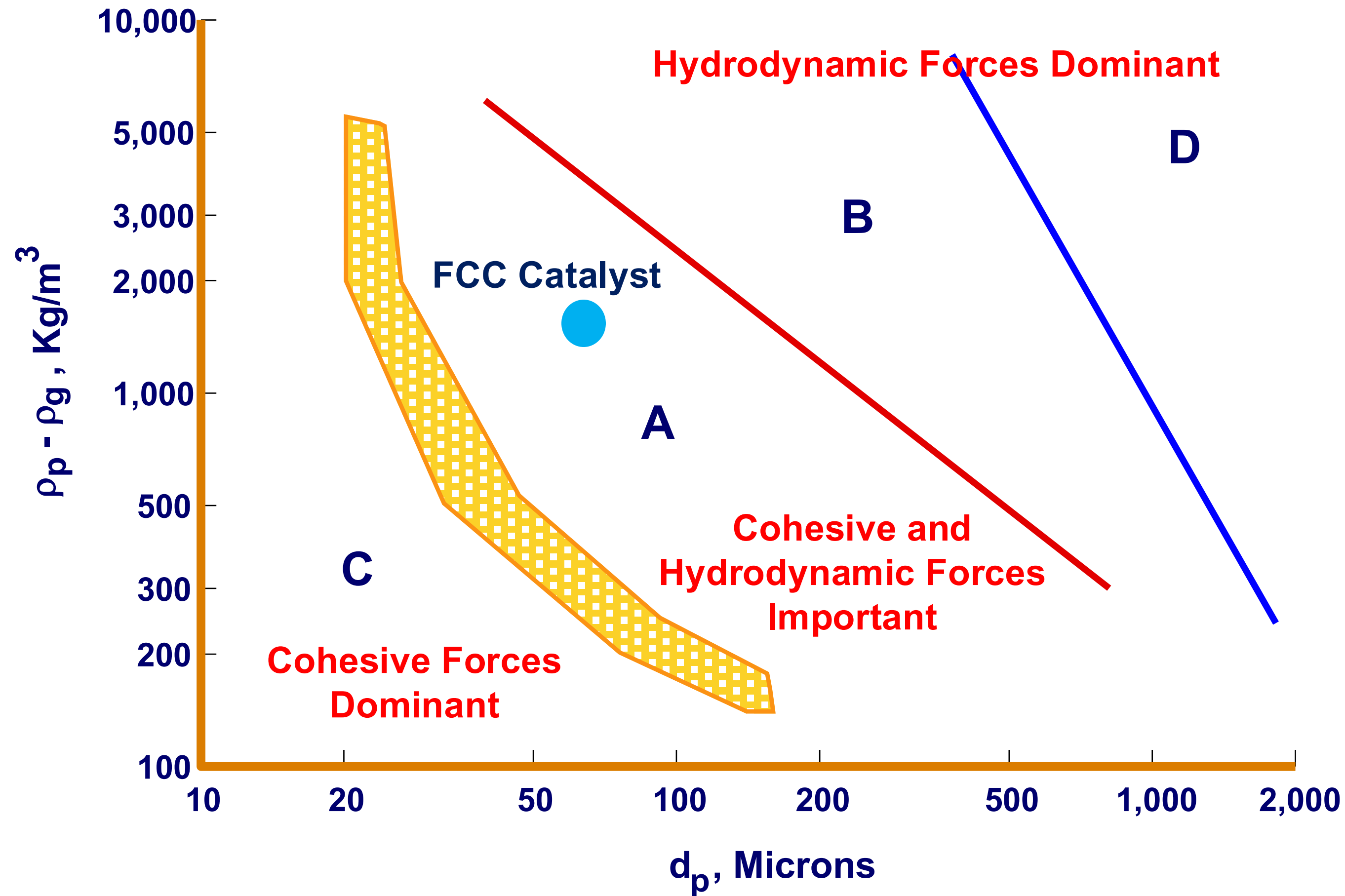
- After World War II, developments in fluidization proceeded rapidly. Fluidized beds were used in the production of phthalic anhydride, acrylonitrile and the Fischer-Tropsch processes, and were also extended to drying of materials in the late 1940's and early 1950's.
- Fluidized bubbling bed combustion processes were developed in the 1960's, and research on bubbles in fluidized beds began. From this and earlier work the Two-Phase Theory of Fluidization was developed. This theory states that all gas in excess of the minimum fluidization velocity passes through the bed in the form of bubbles.
- The 1970's saw the development of circulating fluidized beds and the famous **Geldart Powder Classification Diagram (1973)** now used by all workers in the fluidization field which shows how particle size affects the operation of fluidized beds.



GELDART'S POWDER CLASSIFICATION

(Geldart, D. Powder Technology, 1, 285, 1973)

Applies at Ambient Conditions



A: Aeratable ($U_{mb} > U_{mf}$) Material Has a Significant Deaeration Time (*FCC Catalyst*)

B: Bubbles Above U_{mf} ($U_{mb} = U_{mf}$) (*500-micron Sand*)

C: Cohesive (*Flour, Fly Ash*)

D: Spoutable (*Wheat, 2000-micron Polyethylene Pellets*)

History of Fluidization

- The embargo of the Organization of Petroleum Exporting Companies (OPEC) against the US in 1973 led to shortages of natural gas and petroleum. People who lived through this time will remember the rationing of gasoline and the long lines of people waiting to fill their automobiles.
- Because of these shortages, the US rapidly increased funding for several coal gasification plants (to produce syngas) to mitigate future oil shocks. The coal gasification processes were operated at high pressure (1000 psig = 70 barg) and high temperature (1800°F = 1000°C). The lack of information in high pressure and temperature saw significant research in these areas during this time. Nearly all of these processes utilized Geldart Group B solids.
- The 1980's saw the development of circulating fluidized beds and the development of the polyethylene and polypropylene fluidized bed processes.

History of Fluidization

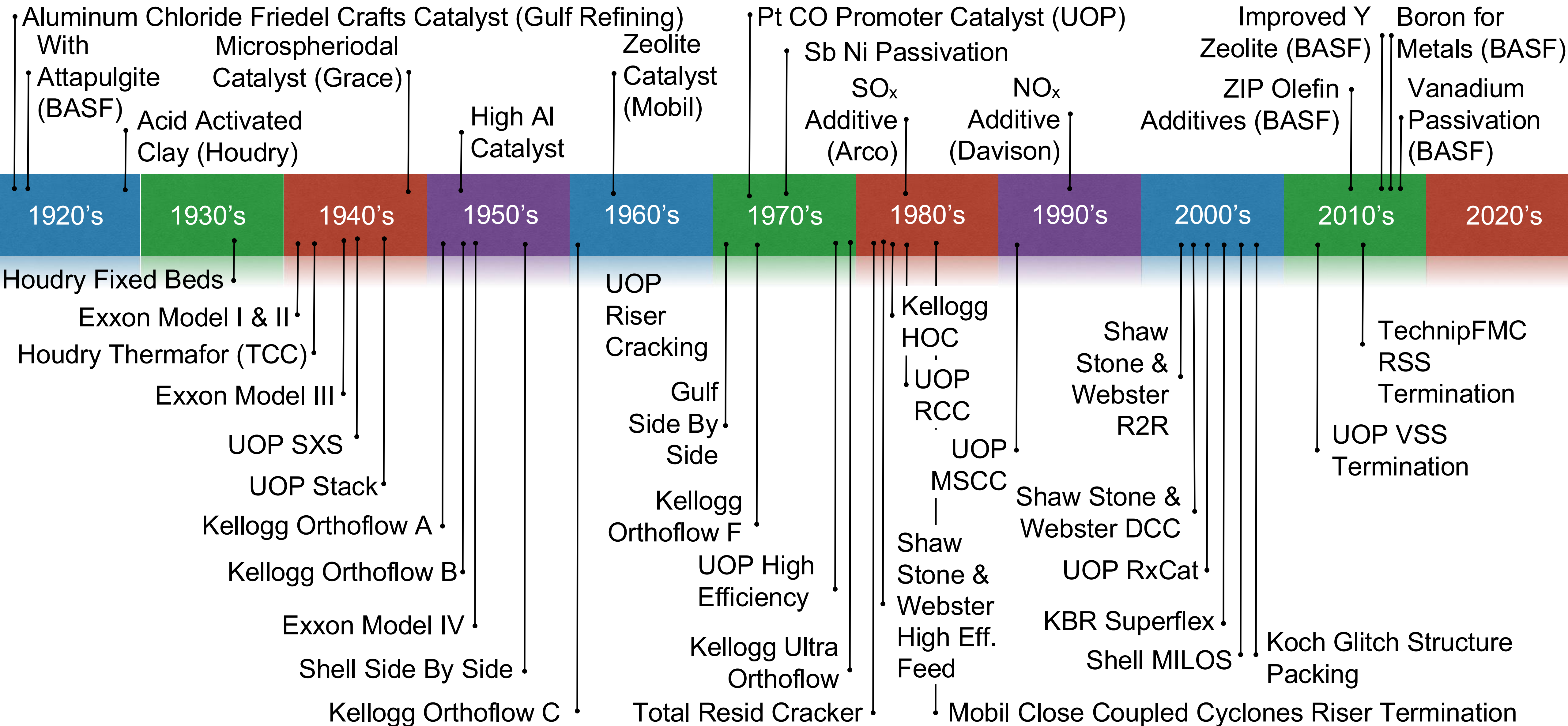
- **The 1990's and the early 2000's and still to this day there became a focus on process scale-up, system analysis and the development of simulation tools. This time also saw the early application of Computation Fluid Dynamic models to fluidized beds, and the start of research into fine (cohesive) particle fluidization. The improvement and focus on modeling in fluidization and work on fine, cohesive particles (including nanoparticles) are areas that will be important in the future.**
- **One other major change over this time was the rapid rise of China in the fluidization field. This can be especially seen by looking at the number of papers produced by countries over the period from 1980 to 2001 as shown in the following table.**
- **The table shows research publications by country in 1980 and 2021. There were no papers from China in 1980. The US and Canada combined had nearly 50% of all of the papers produced in 1980. However, by 2021, China alone essentially equaled the papers produced by the US and Canada.**

History of Fluidization

Table 1. Publications by the Top Ten Countries – 1980 and 2021

Countries	1980 Publications		Countries	2021 publications	
	Number	Percentage		Number	Percentage
United States	730	38.9	China	12,569	29.8
United Kingdom	244	13	United States	9484	22.5
Japan	237	12.6	Japan	3342	7.9
Canada	188	10	Canada	3293	7.8
Russia	140	7.5	United Kingdom	3067	7.2
Germany	81	4.3	Germany	2797	6.6
France	74	3.9	India	2333	5.5
India	70	3.7	France	1933	4.6
Australia	67	3.6	Spain	1847	4.4
Netherlands	48	2.5	Italy	1556	3.7
TOTAL	1879	100	TOTAL	42,221	100
US + Canada	918	48.9	US + Canada	12,787	30.3

History of FCC Process



Based on R. Fletcher, Innovations in Industrial and Engineering Chemistry, (2009) 1-61.

Benefits of Using Fluidized Beds

- Fluidized beds have been spectacularly successful as devices to produce industrial products over the last 100 years, especially in the chemical and petrochemical industries. The characteristics/advantages of fluidized beds that make them such widely-accepted and highly-efficient devices are listed below:
- ***Excellent heat and mass transfer:*** The rapid mixing of solids in the fluidized bed enhances heat transfer and mass transfer relative to fixed beds. Heat transfer rates are approximately 10 times the heat transfer rates in fixed beds.
- ***Precise Temperature Control:*** The rapid solids mixing in fluidized beds results in nearly isothermal conditions with temperatures throughout the bed within 2 to 5°C. This prevents hot spots from occurring in the fluidized bed.
- ***Small footprint:*** Due to the excellent gas-solids contacting, fluid beds require smaller reactor volumes to achieve the same throughput as other technologies.
- ***Fuel and Material Flexibility:*** Fluid beds can accommodate a wide range of particle sizes and use combinations of different materials (e.g. coke and titanium)

Fluidization Today

- Today, the fluidization field is at a stage of knowledge development that is significantly greater than 20 years ago.
- Diagnostic techniques have been developed that allow the determination of solids and gas mixing and mathematical models are at a helpful stage of development. Scale-up of fluidized beds is still an issue taking time and money, but there is less variability in scaling up and more understanding of how to proceed with it now.
- Knowledge of fluidization regimes and how each regime should be used with each type of reaction and particle size is well understood.
- What is not known definitively is how to predict interparticle forces and the behavior of cohesive particles. This is an area that will be studied more extensively in the future.

Important Diagnostic Techniques

- Today there are extensive techniques that have been developed and perfected over the years that can be used to evaluate what is occurring inside laboratory and some can be applied to hot fluidized beds. These techniques are listed below:
- ***Optical Probes:*** These probes use optical fibers to transmit laser light into the bed and detect backscatter. The probes can determine bubble properties and particle concentration in the bed.
- ***Gas tracers:*** (generally using Helium with thermal conductivity detectors) can determine the degree of gas backmixing and the amount and direction of gas flow in a fluidized system
- ***Fluorescent Coated Solid Tracer Probes:*** The motion and concentration of solids dyed with a fluorescent coating can be determined with probes using ultra-violet light
- ***Electrical Capacitance Tomography:*** a non-invasive technique that determines the spatial distribution of solids in the fluidized bed

Important Diagnostic Techniques (cont'd)

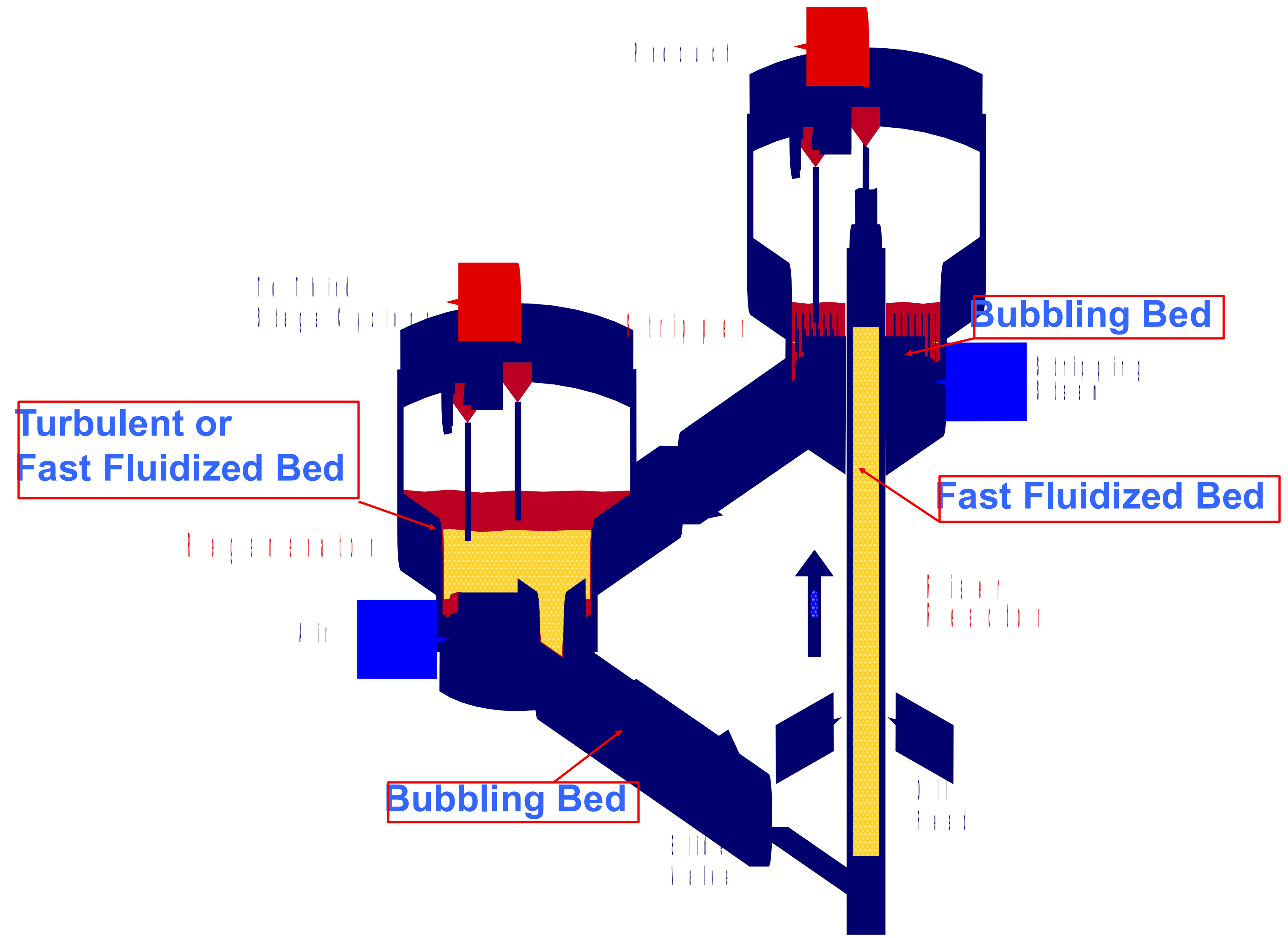
- ***Electrical Capacitance Tomography:*** a non-invasive technique that determines the spatial distribution of solids in the fluidized bed.
- ***High-Frequency Differential Pressure Probes:*** Fluidized bed behavior can often be related to measuring the standard deviation of bed differential pressure drop fluctuations between 25 to 100 Hz (the normal frequency of a fluidized bed is between 2 to 5 Hz).
- ***Moveable Extraction Probe:*** A tube placed in a dilute-phase line to measure the mass flux distribution across the dilute-phase line.
- ***Positron Emission Particle Tracking (PEPT):*** A non-invasive technique where a single particle is labeled with a positron-emitting isotope and inserted into an unlabelled bed of particles. Detectors surrounding the bed monitor the position of the particle in the bed as a function of time.

Major Fluidized Bed Processes Today

- There are hundreds of fluidized bed processes that exist today. However, there are several that are deemed to be important due to the size of the area or the importance of the area. Many of these processes are described below:
- **FCC:** This process is the oldest and is still the most important application of fluidized beds today. This process converts crude oil into gasoline, diesel fuel, jet fuel, LPG, propylene, etc.
- **Synthesis of Polyethylene and Propylene:** The fluidized bed allows effective heat removal and precise temperature control to prevent melting of the resin.
- **Fluidized Bed Combustion (CFBC):** A circulating bed burns (coal/biomass) fuels in a suspended (dilute-phase) mixture of ash and limestone for power generation. Captures sulfur and reduces NOx. Very large units.
- **Polysilicon:** Fluid beds are used for chlorination and thermal decomposition of Si and produce ultra-high silicon for semiconductors and solar panels

Major Fluidized Bed Processes Today (cont'd)

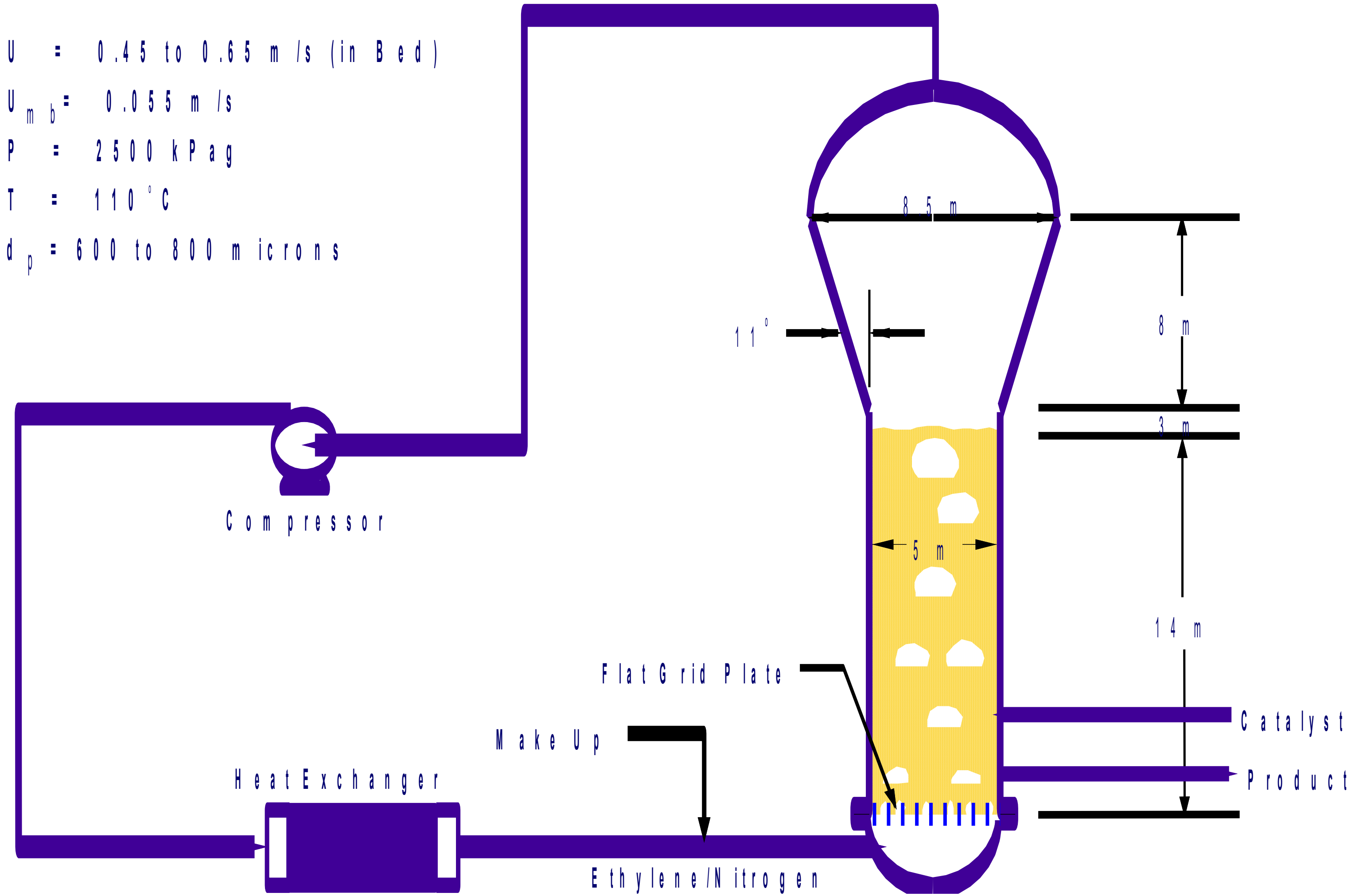
- ***Biomass and Waste gasification:*** Fluidized beds are used to convert municipal solid waste and biomass to syngas.
- ***Roasting of Sulfide Ores:*** Copper, gold and zinc sulfides are roasted to extract metal oxides and produce SO₂ used for sulfuric acid production.
- ***Drying:*** Different types of fluidized beds are used to rapidly and uniformly remove water from a wide variety of different materials, especially pharmaceuticals and food
- ***Granulation/Coating:*** A liquid is sprayed onto a dilute-phase suspension of particles which produces free-flowing granules (food, pharmaceuticals, catalysts, fertilizer, etc.)

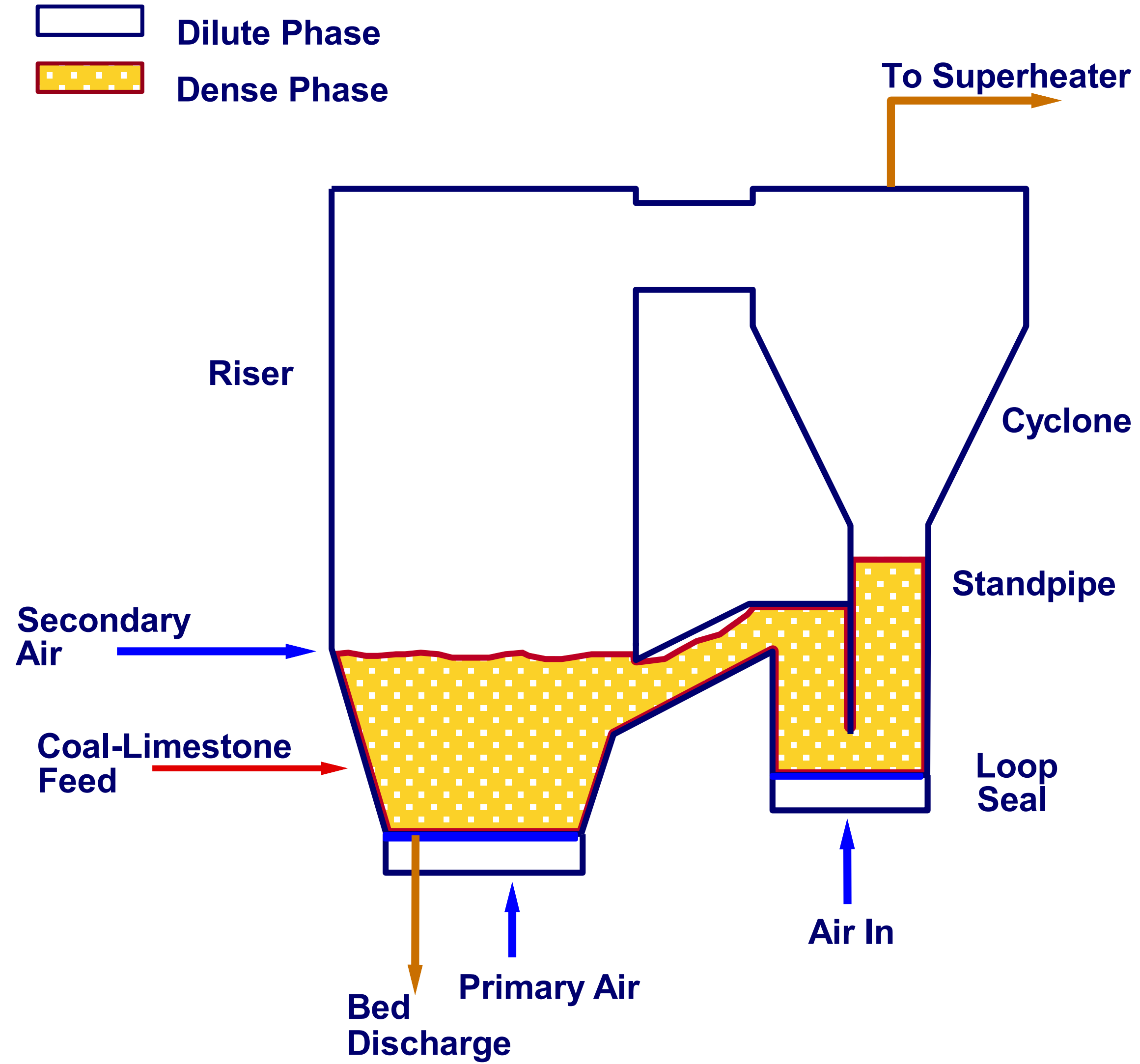


Schematic Drawing of UOP Side-by-Side FCC Unit

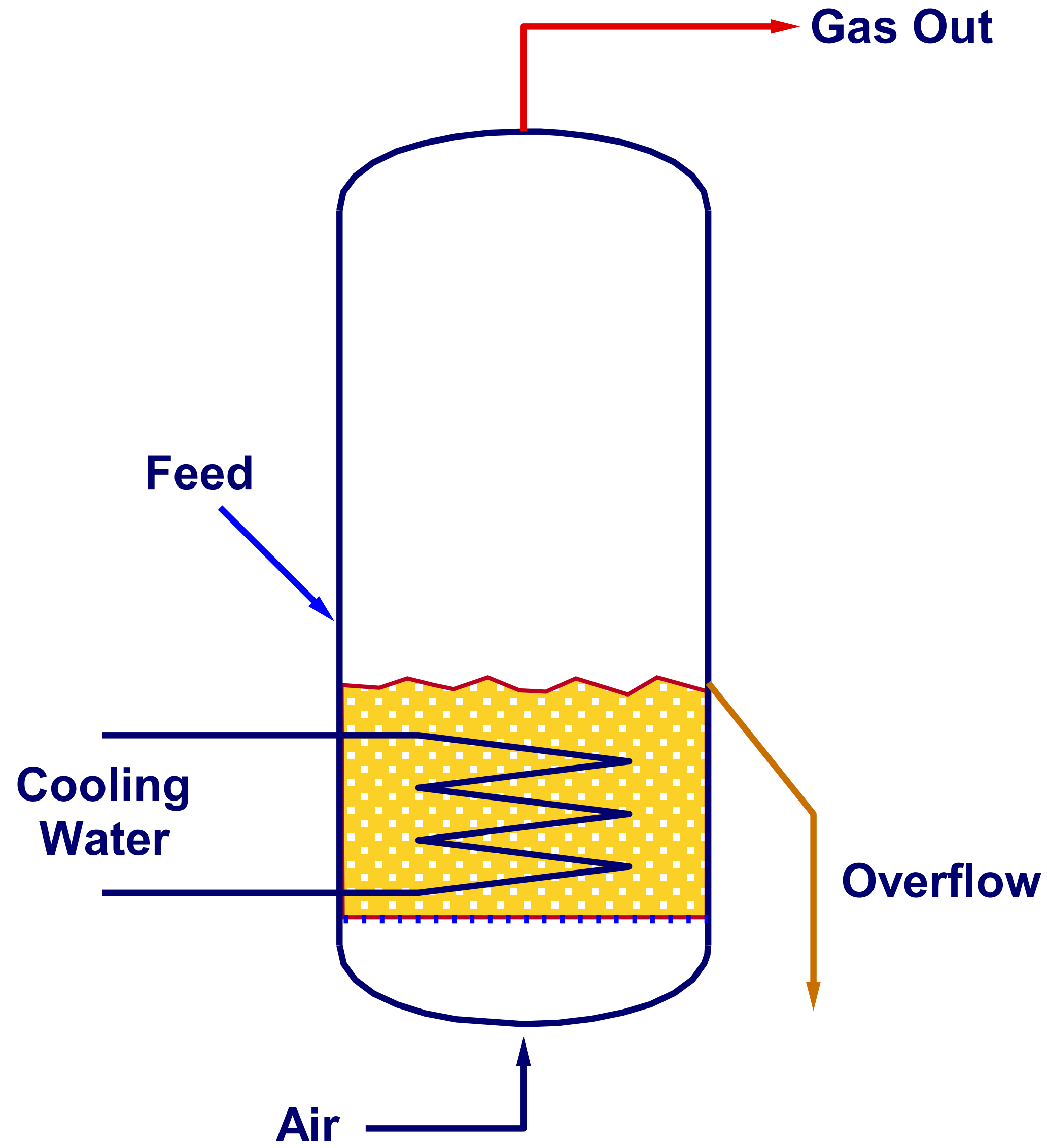
Polyethylene Process Spreadsheet (Unipol)

$U = 0.45 \text{ to } 0.65 \text{ m/s (in Bed)}$
 $U_{mb} = 0.055 \text{ m/s}$
 $P = 2500 \text{ kPag}$
 $T = 110^\circ \text{C}$
 $d_p = 600 \text{ to } 800 \text{ microns}$



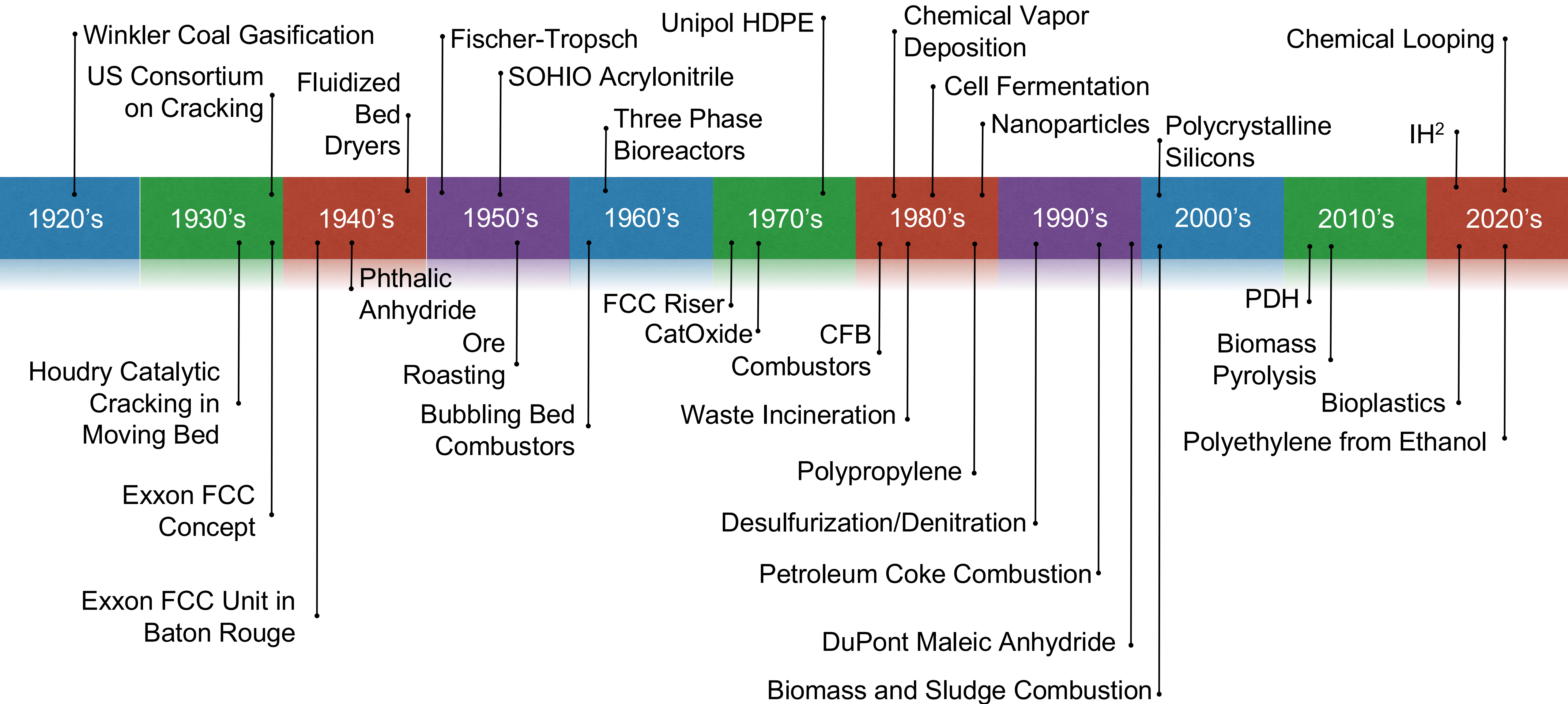


**Circulating Fluidized Bed Combustor
(Foster-Wheeler Type)**



FLUID BED ROASTER

Selected Fluidization Application Through the Years



Future Direction of Fluidization

- **As that famous philosopher and baseball player Yogi Berra once said:**

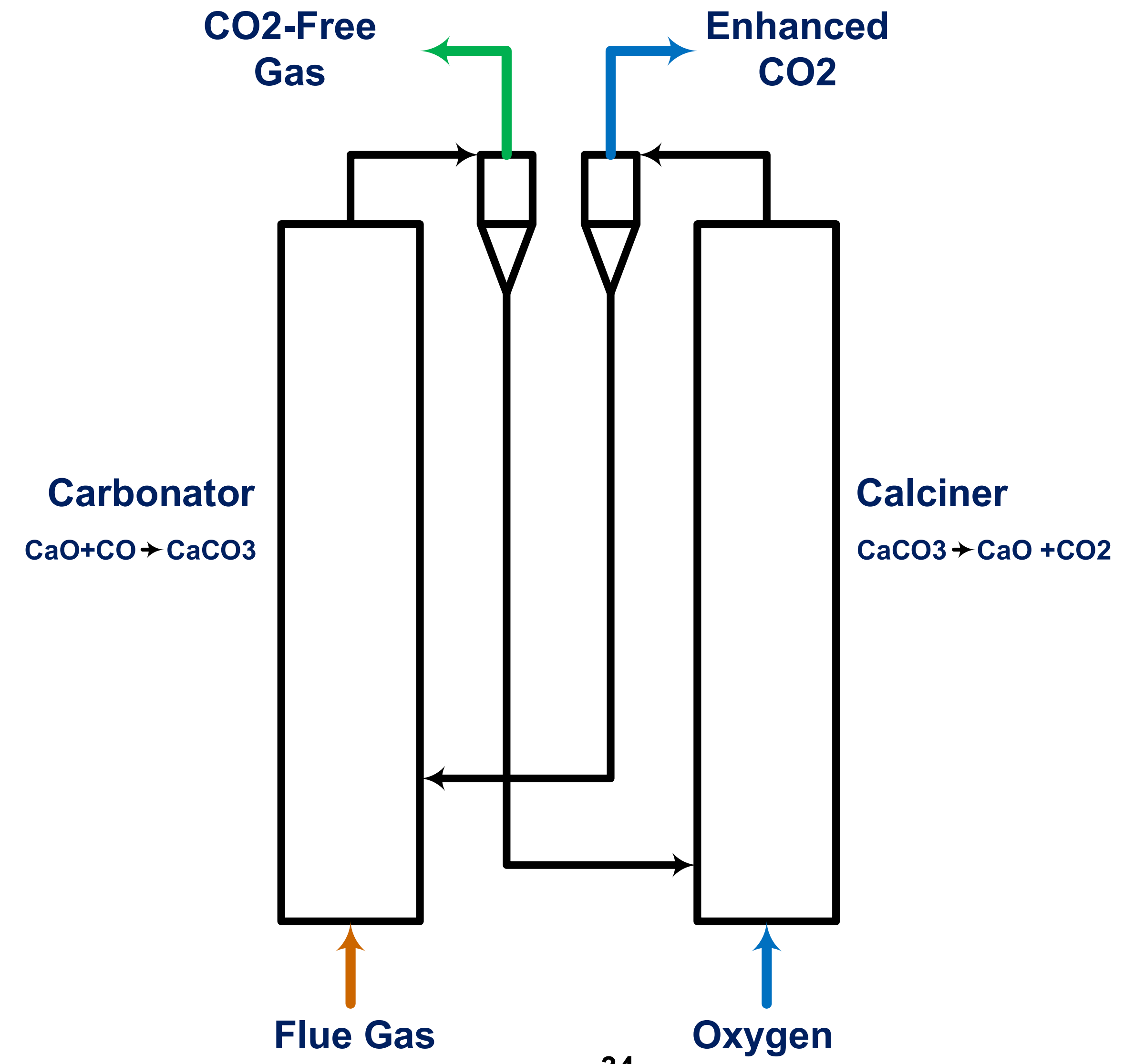
“It is tough to make predictions, especially about the future”.

- **Even though it is difficult I will try to make some predictions regarding some of the fluidized processes that could be more prominent in the future, and also the direction of some fluidization research.**

Future Fluidized Bed Processes

- Today the fossil-fuel processes that have been the backbone of the fluidization field are slowly declining in importance as the world shifts to more sustainable and green technologies. Some processes that are expected to become more prominent are listed below:
- ***Calcium Looping (Chemical Looping):*** This is a regenerative , cyclic high-temperature process that uses inexpensive limestone to capture CO₂ from flue gases. It produces a nearly pure stream of CO₂ which can be sent to storage or used industrially (EOR, etc.).
- ***Methane Pyrolysis:*** Also called “methane cracking”, methane is broken down into clean hydrogen plus a valuable carbon product. This process does not release CO₂ and is a highly-efficient method of producing hydrogen.
- ***Plastic Pyrolysis:*** This process heats plastics in a high-temperature fluidized bed. It breaks down long polymer chains into shorter hydrocarbon molecules and produces oils, gas and char.

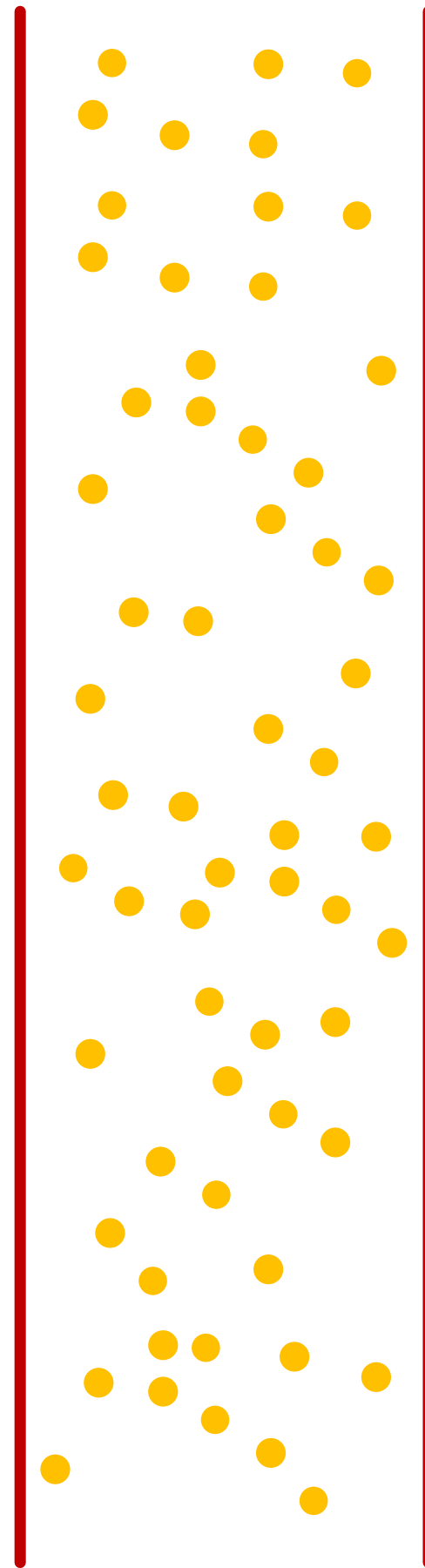
Circulating Fluidized Bed Calcium Looping System



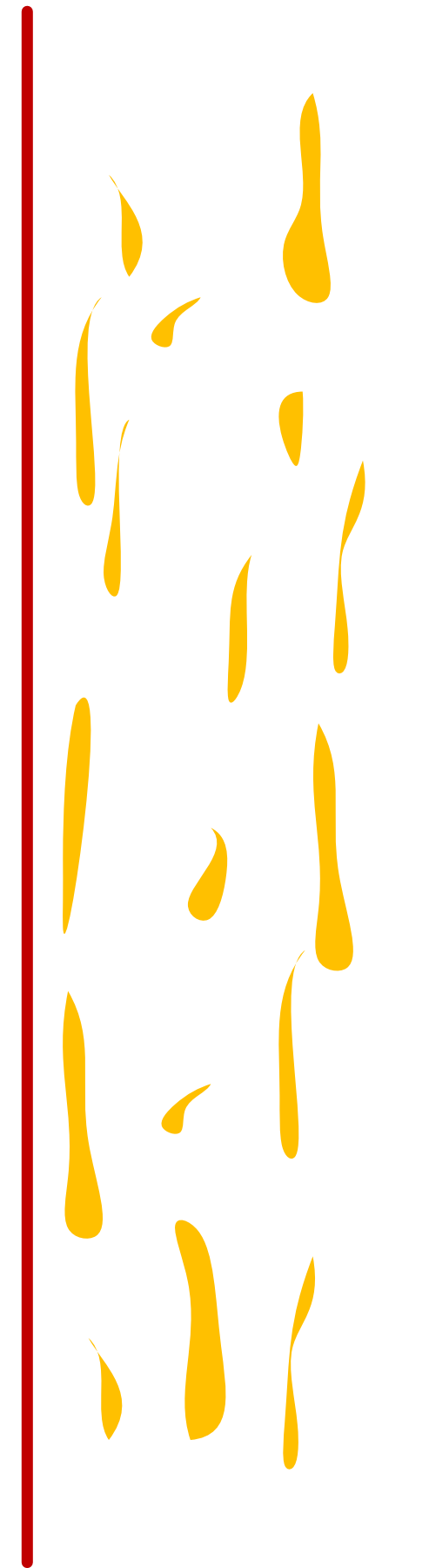
Future Direction of Fluidization

- **In the near future, more experimental work will be directed toward cohesive solids (material smaller than 30 microns) which are very difficult to fluidize and transport. PSRI has already seen much more interest in these materials in the last few years and has developed techniques and equipment to allow fluidization of these materials.**
- **The interparticle forces which cause cohesion can cause small individual particles to agglomerate together instead of behaving like individual particles. These interparticle forces are van der waals forces, electrostatic forces, capillary forces, etc. These forces can also cause material larger than Group C (such as Geldart Group A) to clump or agglomerate. This is apparent in risers as well as in the freeboard of some Group A particle beds.**
- **However, the interparticle forces which cause cohesion are different with each particle and have not been systematically measured and studied. It is expected that there will be a large increase in work in this area in the coming years.**

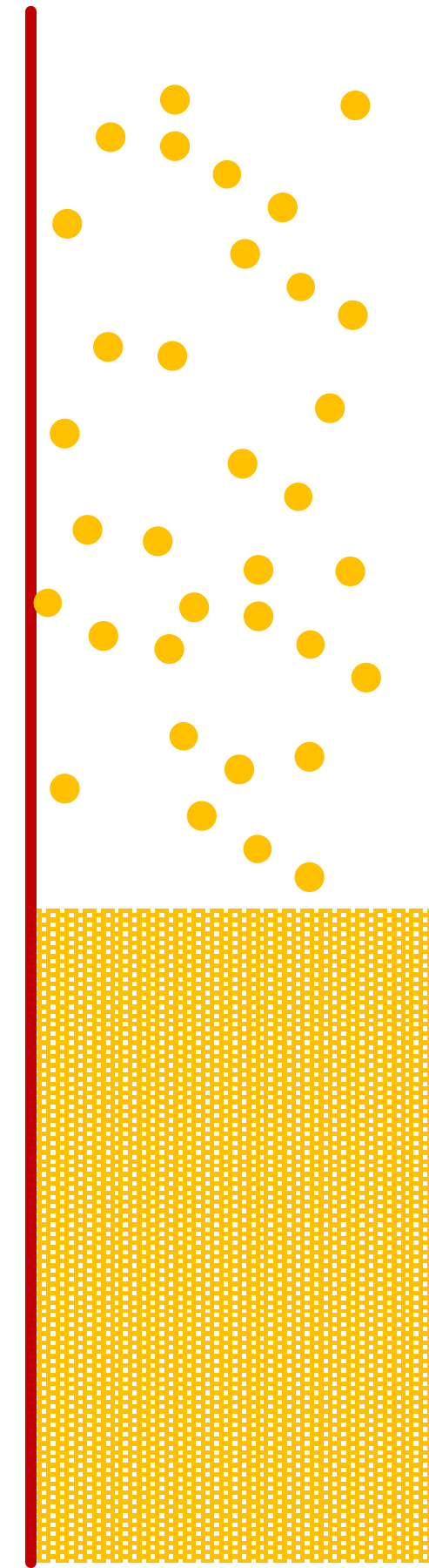
Particle Agglomeration



Riser with Individual Particles



Riser with Agglomerated Particles



Fluid Bed with Individual Particles in Freeboard



Fluid Bed with Agglomerated Particles in Freeboard





Fluidization of Geldart Group C Material



Group C

FCC Risers

PSRI high speed videos at the wall of a 12-in (30-cm)-dia CFB riser for FCC catalyst particles

	Low gas velocity 30 ft/s (9 m/s)	High gas velocity 60 ft/s (18 m/s)
Low solids flux 10 lb/s.ft ² (50 kg/s.m ²)		
High solids flux 80 lb/s.ft ² (400 kg/s.m ²)		

**FCC Riser
Operation**



Refluxing flow

Upward flow

Phantom VII Camera @
3000 frames per sec

Mathematical Modeling

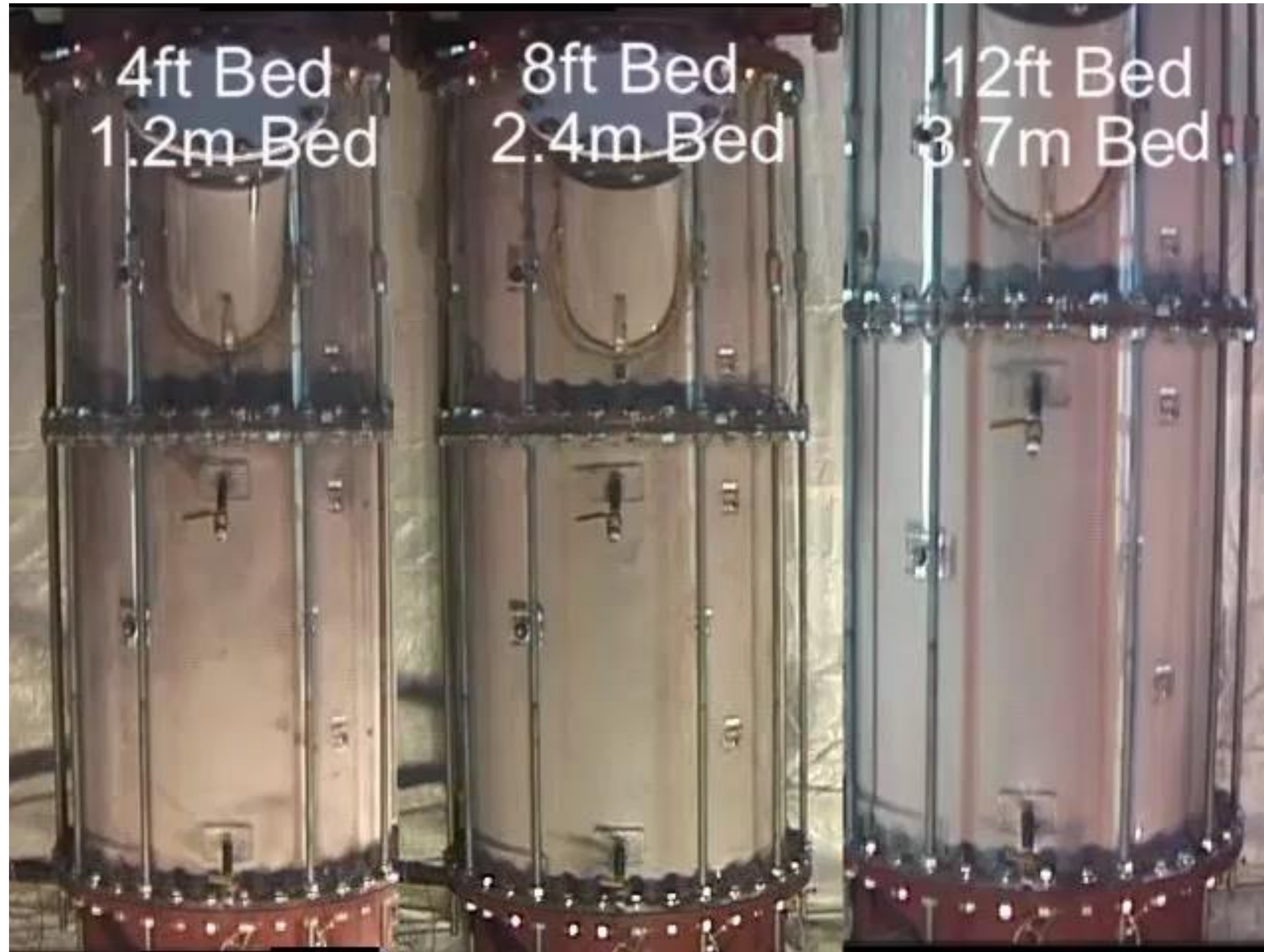
- **It is readily apparent to people working in the fluidization field that the number of papers on mathematical modeling has increased nearly exponentially over the past 35 years. Because of this increase in modeling, PSRI issued 3 Challenge problems to modelers to obtain a sense of how accurate the models were and if the models were improving. Data was produced in the PSRI test units, and the modelers were asked to predict measured values.**
- **The first PSRI Challenge Problem results were shown in 1995. The second Challenge Problem results were published in 2001, and the third PSRI Challenge results were presented in 2011.**

Mathematical Modeling

- In Challenge Problem 1 in 1995, the modelers were asked to predict the measured radial distribution of solids mass flux in an 8-in (20-cm) diameter riser/CFB as a function of gas velocity and overall solids flux. The conclusion of the exercise was that the *“models were not sophisticated enough to be used to predict the hydrodynamics in a CFB”*.
- In Challenge Problem 2 in 2001, the modelers were asked to predict the measured radial distribution of solids mass flux in the same 8-in (20-cm) diameter riser/CFB as a function of gas velocity and overall solids flux. The conclusion of this exercise was that the *“models still need substantial development to be able to predict CFB hydrodynamics”*.

Mathematical Modeling

- **Challenge Problem 3 in 2011 was slightly different. Modelers were asked to predict the radial distribution of solids flux in a 12-in (0.3-m) diameter riser and also predict the density profiles in a 3-ft (0.9-m) diameter bubbling fluidized bed using FCC catalyst operating at different gas velocities and with different fines levels. In some cases, the bed was operating with gas bypassing in the bed.**
- **Definite improvement was noticed in the models in this last Challenge. However, the inclusion of a **gas bypassing case** in the operation of the fluidized bed was a very difficult condition to model, and all the models failed to predict gas bypassing. The difficulty in predicting this condition can be appreciated by the next slide depicting gas bypassing in the fluidized bed.**
- **Although models have been steadily improving, there are areas where they are lacking hydrodynamically (as in predicting gas bypassing).**



Gas Bypassing: $U = 0.46$ m/s; $D_{bed} = 0.9$ m; FCC Catalyst

Mathematical Modeling

- There are two areas where modeling can really make a difference in the fluidization area in the future. One area is in decreasing the time to scale-up processes and then troubleshooting of existing processes using (especially) Geldart A and the larger Group B and Geldart D particles. Scale-up assistance and troubleshooting with models are being utilized now, but demonstrated improvement in the accuracy of the models would engender much more confidence in using them. For instance, it would help if the models could predict gas bypassing. It would also help if they could predict what is happening in Group A standpipes.
- Even now when not fully developed, modeling is a valuable tool to use in assisting in scale-up and troubleshooting. CPFD Software has been remarkably successful in modeling large fluidized beds such as FCC regenerators and predicting trends which are helpful to the operators.
- Although it is a very useful tool, most people do not have the confidence to solely use CFD models for scaling up a process. This may never occur, at least in the near future. The traditional experimental route of pilot and demonstration plants takes a lot of time and is costly, but it is proven and it will take significant advances in modeling to replace this approach with modeling alone.

Mathematical Modeling

- **The capability of models will continue to improve as computers/GPUs become faster and model development continues. Fluidized beds contain trillions of particles (perhaps even a quadrillion, 10^{15}), and the capability to apply models to individual particles to determine particle-to-particle interactions and determine if they will form agglomerates appears to be a significant distance in the future. With CFD-DEM coupling, perhaps as many as 10^7 or 10^8 particles can be accommodated today.**
- **For modeling to achieve this ability to take on a greater role in scale-up, as well as to be able to predict the hydrodynamics in beds with different particle sizes (especially Group A and C particles) there will have to be an increase in capability. Normally in the fluidization area improvements are evolutionary instead of revolutionary. If this progression continues, it seems that a significant increase in processing power will have to occur to be able to apply hydrodynamic modeling to individual particles on the scale of industrial fluidized beds.**
- **Can Quantum Computing be applied to CFD-DEM?**

