Project Kickoff Meeting

DE-FE0029787

High Energy Systems for Transforming CO_2 to Valuable Products

> July 13th, 2017

Osman M. Akpolat
Gas Technology Institute

Meeting Objectives

- Introduction of Project Team Members
- Short Primer on the Science and Technology of Electron Beam Deposition into Gas
- Discussion of Electron Beam Technology and Technical Aspects of the Project
- Quick Overview of Administrative Efforts
- Comments and Questions

Meeting Agenda

• 1:00 PM	Introductions
• 1:10 PM	Background Information on Project Team Members
• 1:30 PM	Technical Approach Discussion
• 2:30 PM	Project Structure / Task description
• 2:40 PM	Schedule
• 2:50 PM	Budget
• 3:00 PM	Comments and Questions
• 4:00 PM	Adjourn

GTI Overview

> Independent, not-for-profit research institute established by the natural gas industry

> GTI tackles tough energy challenges turning raw technology into practical solutions

> Downhole to the burner tip including energy conversion technologies

Diverse Customers from Industry and Government

U.S. DEPARTMENT OF ENERGY	BMW	Shell	SES SYNTHESIS ENERGY SYSTEMS	ExxonMobil	GDF SUEZ	Chevron	DEPARTMENT OF DEFENSE UNITED STATES OF AMERICA	NW Natural
TOTAL	TOKYO GAS	Sumitomo Corporation	Spectra Energy	GRI DELIVERING INNOVATION	UPM	Cummins Westport	HALDOR TOPSOE CATALYSING YOUR BUSINESS	RTI INTERNATIONAL
ANDRITZ CARBONA	NETL NATIONAL ENERGY TECHNOLOGY LABORATORY	nationalgrid	Argonne NATIONAL LABORATORY	NREL NATIONAL RENEWABLE ENERGY LABORATORY	arpa-e	EDISON INTERNATIONAL	HONDA	RPSEA Research Partnership to Secure Energy for America
ConocoPhillips	OAK RIDGE National Laboratory	Design Your Energy 夢ある明日を OSAKA GAS		ATMOS energy	CenterPoint Energy	AGA American Gas Association	THE LINDE GROUP	CCEMC
uop A Honeywell Company	nyserda Energy. Innovation. Solutions.	CEE	DUKE ENERGY	PG&E	PROPANE education & research COUNCIL	Washington Gas	Pratt & Whitney A United Technologies Company	LAREDO PETROLEUM
AEROJET ROCKETDYNE	devon	Discovery	ALBERTA INNOVATES	سابك sabic		schülke	أرامكو السعودية saudi aramco	SoCalGas A Sempra Energy utility

Business Highlights

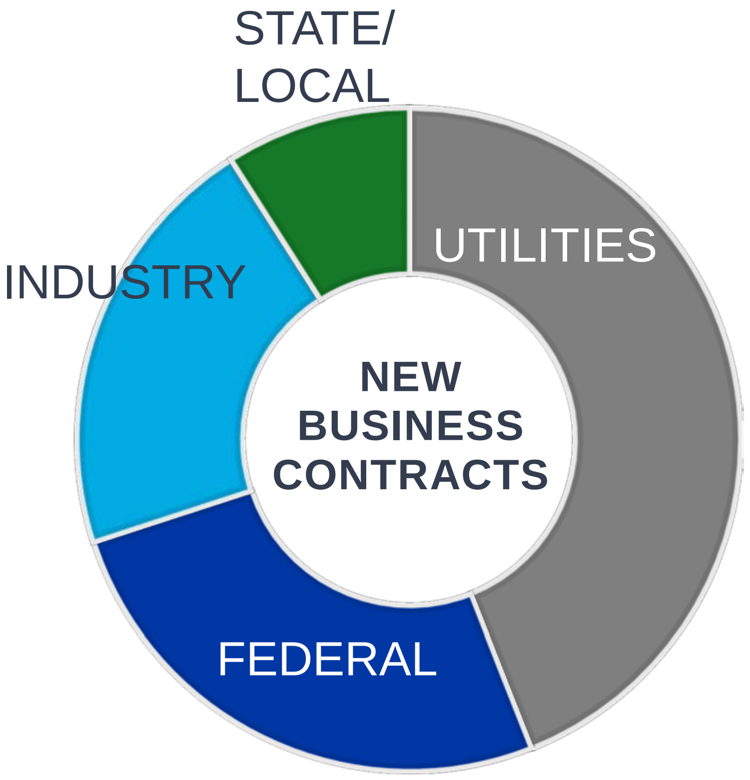
DIVERSE CUSTOMER BASE

GTI provides solutions to clients in the private sector, federal government, and state government agencies

> 300+ active projects

> 20 patents issued

> 10 patent applications



2016 Results

Company History

1940 | 1950 | 1960 | 1970 | 1980 | 1990 | 2000 | 2010

IGT EDUCATION · RESEARCH

1941

Institute for Gas Technology (IGT) formed at the Illinois Institute of Technology (IIT)

1947 IGT Laboratory
Chicago, Illinois

Dr. James L. Johnson
Pioneer in Coal Gasification

1970 Blue Flame natural gas powered rocket car sets world land speed record of 630 mph

1970 HYGAS® Pilot Plant
Chicago, Illinois

1973

Oil Crisis

Dr. Henry Linden
GRI President

GRI gas research institute

1976

Federal Power Commission approved surcharge on pipeline transmission for research funding and Gas Research Institute (GRI) formed

1991

GRI sponsors Mitchell Energy's first horizontal well in the Barnett shale

George Mitchell

1992

FERC Order No. 636, Restructuring Rule mandated unbundling to separate sales from transportation services

1995 U-GAS® Plant
Shanghai, China

gti®

2000

GRI and IGT combined to form the Gas Technology Institute (GTI)

2009 GTI Advanced Gasification Facility
Des Plaines, Illinois

2015

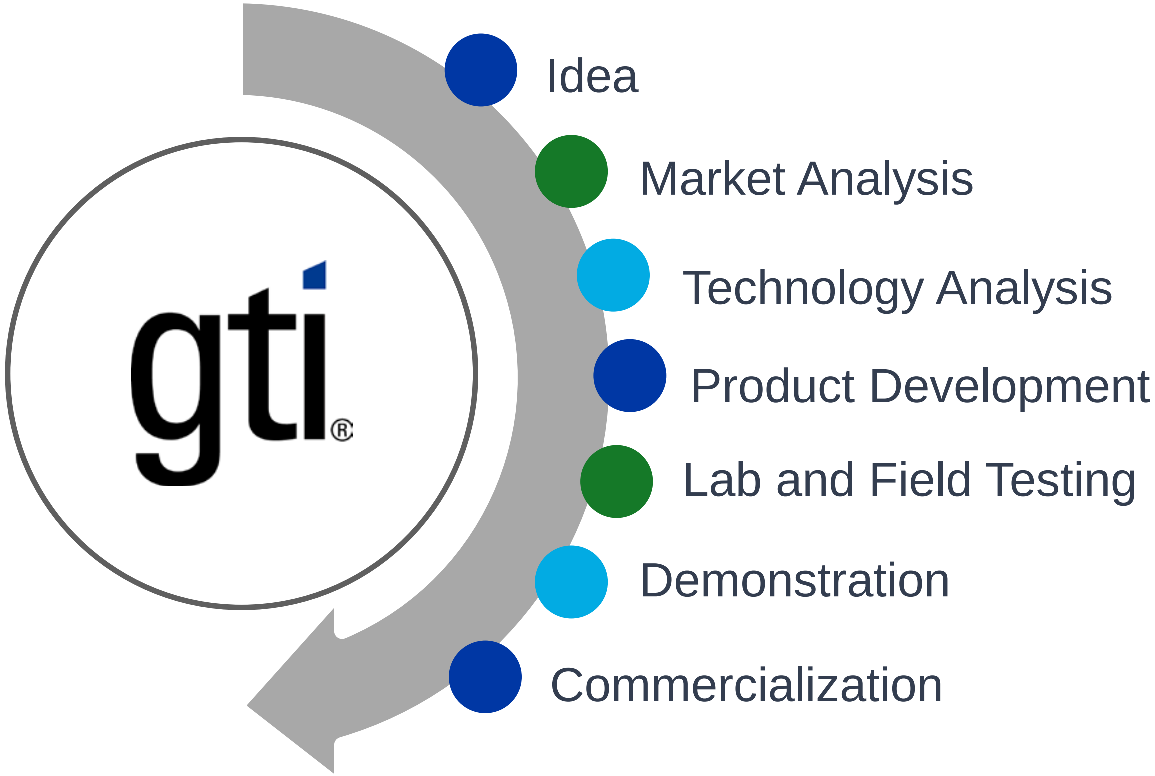
GTI acquires Aerojet Rocketdyne's fossil energy business

AEROJET ROCKETDYNE

gti 75 YEARS ENERGY EXCELLENCE EST 1941

From Concept to Commercialization

> Partnering at every phase of the technology development cycle



ENERGY SOLUTIONS… DELIVERED

U.S. Office Locations

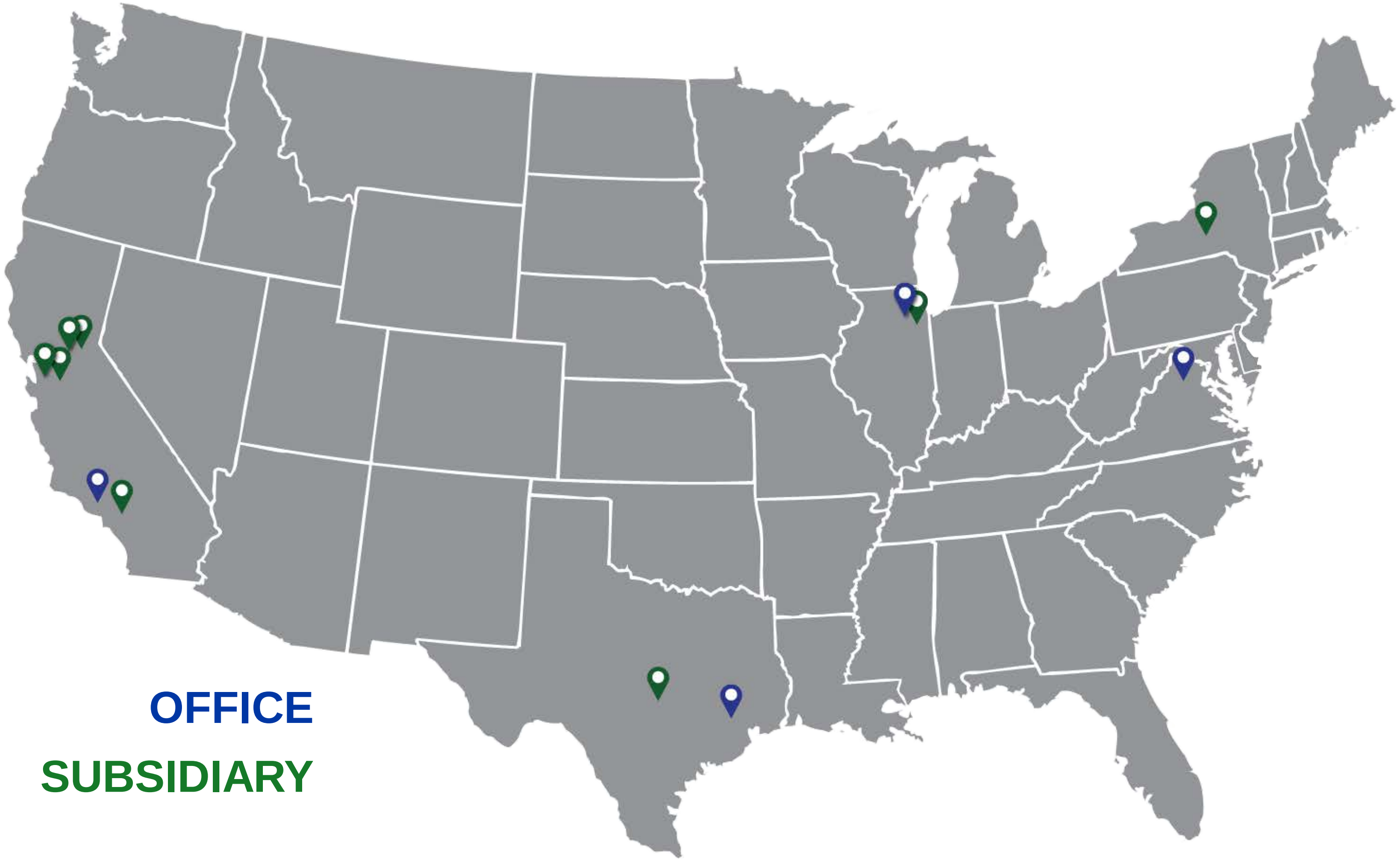
California
- Oakland, West Sacramento, Davis, San Ramon, Los Angeles (Frontier Energy)
- Woodland Hills

Illinois
- Chicago (LocusView)
- Des Plaines (*Headquarters)

New York
- Cazenovia (CDH Energy)

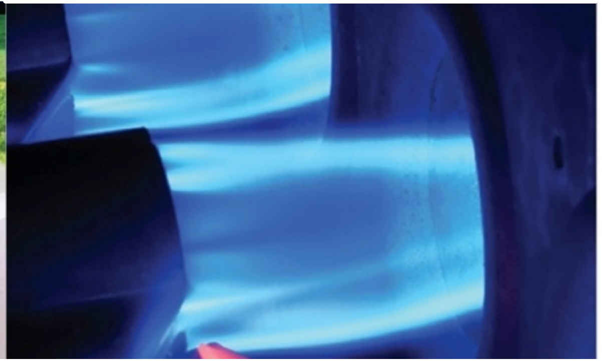
Texas
- Houston
- Austin (Frontier Assoc)

Washington, DC
- Capitol Hill



Addressing Key Issues Across the Energy Value Chain

FOR A BETTER ENVIRONMENT AND A BETTER ECONOMY

SUPPLY	CONVERSION	DELIVERY	UTILIZATION
			
Expanding the supply of clean, abundant, and affordable natural gas	Transforming natural resources into clean fuels, power, and chemicals	Ensuring a safe and reliable energy delivery infrastructure	Promoting the clean and efficient use of energy resources

IBA Industrial - Background

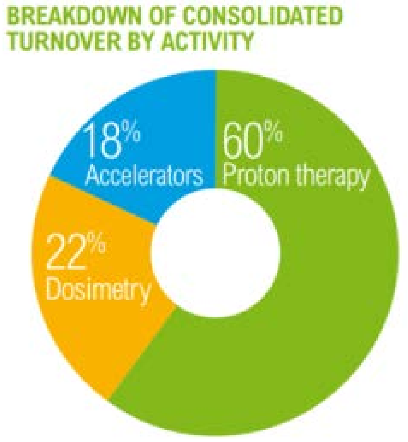
IBA Industrial

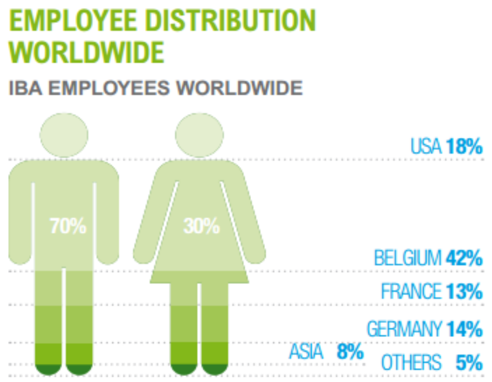
General Overview

July - 2017

IBA in a nutshell

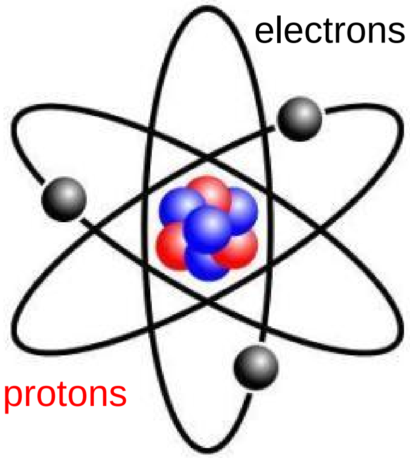
- Based in Belgium, listed on Euronext Brussels
- Focused on **particle accelerators**
- >**400 accelerators** worldwide
- 2016 sales of €329 million
- **1,200+ people** worldwide, 40 nationalities
- 15 offices on 3 continents





IBA's core competence – Particle accelerators

Atom



Particle Accelerators

Proton or electron acceleration

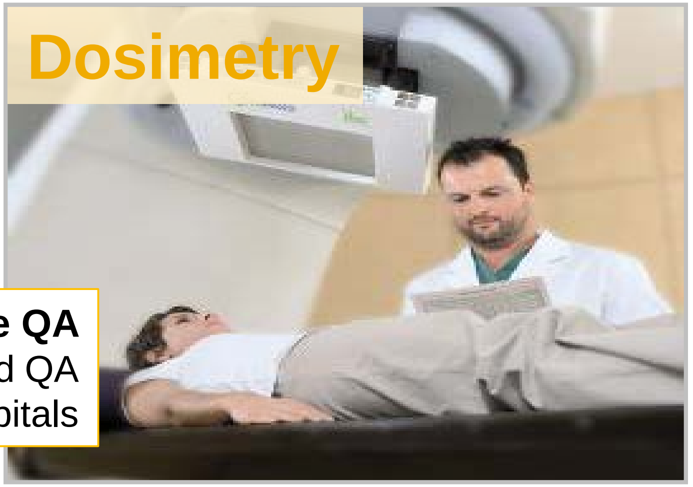
Patient or Product

IBA Main Activities

Proton Therapy

Cancer treatment
Accurate protons
Minimized side effects
55% market share
22 IBA supplied centers

Dosimetry



Patient and machine QA
Calibration, validation and QA
Used in most hospitals

RadioPharma

Cancer diagnostic
160+ Cyclotrons installed
Synthera multi-tracer system
From Cyclotron to turnkey

Industrial

Industrial applications
Medical Device Sterilization
Polymer crosslinking
Food pasteurization

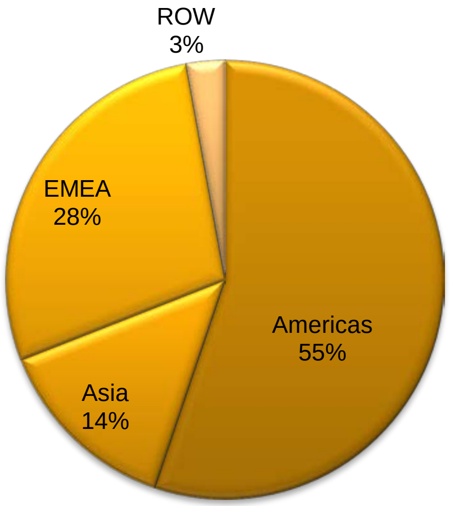
IBA Industrial

250+ Electron beam accelerators installed worldwide

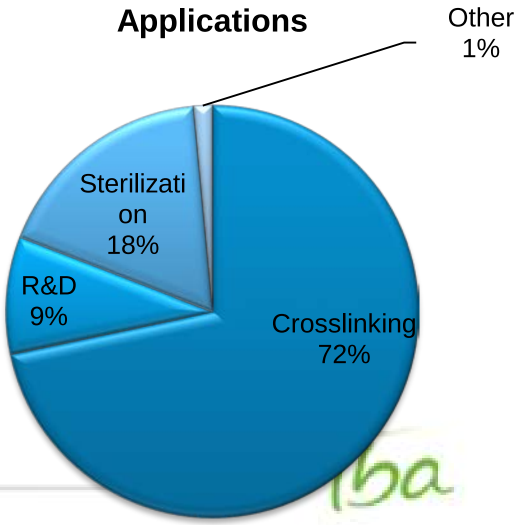
200 +
Dynamitron

36 +
Rhodotron

IBA Installed base



Applications



IBA's product portfolio

Dynamitron
0.5 -> 5 MeV | 160 mA
Electron beam

Main application : **E-beam Crosslinking**

Rhodotron
3 -> 10 MeV | 245 kW
Electron beam and X-rays

Main application : **E-beam box sterilization**

eXelis
5 – 7 MeV | 560kW
X-rays

Main application : **X-ray pallet sterilization**

Rhodotron and Dynamitron product ranges

Dynamitron product range *

Dynamitron® 500 KeV

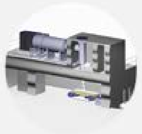
550 KeV, up to 160 mA (Optional Self-shielding)

Dynamitron® 800 KeV

800 KeV, up to 160 mA (Optional Self-shielding)

Dynamitron® 1 MeV

1000 KeV, up to 100 mA (Optional Self-shielding)



Dynamitron® 1.5 MeV

1.5 MeV, up to 65 mA

Dynamitron® 3 MeV

3 MeV, up to 50 mA

Dynamitron® 5 MeV

5 MeV, up to 30 mA

*Other models can be available on request

Rhodotron product range

TT100 Compact 10 MeV

40kW, 4mA

TT200 Standard 10 MeV

100kW, 10mA

Models available from 35 kW to 100 kW

TT300 High power 10 MeV

245kW, 35mA

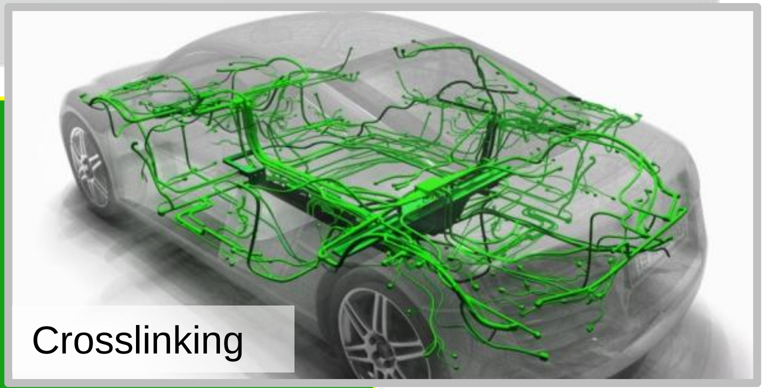
Models available from 50 kW to 245 kW

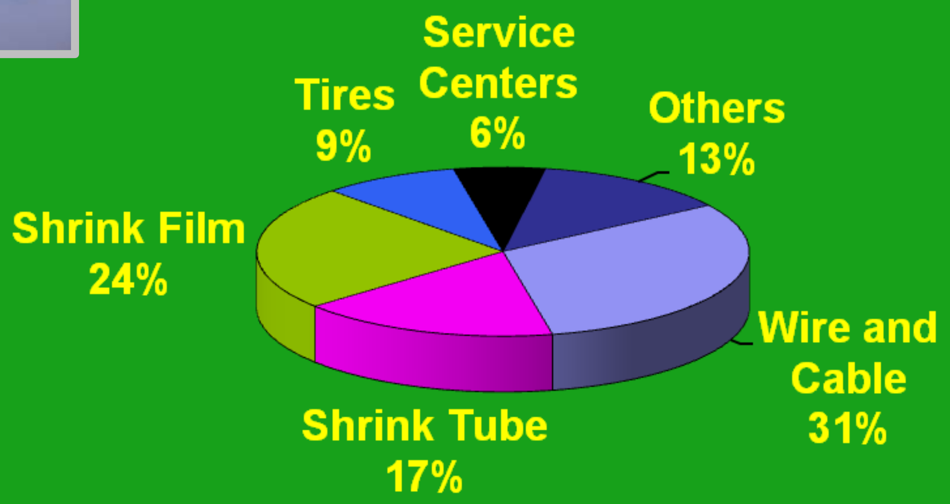
TT1000 High power 7 MeV

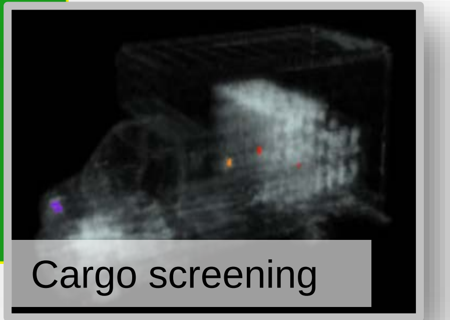
560kW, 80mA

Models available from 100 kW to 560 kW

IBA Industrial Inc. – Markets







SUNY - Background

ESF

State University of New York
College of Environmental Science and Forestry

SUNY-Environmental Science and Forestry

- 8 Departments (Bio., Paper Sci., Forestry, Landscape Arch., Env. Studies / Sci. / Eng.
- 2000 undergrads, 550 grad students

<u>Chemistry M.S. and Ph.D.</u>
- Biochemistry
- Environmental Chemistry
- Organic Natural Products
- Polymer Chemistry

15 Faculty
40 grad students

Theodore S. Dibble

Professor of Chemistry

SUNY-Environmental Science & Forestry

(tsdibble@esf.edu)

- SUNY-ESF:
  1 of 7 PhD-granting SUNY campuses
  Located in Syracuse
- My Training:
  PhD (Physical Chemistry) U. Michigan, 1992
- My Research Group:
  1 MS, 1 PhD, 1 undergrad
  (1 MS and 1 PhD student arriving in Fall)

Research Background

Research is 90% Kinetics

- **Tools: Experiment, Theory, Kinetic Models**
  - Lasers to generate and monitor radicals
  - Gas chromatography-mass spectrometry
  - Infrared spectroscopy
  - Quantum chemistry, theoretical kinetics
  - Reaction mechanisms
  - Large kinetic models
- **Topics:**
  - Atmospheric ozone and mercury
  - Combustion
  - Electron beams

Kinetic Modeling of Electron Beams

Previous Work: Humid Air (N_2, O_2, H_2O)

Goal: understand sources of OH radical (removes SO_2 and NO_x from flue gas)

- Started with a published model
  - added reactions
  - edited rate constants & reaction products
  - iterated until "self-consistent" (~900 reactions)
- Ran model
  - tested against/reintepreted exp. results
  - analyzed sources of OH & error

Technical Details

- Software: Kintecus Chemical Modeling
  - Plug flow reactor
  - huge # number of reactions
  - Accurate numerical integration
- Input Parameters
  - Dose rate (Joules absorbed/kg gas) from IBA
  - Initial species concentrations
  - Set of reactions and rate constants
- Outputs
  - Concentrations vs. time
  - Sensitivity coefficients

Technical Approach Discussion

High Energy Systems for Transforming CO_2 to Valuable Products

- **Sponsor** U.S. DEPARTMENT OF ENERGY · NATIONAL ENERGY TECHNOLOGY LABORATORY — **DE-FE0029787**
- **Funding**: $799,997 DOE ($206,000 co-funding), two year effort,
- **Objective**: Develop a direct electron beam (E-Beam) synthesis (DEBS) process to produce valuable chemicals such as acetic acid, methanol, and carbon monoxide using carbon dioxide (CO_2) captured from a coal-fired power plant and methane (natural gas).
- **Team:**

Member	Roles
gti	• Overall project integration and management • Design, construct the E-Beam reactor and the testing unit • Conceptual design for coal-fired power plants with DEBS
Iba	• Provide guidance in E-Beam reactor design and E-Beam accelerator for testing
ESF State University of New York College of Environmental Science and Forestry	• Develop a kinetic model for the E-Beam reactor

Project Objectives

OBJECTIVES

The objective of this project is to develop the Direct E-Beam Synthesis (DEBS) process to produce valuable chemicals, such as acetic acid, methanol, and carbon monoxide, at relatively low severity (pressure being near one atmosphere and temperatures of <150°C) from near-pure CO_2 captured from a pulverized coal (PC)-fired power plant and methane, imported as natural gas. Creating valuable products will offset the cost of carbon capture and storage (CCS). The high energy output from an electron beam (E-Beam) accelerator will be used to break chemical bonds. The project comprises two budget periods (BP) of 9 and 15 months each for a total duration of 24 months.

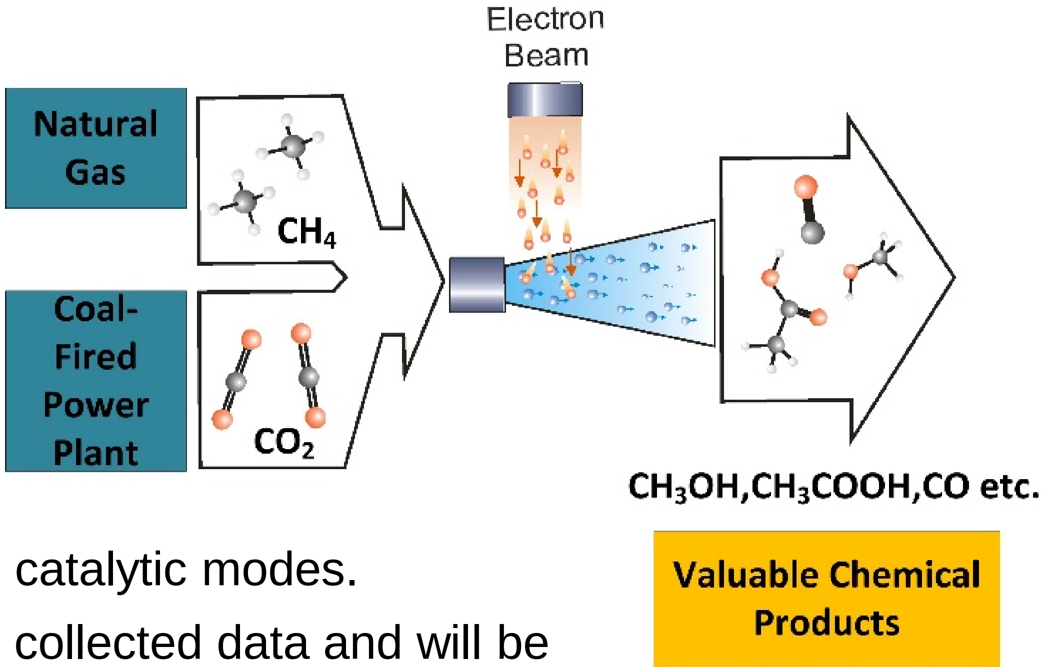
Project Objectives

BP	Objectives
1	• Complete design and manufacture of testing skid with E-Beam reactor for testing at IBA • Successful commissioning of DEBS equipment at GTI and IBA • Identify at least two catalysts to control the recombination and increase the yields for more valuable products • Develop preliminary predictive kinetic model to guide BP2 testing
2	• Determine key operating parameters at various E-Beam energies to maximize the per pass conversion of CO_2 to valuable products, control selectivities between various products, and minimize E-Beam energy requirements • Identify operating conditions and catalyst combinations to further control selectivities between products and minimize overall energy requirements • Review experimental data to optimize and improve preliminary kinetic model developed in BP1. • Complete data analysis and reporting of the experimental runs • Complete economical assessment, techno-economic analysis, and perform life cycle analysis for the process

Innovation: non-equilibrium process that breaks bonds directly unlike conventional chemistry that requires heating the entire molecule

This project will expand on the concept of DEBS to:

- Develop a commercially viable process
- Minimize E-Beam energy requirements
- Maximize CO_2 conversion
- Selectively control the yield of more valuable products using catalysts



- Experiments will be conducted in non-catalytic as well as catalytic modes.
- A kinetic model will be developed by SUNY based on the collected data and will be used to predict the chemical performance of the DEBS process.
- A conceptual design for coupling the DEBS process to a coal-fired power plant will be developed.

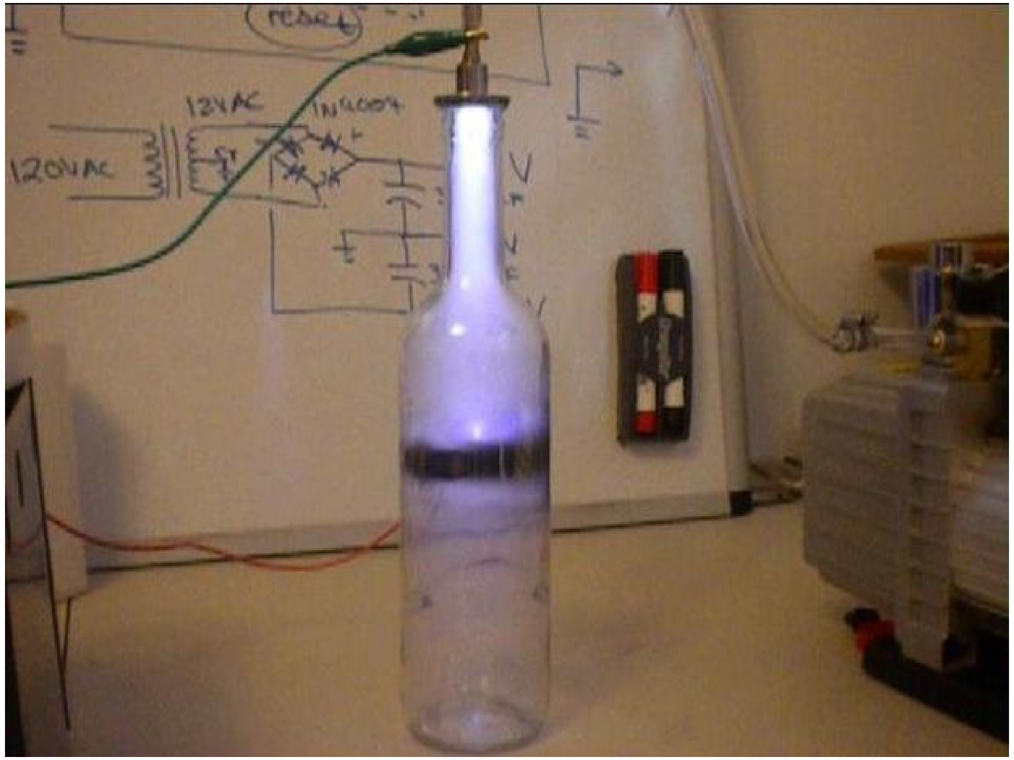
Advantages Over Traditional Processes

- Current technology for the commercial production of acetic acid, methanol, and carbon monoxide requires:
  - High temperatures and pressures
  - Expensive catalysts in multiple process steps
  - High capital and operating costs

- The DEBS process uses **high-energy electron beams** to break chemical bonds, allowing production of the desired chemicals at **near-ambient pressure and temperatures** and has been demonstrated by other research groups at bench-scale.

- Successfully combining DEBS technology with CO_2 captured from coal-fired power plant flue gas provides a low-cost, energy-efficient process to produce valuable chemicals and reduce emissions.

Electron Beam Deposition into Gas



Electron Beam Primer

V = Voltage (eV)

I = Current (amp)

V x I = Power (watt)

1 eV x 1 amp= 1 watt = 1 J/sec

1 eV = 1.602×10^{-19} J

1eV = Kinetic energy of an electron accelerated to 1 volt

Charge of an electron = 1.602×10^{-19} coulombs

1 coulomb = 6.25×10^{18} electrons

Current = Charge/Time

1 amp = 1 coulomb / 1 sec

Electron Beam Primer

500keV & 1.5mA/sq.in. E-Beam on a 1 sq. in. area:

E-Beam power = 750 watt or 750 J/sec

Each electron will have:

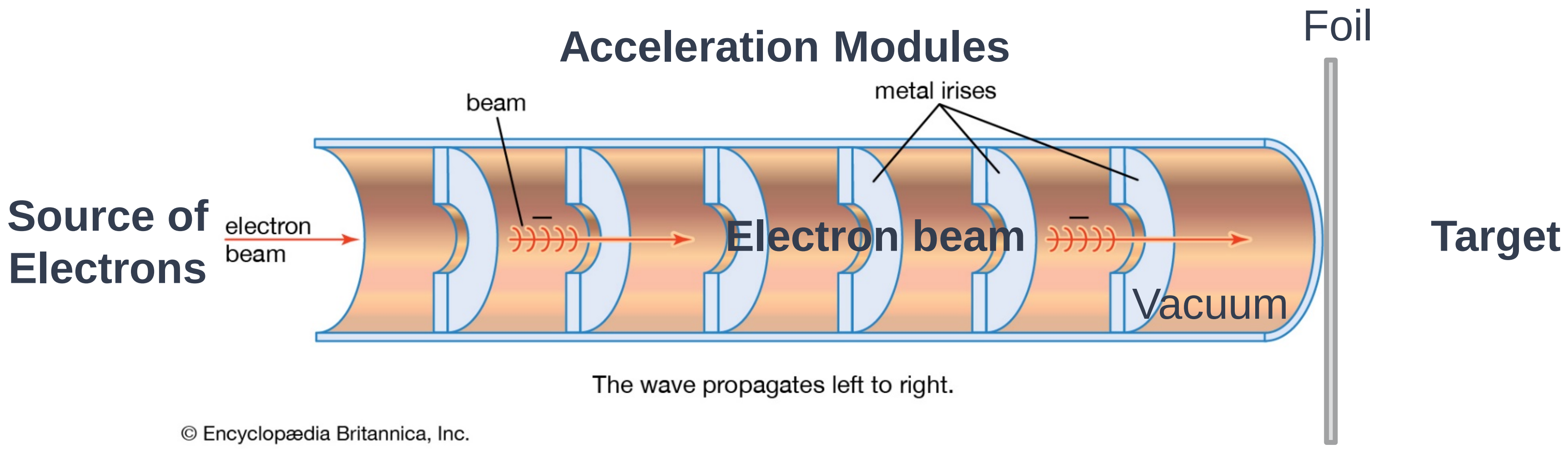
$500,000 \times 1.602 \times 10^{-19} = 8 \times 10^{-14}$ J of energy

E-Beam will have:

$1.5 \times 10^{-3} / 1.602 \times 10^{-19} = 9.3633 \times 10^{15}$ electrons per second

Each electron has the potential to achieve ~100,000 interactions

Industrial Accelerator Design (linear)

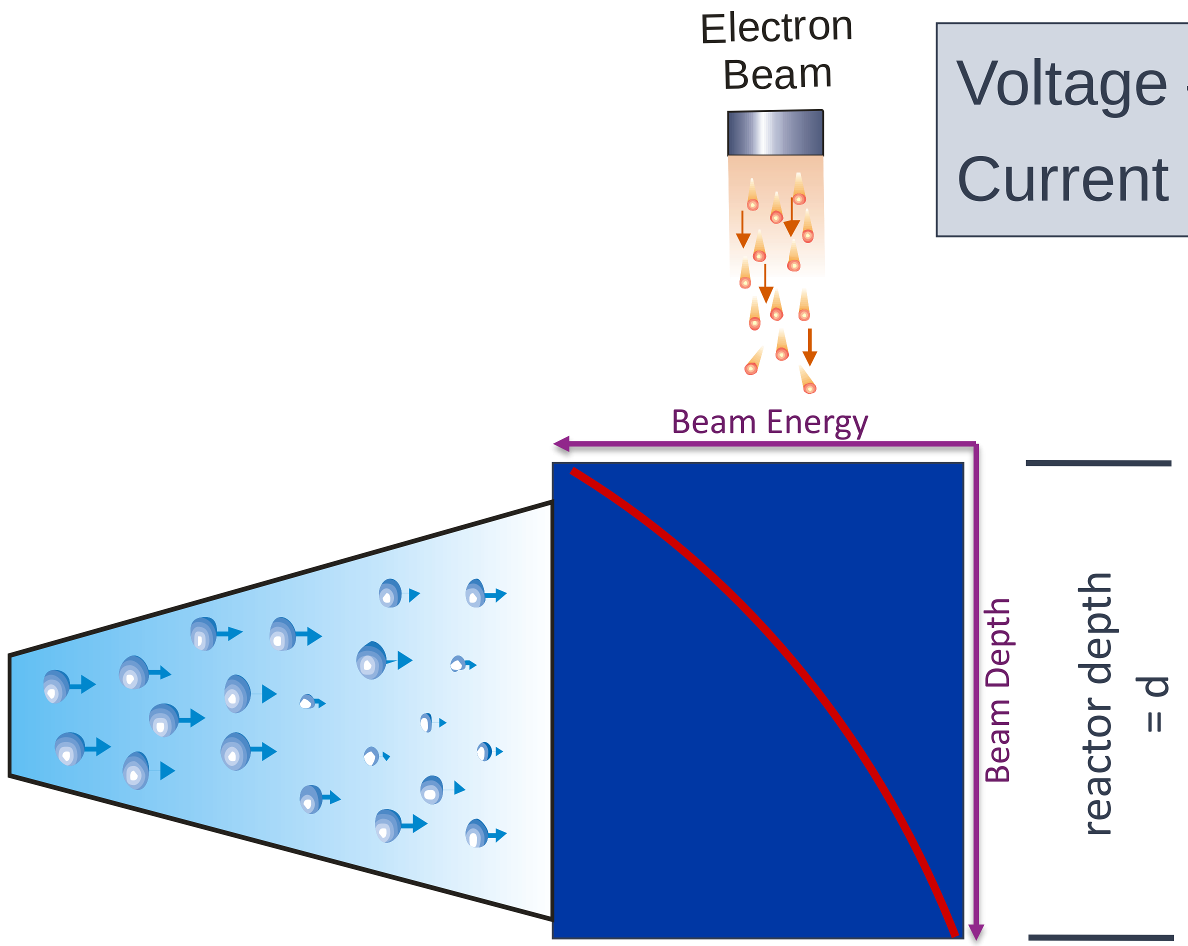


Typical Numbers in range of interest;
450 to 1000 keV
25 to 250 mA
11 - 100 kW[1]
Efficiency: 45 – 60%[2]

Large Scale Industrial Applications;
800 keV
500 mA
400 kW[3]
Efficiency: up to 88%[3]

1. Robert W. Hamm, R&M Technical Enterprises, Inc. 9th ICFA Seminar – October 30, 2008
2. Applied Energetics: http://www.appliedenergetics.com/downloads/product-offerings/nested-high-voltage-generator.pdf
3. Kim et. Al & NHV Japan & Bulgaria Power Plant

Electron Beam Deposition



Voltage – Controls how FAR the electrons will go

Current - Controls how MANY electrons will go

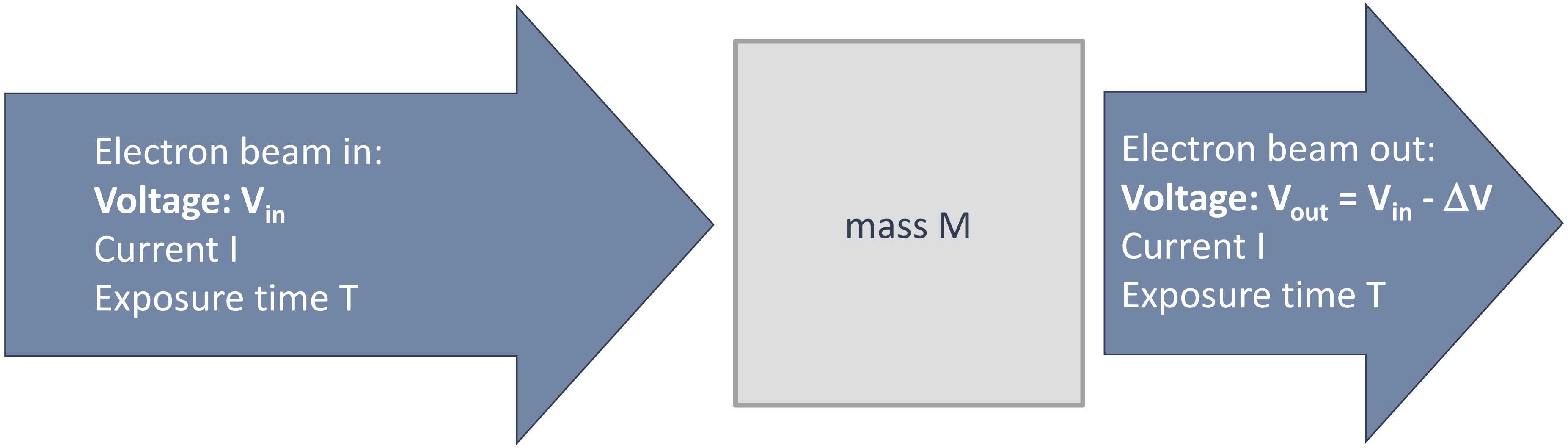
Maximum efficiency occurs when electron beam deposition depth is equal to reactor depth.

Deposition depth depends on these parameters:

- Electron beam voltage
- Gas composition
- Gas pressure (Limited by foil)
- Foil composition and thickness

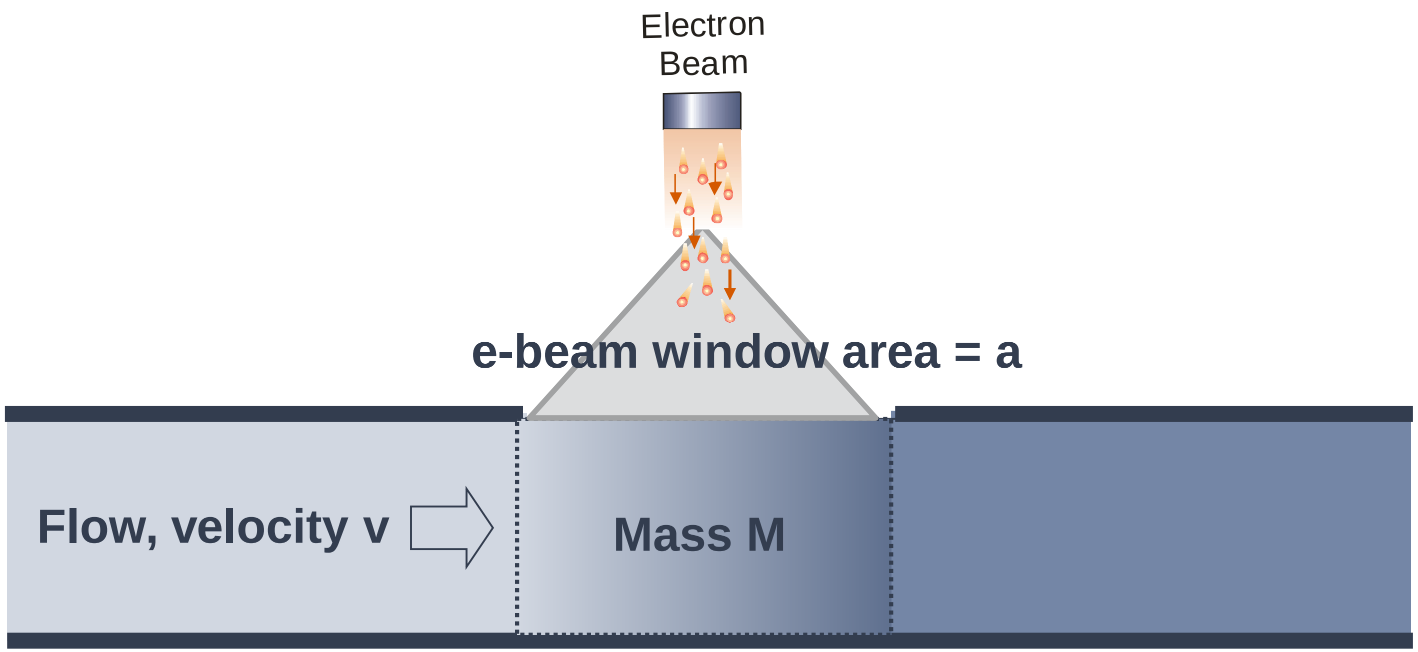
Electron Beam Deposition (continued)

Dose = energy deposited per unit mass
Unit of dose: 1 Joule/kg = 1 Gray



$$Dose = ((V_{in}-V_{out}) \times I \times T) / M$$

Deposition into a Gas Flowing in a Reactor



Dose = (V (potential) × I (current/area) × a (window area) / v (velocity)) / M (mass)

Electron Beam Primer

Bond Dissociation Energies

Bond	ΔHf_{298} (kJ/mol)
C-C	607
C-H	337.2
C-O	1076.5
C=O	749
C≡O	1075

C-H bond energy ~5eV

One 500keV electron can break approximately 100,000 x (5 eV) bonds

Dehydrogenation of CH_x

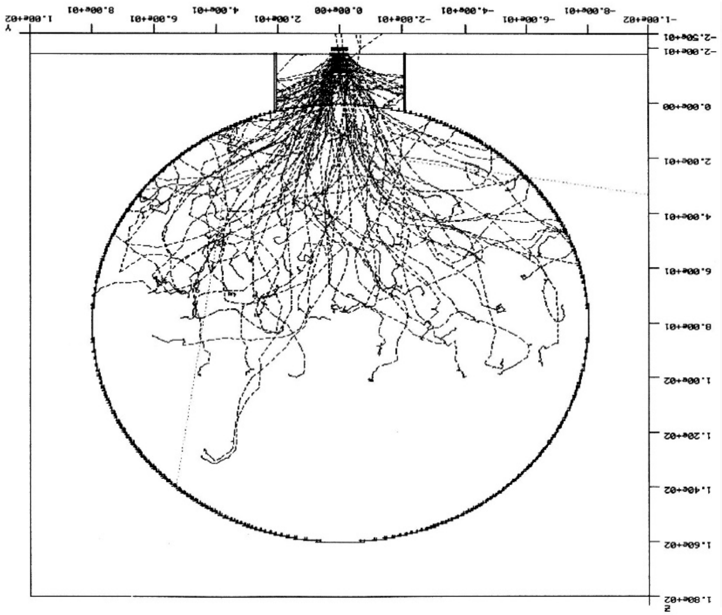
	ΔH (kJ/mol)
$CH_4 \rightarrow CH_3\cdot + H\cdot$	405
$CH_3\cdot \rightarrow CH_2\cdot + H\cdot$	439
$CH_2\cdot \rightarrow CH\cdot + H\cdot$	488
$CH\cdot \rightarrow C + H\cdot$	685
$CH_4 \rightarrow CH_2\cdot + 2H\cdot$	808
$CH_4 \rightarrow C + 4H\cdot$	1266
$CH_2\cdot \rightarrow C + 2H\cdot$	857

Monte Carlo Simulation

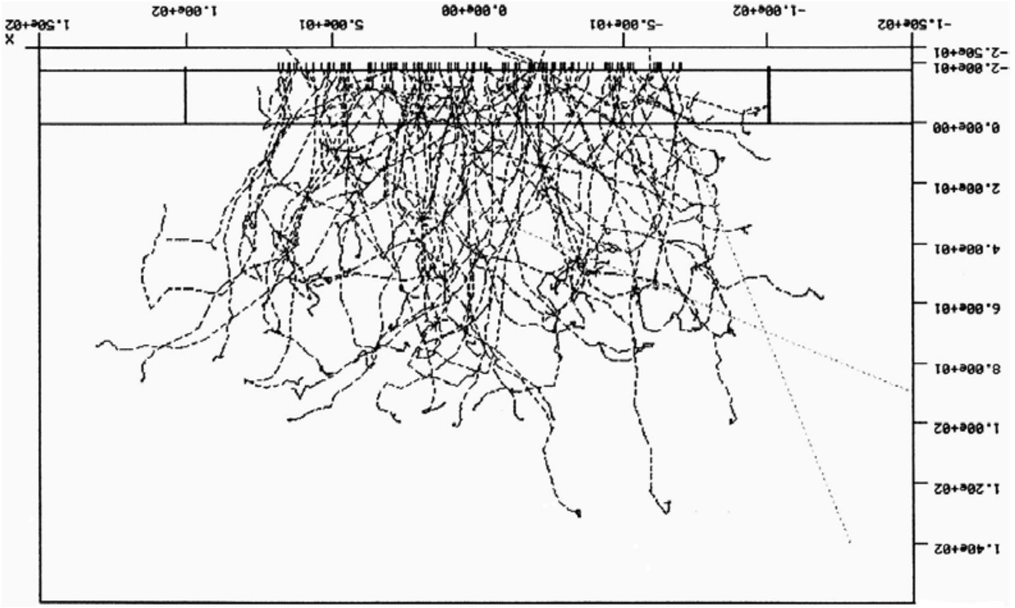
Monte Carlo simulations are used to model the probability of different outcomes in a process that cannot easily be predicted due to the intervention of random variables.

- The electron trajectories are simulated by using a Monte Carlo method.
- Each electron enters the reactor with a given energy, and its trajectory is followed until it comes to rest or exits the reactor.
- To simulate a beam, the process is repeated for a large number of electrons.
- Secondary electrons are generated and tracked within the "fast secondary" model.

Estimation of Electron Paths in Flue Gas Treatment



Y crossection of RV

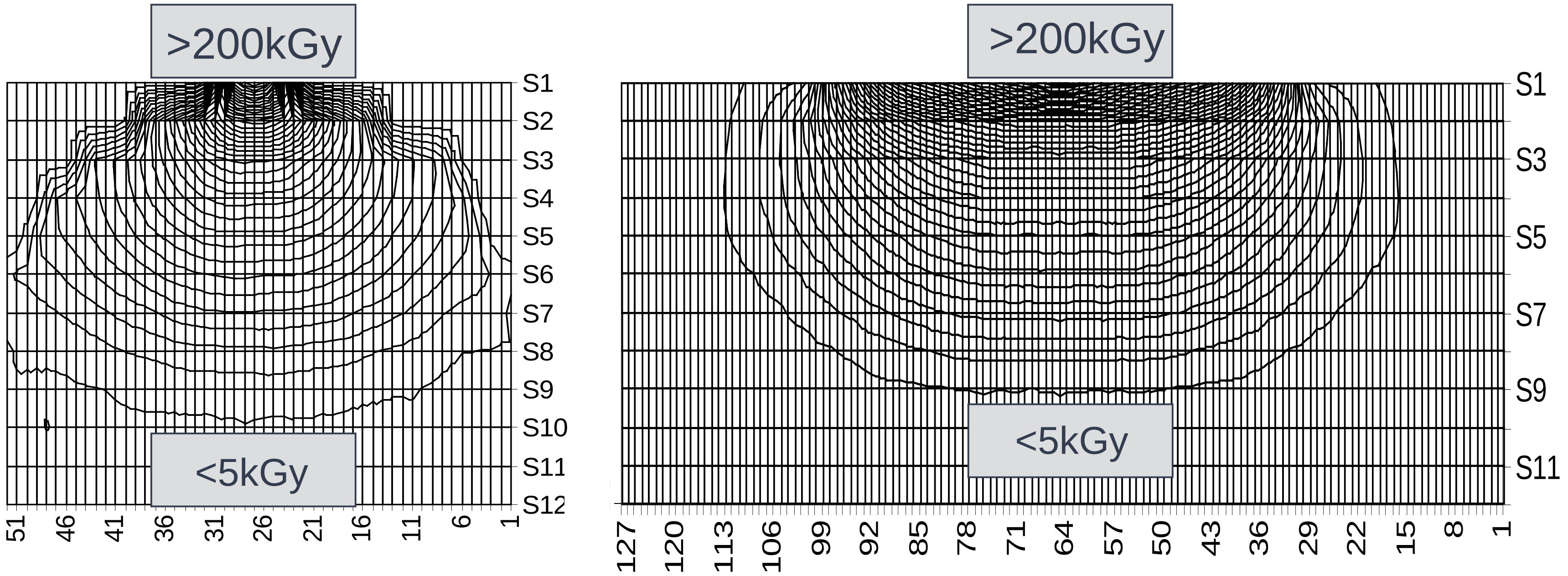


X crossection of RV

Initial electrons energy: 800 keV
Energy cut-off: 1 keV
Results from EGS-4 code calculated at JAERI Takasaki

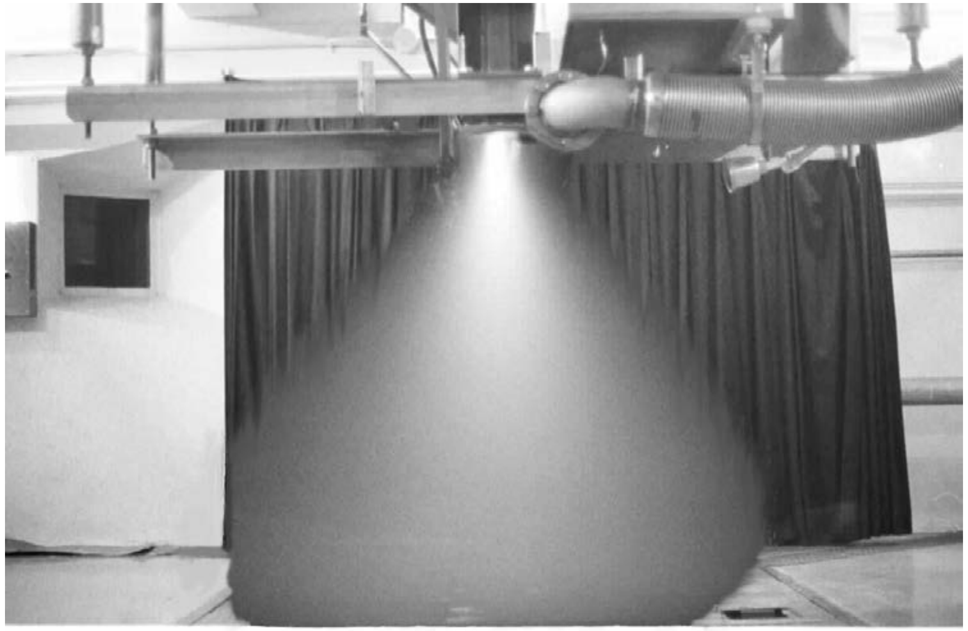
Ref. : Presentation by Sylwester Bułka et al. International Atomic Energy Agency Meeting on Electron Beam Flue Gas Treatment, Warsaw, Poland 14 – 18 May 2007

Dose Maps for Crossections of a Reaction Vessel



Ref. : Presentation by Sylwester Bułka et al. International Atomic Energy Agency Meeting on Electron Beam Flue Gas Treatment, Warsaw, Poland 14 – 18 May 2007

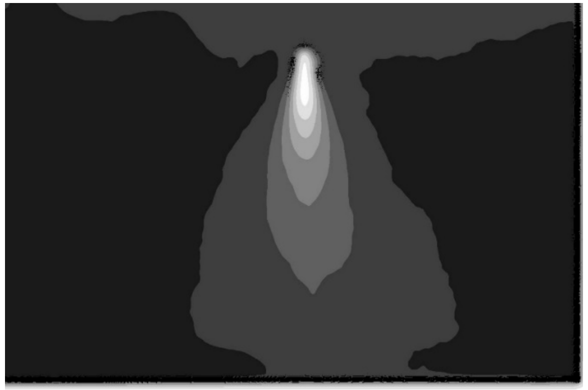
Dose Distribution Visualization



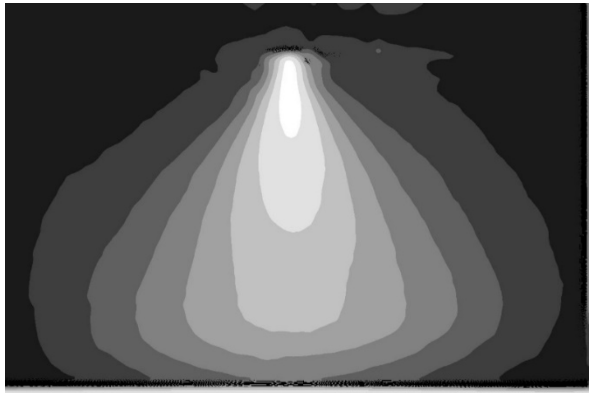
The luminance of air nitrogen within Radiation Field area.

Picture taken at Acc.no 2 JAERI TRCRE

500 keV



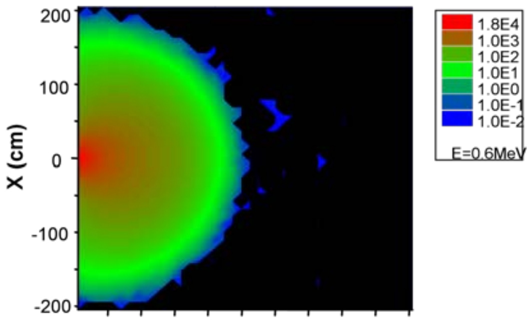
800 keV

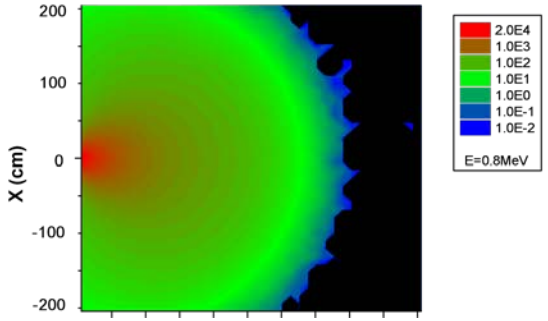


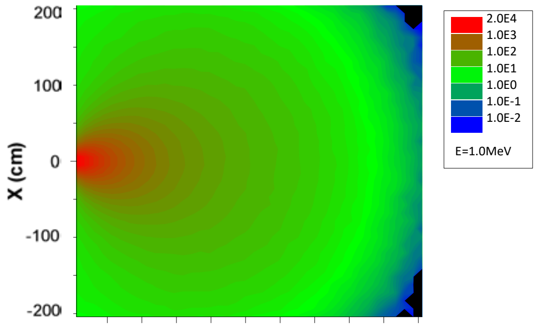
Ref. : Presentation by Sylwester Bułka et al. International Atomic Energy Agency Meeting on Electron Beam Flue Gas Treatment, Warsaw, Poland 14 – 18 May 2007

Determination of Reactor Depth in Flue Gas Treatment

Utilization of E-beam (%)	Depth of Reactor (cm)				
	0.6MeV	0.7MeV	0.8 MeV	0.9MeV	1.0 MeV
85	172	230	263	287	308
90	192	253	291	315	332
95	218	280	325	345	359
96	226	290	336	353	366
97	233	295	344	360	373
98	243	305	356	365	378
99	265	325	374	384	390







Ref. : Mao Benjiang, “Flue Gas Desulphuration and Denitration with Electron Beam Irradiation and Ammonia reagent”, 2005

Technology / Technical approach

Key Experimental Parameters

- E-Beam dose, (kJ/gm)
- Gas residence time in beam and off beam (ms)
- E-Beam energy : 300-500 keV
- Use of a promoter, such as, carbon monoxide
- Use of catalyst(s)

Target Range of E-Beam Dose

- **E-Beam Energy Consumption : kJ/gm of Methane**
- **Estimate based on the heat of reaction for a model reaction (direct production of liquid fuels from methane).**

<u>Example Reaction</u>

> **$8\ CH_4 = C_8H_{18}$ (Isooctane) + $7\ H_2$**

- (Endothermic Heat of Reaction = 2.93 kJ/gm methane)
- H_2 yield ~11.0 wt.% of feed methane

Target Range of E-Beam Dose (continued)

> Experimental Data indicate ~ 4-7 kJ/gm methane (as electrical energy) for E-Beam based pure methane conversion to H_2, C_2-C_4 gases & C_5+ liquid fuels

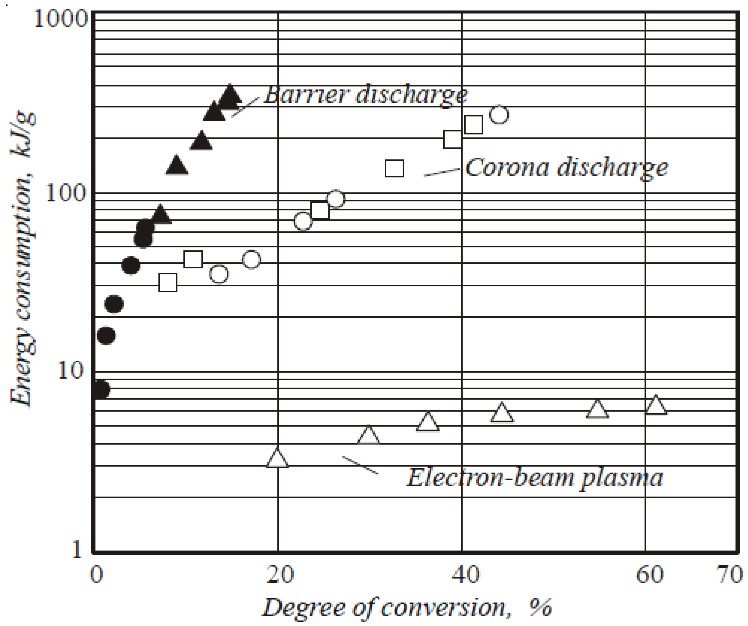


Fig. 1. Energy consumption vs. degree of conversion of methane using different methods of activation: ●, □, △ : 100% CH_4; ○,▲: mixture (1:1) of CH_4 and CO_2.

Ref. : Vinokurov et al., Chemistry & Technology of Fuels and Oils, V-41, #2, 2005

Target Range of E-Beam Dose (continued)

- For a mixture with 50 mol.% CH_4 and 50 mol. % CO_2

  based on the endothermic heat of reaction for

$$CO_2 + CH_4 = CO + CH_3OH$$

  the theoretical energy need would be about 7.7 KJ/gm of methane

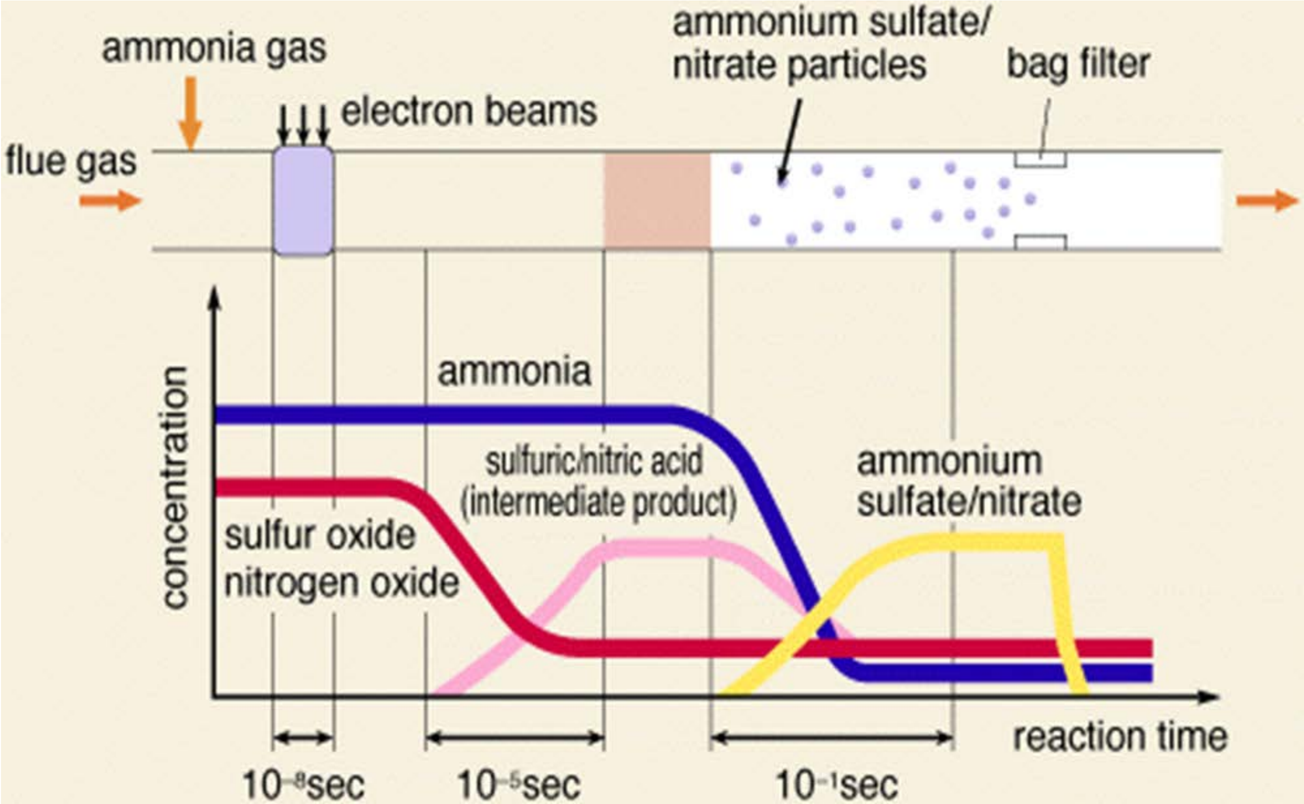
- Assuming 30% E-Beam losses in the reactor, this would be ~11 KJ/gm methane.
- Initially, we can use a target value of ~15 KJ/gm methane feed

E-Beam Plasma-based Chemical Reactions are Ultra-fast

> “Due to very high concentrations of ions, radicals, ion-radicals and other reactive particles in E-Beam plasma, chemical reactions take place at extremely high rates of ~0.01-10 milliseconds”

Ref. : Vinokurov et al., “Plasma-Chemical Processing of Natural Gas”, Chem & Tech. of Fuels and Oils, Vol. 41, No. 2, 2005

Electron Beam Flue Gas Treatment



Schematic diagram of the EBFGT technology

Ref. : Kim et al., “Electron-beam Flue-gas Treatment Plant for Thermal Power Station “Sviloza” AD in Bulgaria”, J. of the Korean Physical Society, Vol. 59, No. 6, December 2011, pp. 34943498

Target Range of Gas Residence Time

For E-Beam based H_2 production from methane, literature data indicates average gas residence time of about 2 milliseconds.

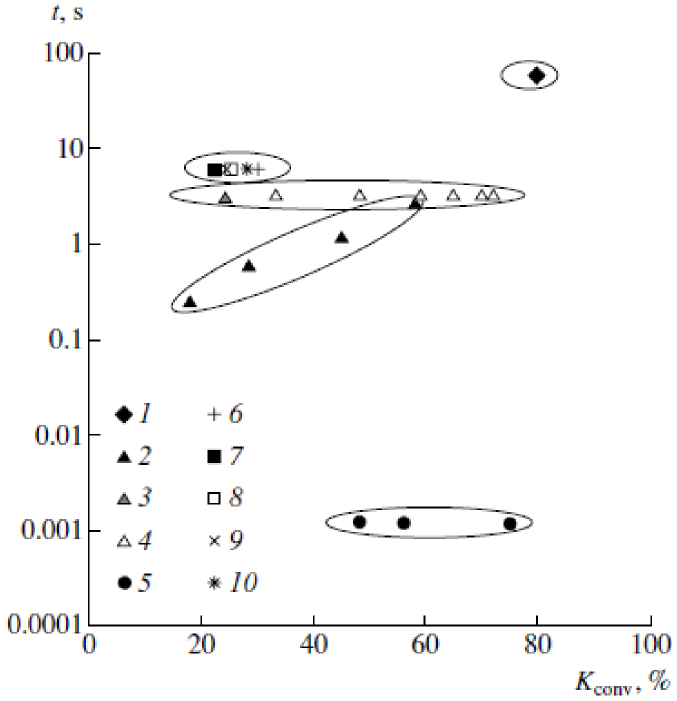


Fig. 2. A plot of the time *t* of gas occurrence in the reactor versus conversion coefficient K_{conv} for various methods of conversion: (*1*) steam conversion; (*2*) streamer discharge [12]; (*3*) barrier discharge [13]; (*4*) barrier discharge [14]; (*5*) this study; (*6–10*) SHS catalysts [15], including MgO (*6*), $LaCaB_6$–MgO (*7*), $SmCaB_6$–MgO (*8*), $LaBaB_6$–MgO (*9*), and $LaCaB_6$–MgO/Mn_3O_4–NaCl (*10*).

Data for H_2 from Methane Residence Time: ~2 ms

Ref. : "H_2 Production from Methane in E-Beam Plasma" ; Sharafutdinov et al., Technical Physics Letter, Vol. 31, 2005

Target Range of Gas Residence Time (continued)

For maximum liquid productions from methane, gas residence time should be about 0.2-1.0 milliseconds.

Gas feed rate, std. liters/min	1	6
H_2 yield (wt. % methane)	23.5	6.7
C_2-C_4 (wt. % CH_4)	8.5	37.7
C_5+ liquids (wt.% CH_4)	none	55.6
Carbon (wt. % CH_4)	68	none

Yield of liquids is favored at lower Gas Residence Times (vs. H_2)

Ref. : Vinokurov et al data, Chemistry and Technology of Fuels & Oils, V-41, #2, 2005

Target Range of Gas Residence Time (continued)

- Literature data for typical gas residence times (or gas velocities) for E-Beam based removal of SO_X/NO_X from power plant flue gas show:

  For pilot plant studies, Williams et al have reported E-Beam reactor gas velocities of about 13-26 meters/second.

- For an experimental E-Beam reactor with a cross-flow interaction of feed gas & E-beam over 3 cc volume & an effective area of 1.5 sq.cm for gas flow, we would need a gas flow of 100 std. liters/min. to allow ~2 ms gas residence time.

  The Gas velocity would be ~11 meters/second.

Ref. : K. Williams et al., “Expts. For Very High Power E-Beam Systems for Utility Stack Gas Treatment”, Rad. Phys. Chem., V-31, #1-3, pp 29-44, 1988.

Target Range of Gas Residence Time (continued)

Vinokurov et. Al. had tested CO_2/CH_4 (1:1 molar ratio) conversion with Corona-discharge and barrier-discharge type plasma.

- ~43% per pass methane conversion with Corona discharge (vs.~15% with Barrier discharge)
- Product liquids contained methanol, formaldehyde, formic acid etc.
- The yield of liquid increased to 52% at 14 liters/min gas flow (vs. 28% at 3 liters/min)
- E-Beam energy need was the lowest with E-Beam conversion of near-pure methane (vs. those with Corona & Barrier discharge)

Target for Promoters

Use of CO as a promoter may increase the selectivity to acetic acid

Mechanism : Koch-Haaf Reaction Initiated by CH_3^+ ions:

$$CH_3^+ + CO = CH_3CO^+ \text{ (plus } H_2O) \Longrightarrow CH_3COOH_2^+$$

As CO would be a product, it can be recycled to the Reactor

With the use of E-Beam, these authors reported higher acetic acid yields at a higher CO_2/CH_4 feed ratios (CO conc. would increase at higher CO_2 contents)

Ref. : H. Arai et al. Zeitschrift fur Phyik. Chemie Neue Folge, Bd 131, S.69-78 (1982)

Limitations of Experimental Approach

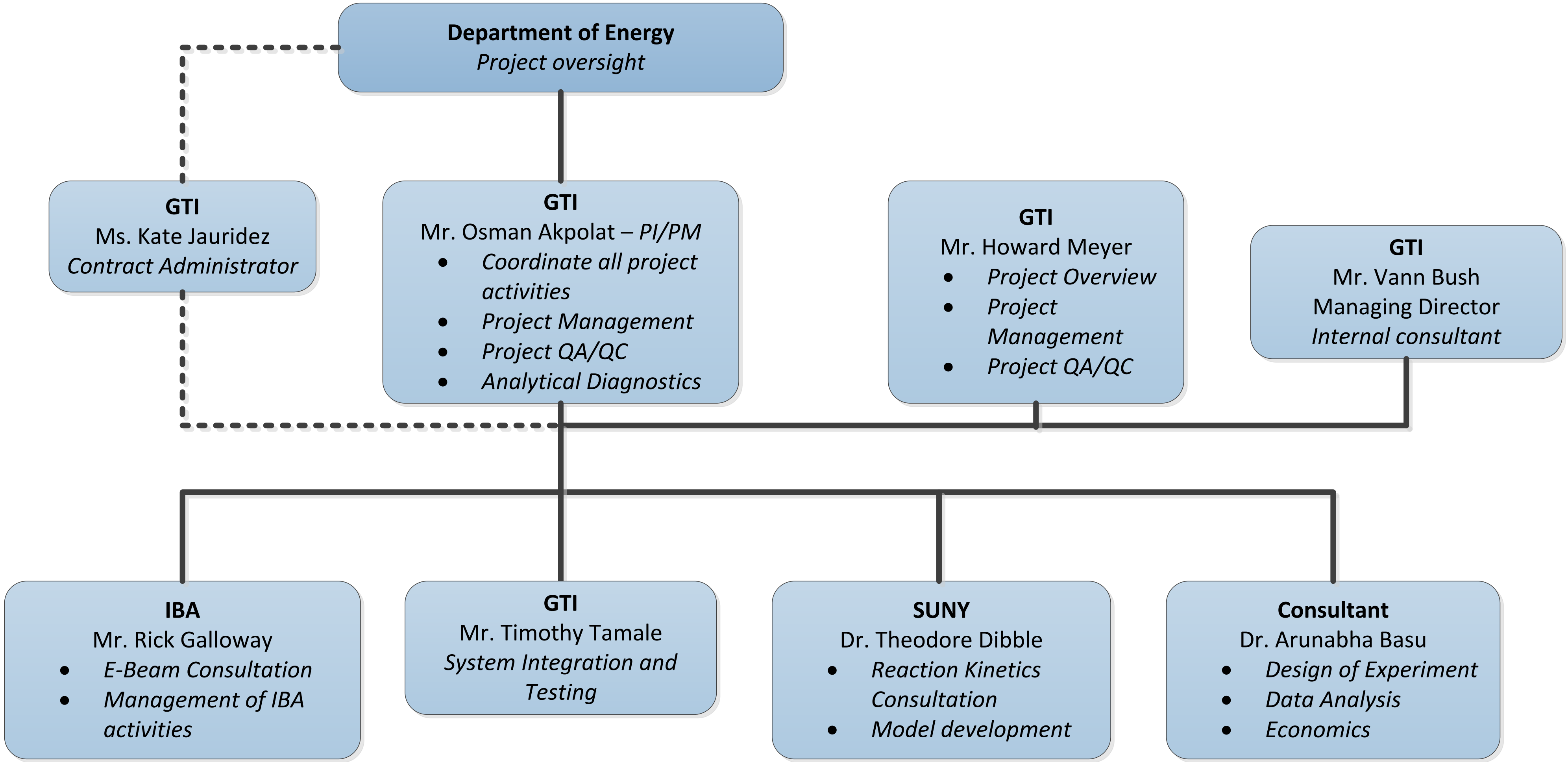
- Reactor size constraints:
  1. Size of Ti-window affects E-Beam dose in the reactor
  2. Volume of reactor affects residence time

- Analytical equipment with detection limit in ppmv

- Duration of experiment to collect enough condensate

Administrative Efforts

Planned Project Team



Project Structure – Task Description

Budget Period 1 and 2

Task 1.0 – Project Management and Planning

- GTI will coordinate and plan the project activities with Team Members at IBA and SUNY. GTI will report technical progress and financial status to DOE/NETL throughout the duration of the project.
- GTI shall coordinate activities in order to effectively accomplish the work and ensure that project plans, results, and decisions are appropriately documented and project reporting and briefing requirements are satisfied.

Go/No Go Decision Point – **Budget Period 2 work under this agreement shall not be authorized without the specific written authorization of the Contracting Officer.**

- Successful completion of all work proposed in Budget Period 1;
- Satisfactory achievement of applicable success criteria as identified in the PMP;
- Submission and approval of a Continuation Application in accordance with the terms and conditions of the award.

Project Structure – Task Description

Budget Period 1

Task 2.0 –Design and Construction of Experimental System

Subtask 2.1 – Reactor Design and Construction

Subtask 2.2 – Test Unit Design and Construction

Subtask 2.3 – Catalyst Selection

Task 3.0 – Start-Up and System Checks at GTI

Task 4.0 –System Commissioning at IBA

Task 7.1 - Develop Preliminary Kinetic Model

Go/No Go Decision Point – Budget Period 2 work under this agreement shall not be authorized without the specific written authorization of the Contracting Officer.

Project Structure – Task Description

Budget Period 2

Task 5.0 - Conduct Parametric Testing

Subtask 5.1: Initial scoping experiments

Subtask 5.2: Co-current flow testing

Subtask 5.3: Parametric testing

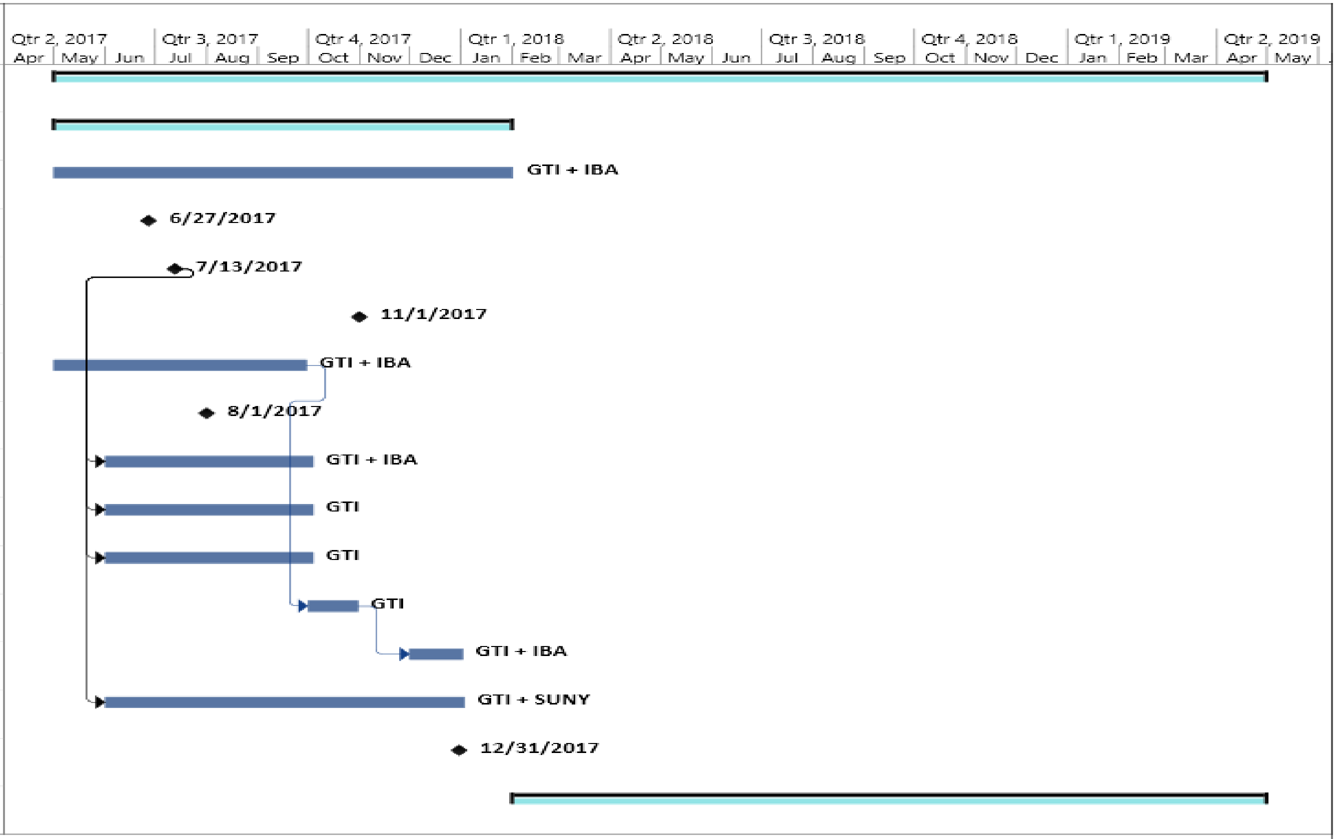
Task 6.0 - Conduct Parametric Testing with Catalyst

Task 7.2 - Develop Kinetic Model

Task 8.0 - Data Analysis, Life Cycle Analysis and Economics

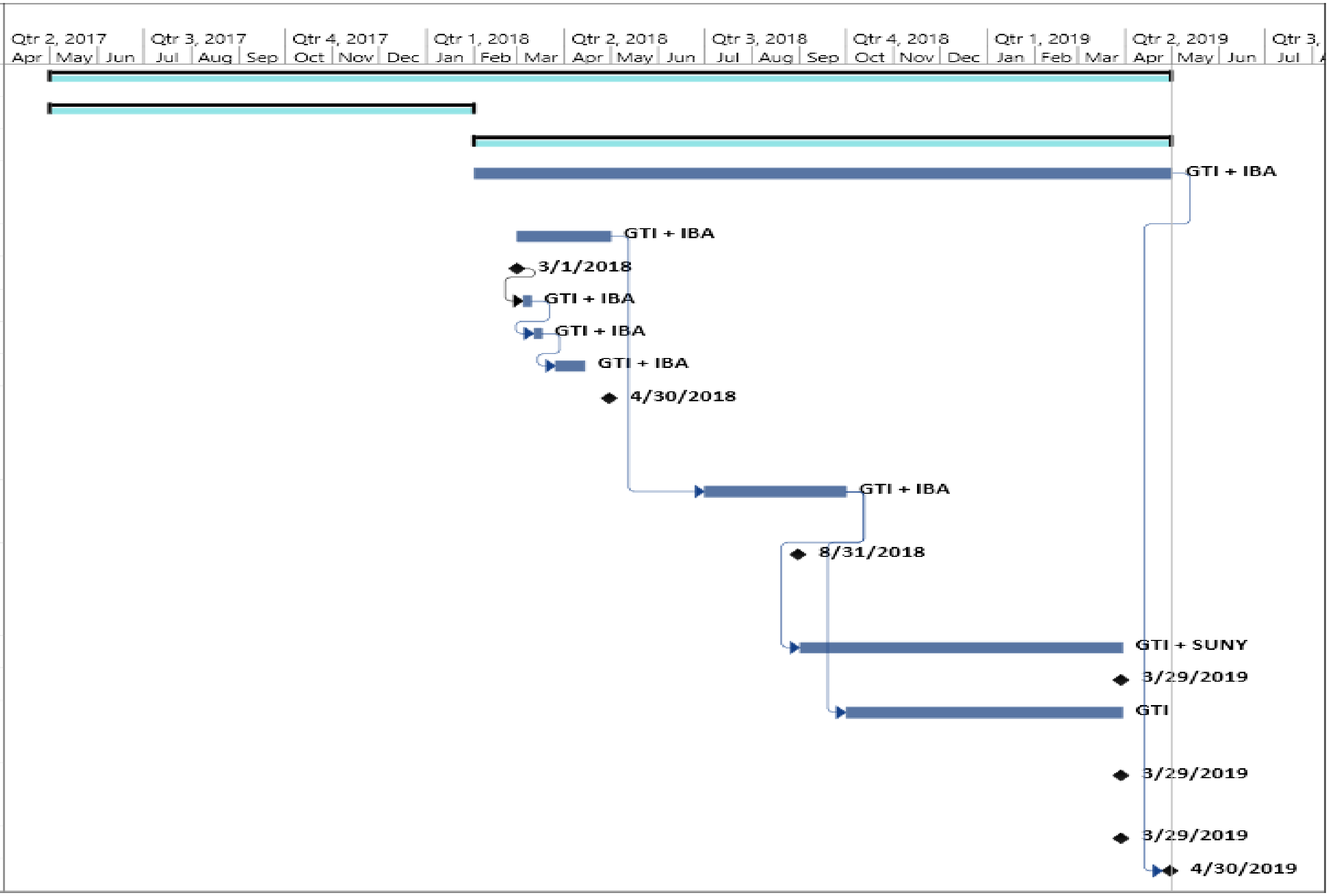
Project Schedule – Budget Period 1

ID	Task	Milestone Number	Task Name
1			**Project Total**
2			**Budget Period 1**
3	1.1		Project Management and Planning (BP1)
4		1.1	Update Project Management Plan
5		1.2	Kickoff Meeting
6		1.3	Submit Continuation Application
7	2.0		Design and Construction of Experimental System
8		2.1	Complete Final Design
9	2.1		Reactor Design and Construction
10	2.2		Test Unit Design and Construction
11	2.3		Catalyst Selection
12	3.0		Start-Up and System Checks at GTI
13	4.0		System Commissioning at IBA
14	7.1		Preliminary Kinetic Model
15		7.1	Develop Preliminary Kinetic Model
16			**Budget Period 2**



Project Schedule – Budget Period 2

ID	Task	Milestone Number	Task Name
1			**Project Total**
2			**Budget Period 1**
16			**Budget Period 2**
17	1.2		Project Management and Planning (BP2)
18	5.0		Conduct Parametric Testing
19		5.1	Start Parametric Testing
20	5.1		Initial scoping experiments
21	5.2		Co-current testing
22	5.3		Parametric testing
23		5.2	Determine key operating parameters that would maximize per pass CO2 conversion
24	6.0		Conduct Parametric Testing with Catalyst
25		6.1	Identify Operating conditions and Catalyst Combinations for Chemical Production
26	7.2		Develop Kinetic Model
27		7.2	Develop Kinetic Model
28	8.0		Data Analysis, Life Cycle Analysis and Economics
29		8.1	Report Analysis of Experimental Data
30		8.2	Complete Economic Analysis
31		1.4	Submit Final Technical Report



Budget – Project Funding Profile

	Budget Period 1		Budget Period 2		Total Project	
	05/01/2017-01/31/2018		02/01/2018-04/30/2019			
	Government Share	Cost Share	Government Share	Cost Share	Government Share	Cost Share
Gas Technology Institute	$150,763	$0	$221,811	$0	$372,574	$0
IBA	$50,000	$65,000	$276,000	$141,000	$326,000	$206,000
State Univ of NY	$25,000	$0	$50,000	$0	$75,000	$0
Dr. Arunabha Basu	$16,623	$0	$9,800	$0	$26,423	$0
Total	**$242,386**	**$65,000**	**$557,611**	**$141,000**	**$799,997**	**$206,000**
Cost Share	79%	21%	80%	20%	80%	20%

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