



METHANE ASSISTED CATALYTIC CONVERSION OF HEAVY CRUDES

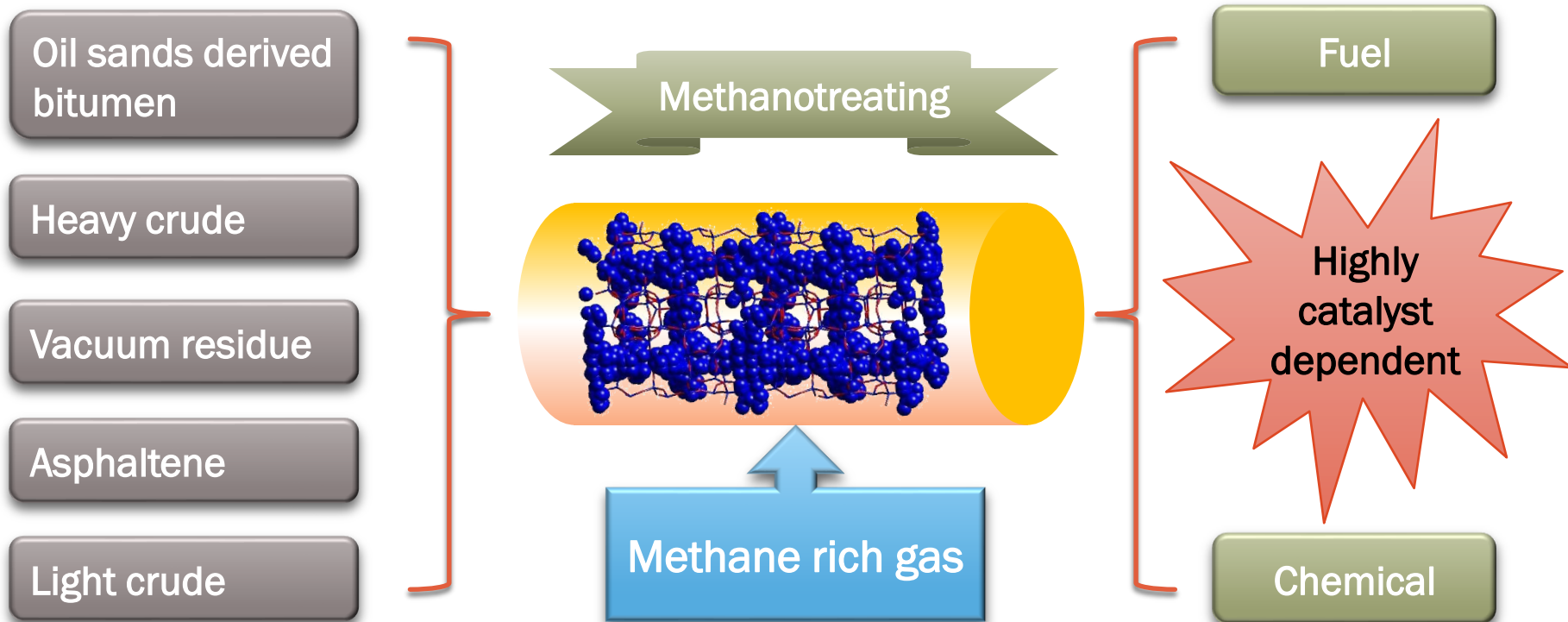
- Highly feed and product flexible
- Dramatic cost saving
- Significant CO₂ emission reduction

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Green Catalysis Research Group (website: <http://ucalgary.ca/gcrg/>)

TECHNOLOGY HIGHLIGHTS



- ❖ A wide variety of petroleum-based feeds ranging from the lightest like naphtha to the heaviest such as asphaltene can be readily upgraded to high value-added fuel or chemicals through a novel catalytic process under methane rich environment with a simple but robust fixed bed configuration.
- ❖ Depending on the charged low-cost catalyst, the highly customized product stream can be formed, which can be simply further refined for end use.

GROUP INTRODUCTION

❖ Green Catalysis Research Group (GCRG) is established in Calgary, Canada in July 2012. GCRG has successfully educated more than 80 highly qualified personnel and disseminated more than 70 peer-reviewed journal articles, 30 patents and 5 book and book chapters. GCRG has grown its research interests in **heterogeneous catalysis** and its applications in **clean energy conversion** and **environmental control** including the following ongoing projects:

- **Heavy oil upgrading using natural gas**
- Light olefin upgrading using natural gas
- Low-cost carbon source pyrolysis under natural gas
- Municipal solid wastes utilization
- Low temperature NO_x control
- Natural gas storage for vehicular application
- H₂ production from low-cost carbon sources



RESEARCH CAPACITY

- Our research facilities are well accommodated in a lab space of ~120 m² fully equipped with state-of-the-art infrastructure and instruments (~ \$ 6.5 million CAD).

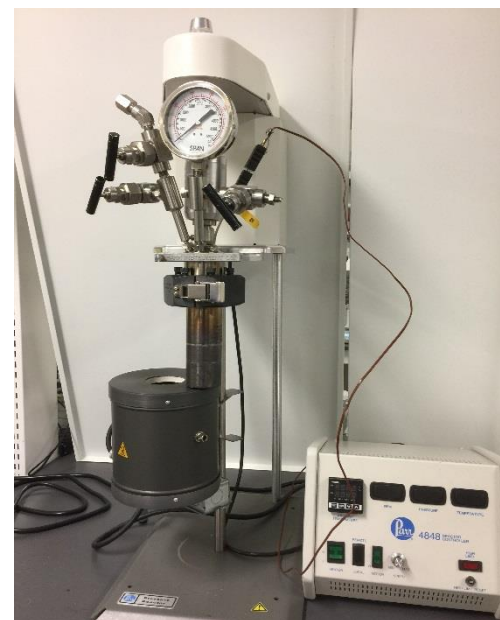
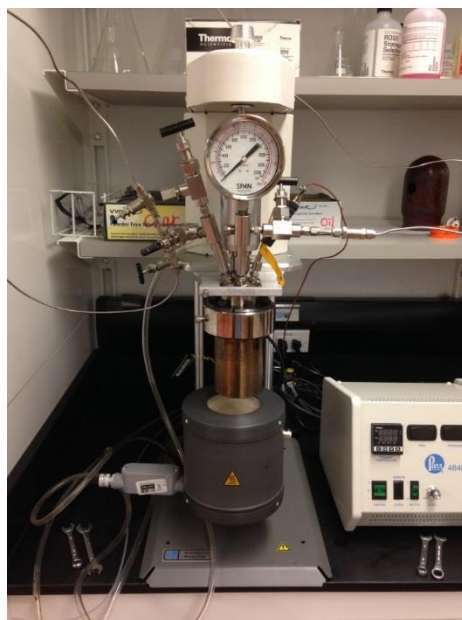


RESEARCH FACILITIES – REACTOR SYSTEMS

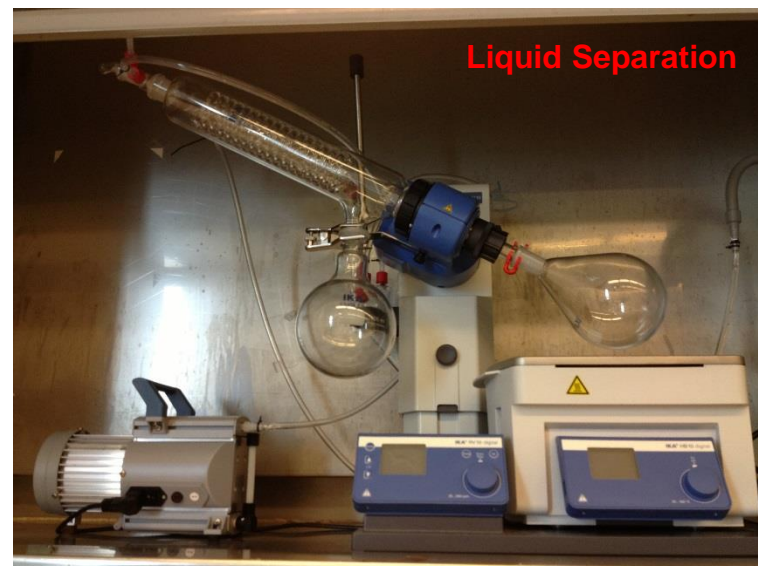
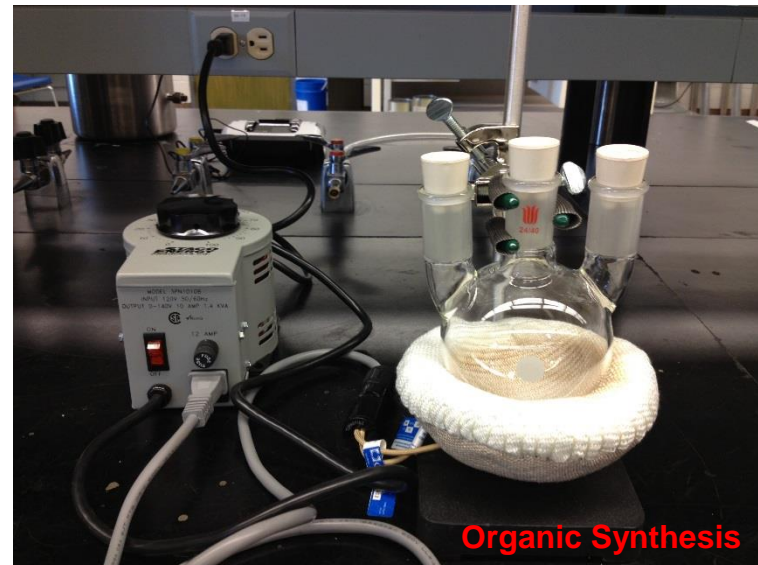
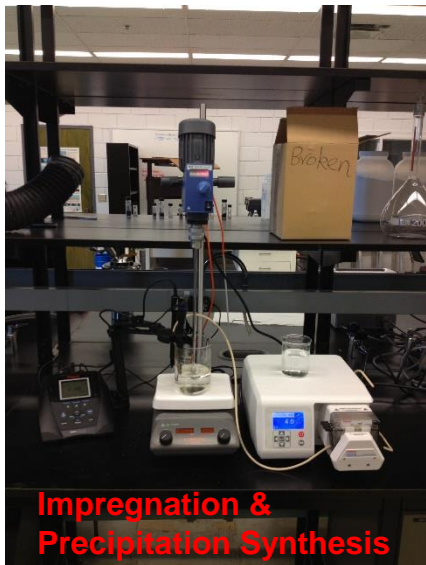


Two continuous reactor systems with pressure rating from 0.1 to 10 MPa, temperature range of 25 ~ 1200 °C, and gas velocity of 0 ~ 1,000,000 hr⁻¹, liquid flow rate up to 10 mL/min.

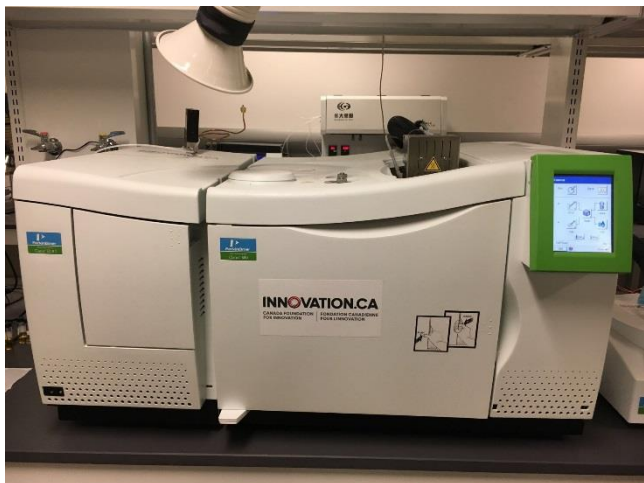
Five batch high temperature, high pressure batch reactor systems with capacity of 100, 300, and 500 mL.



RESEARCH FACILITIES – CATALYST SYNTHESIS EQUIPMENT



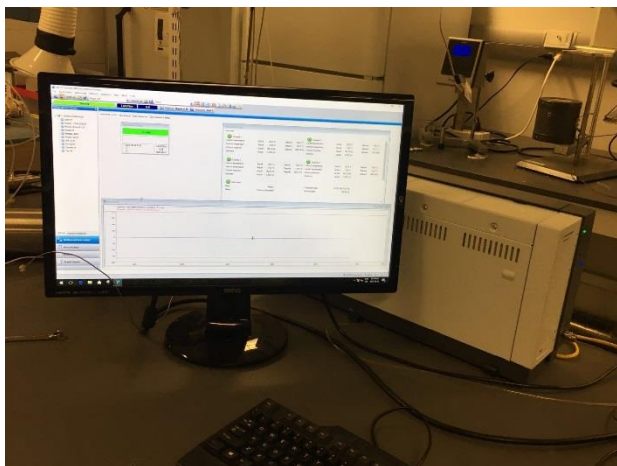
RESEARCH FACILITIES – SAMPLE CHARACTERIZATION INSTRUMENTS



GC-MS



FTIR with in-situ chamber and gas cell



Micro-GC

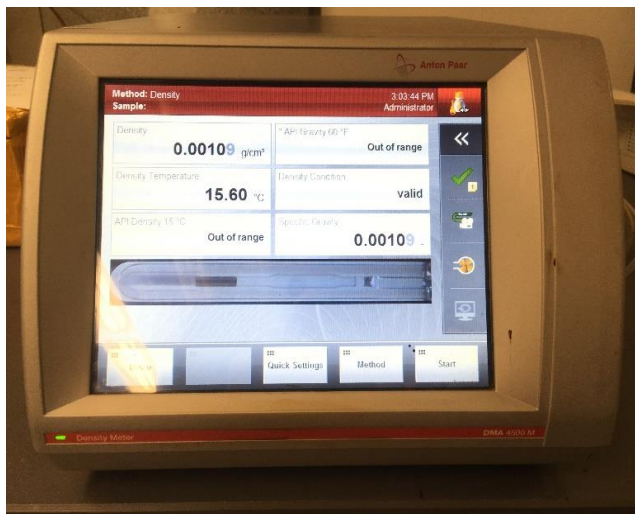


Gas pycnometer

RESEARCH FACILITIES – SAMPLE CHARACTERIZATION INSTRUMENTS



ICP-OES



Density Meter



Spot tester



Extraction-Distillation Apparatus



Computational Workstation



Micro-GC for field operation

RESEARCH FACILITIES – SAMPLE CHARACTERIZATION INSTRUMENTS



Vapor
pressure
osmometer



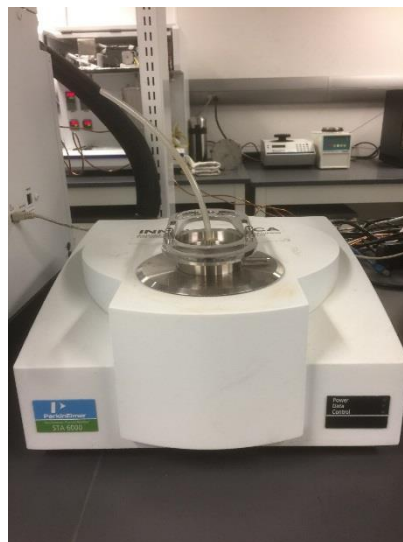
TAN/Br No.
titrator



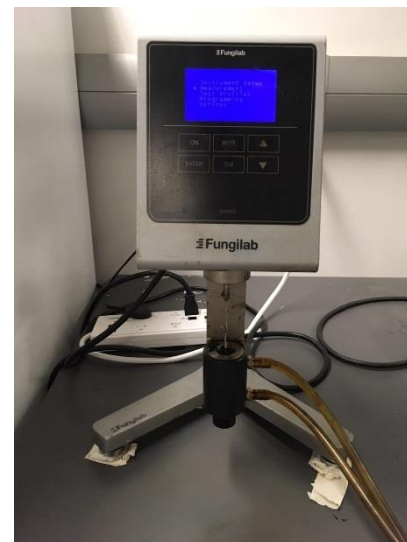
KF titrator



Simulated
distillation
analyzer



TGA-DSC



Viscometer

RESEARCH FACILITIES – SAMPLE CHARACTERIZATION INSTRUMENTS



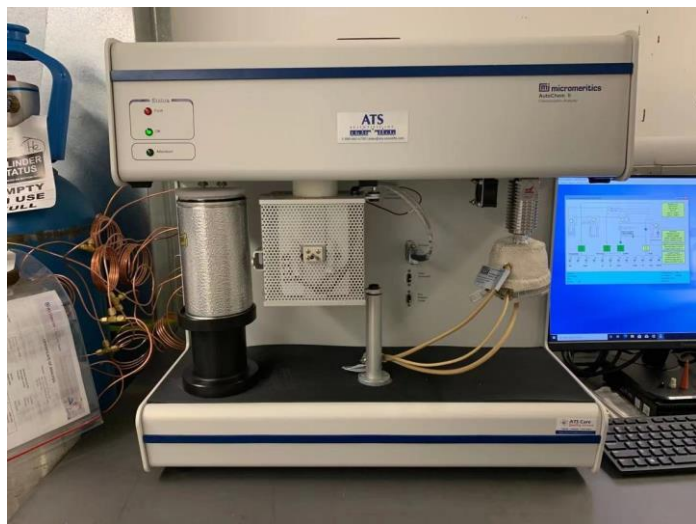
Surface Area and Porosimeter System



UV-Vis Spectrometer



Online Mass Spectrometer



Chemisorption System (AutoChem II 2920)

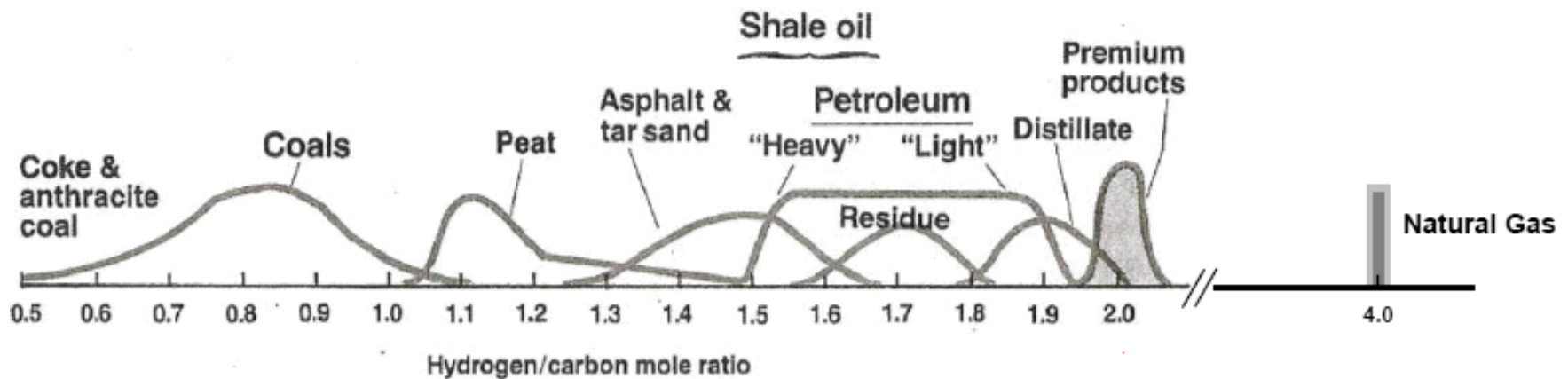


Benchtop XRD (Bruker D2 PHASER)

BACKGROUND INTRODUCTION

Heavy crude

- ❑ long carbon chain (> 30) with complicated molecular structure (e.g. polyaromatics)
- ❑ high viscosity ($1 \times 10^3 - 2 \times 10^6$ cP)
- ❑ High impurity content (e.g., Heavy metals, S, N)
- ❑ low H/C molar ratio



UNSATURATION FORMATION

❖ Heavy oil cracking

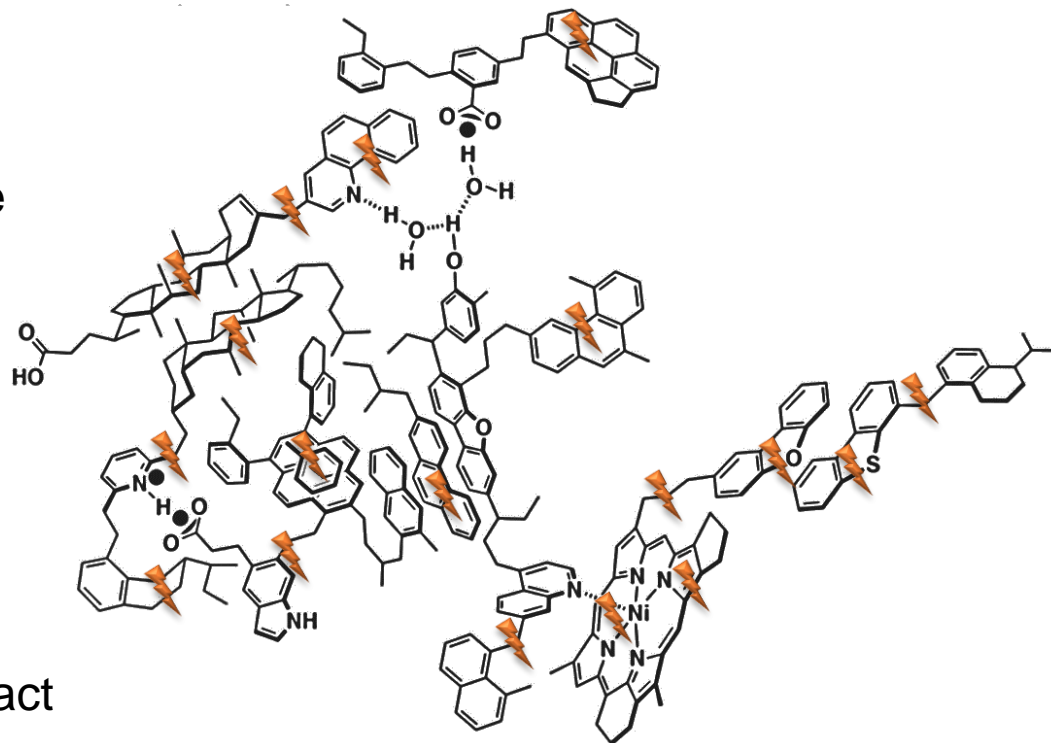
- ❑ Reduce carbon chain length
- ❑ Break polyaromatic structure
- ❑ Lower viscosity
- ❑ Produce unsaturated bonds

❖ Problems induced

- ❑ Thermal instability
- ❑ Incomplete combustion
- ❑ Negative environmental impact
- ❑ Clogging during pipeline transportation

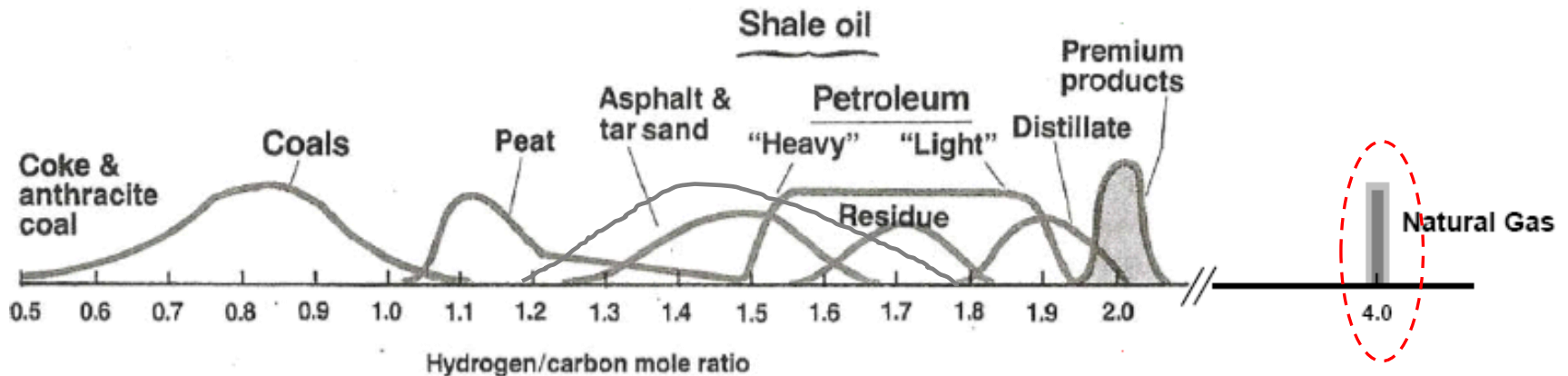
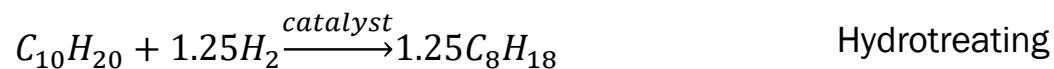
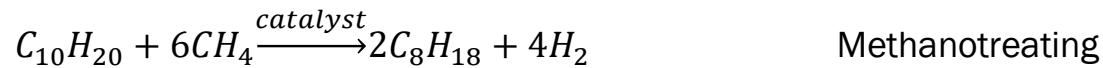
❖ Saturation by adding H₂

- ❑ High pressure
- ❑ Availability

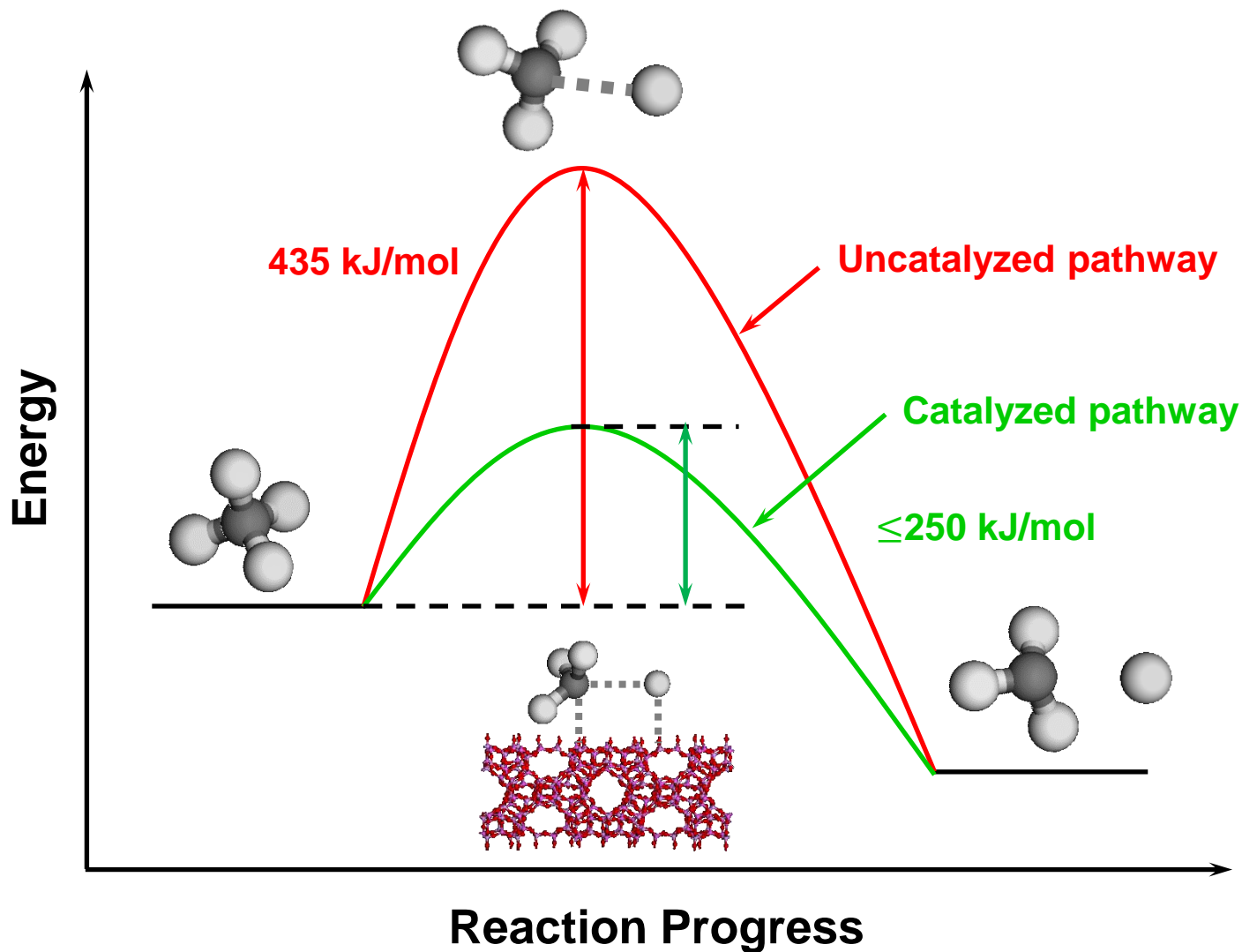


ADVANTAGE OF METHANOTREATING

- ❖ The usage of cheap and abundant natural gas as the upgrading agent rather than H₂ significantly reduces the consumption of H₂, resulting in the notable reduction of operation cost and CO₂ emission.
- ❖ Operation pressure might be significantly lowered during methanotreating (<5 MPa), resulting in notably reduced capital and operation cost.
- ❖ Extra liquid products will be formed due to the participation of natural gas.
- ❖ Hydrogen might be formed as valuable byproduct, depending on the saturation degree of cracked distillates.

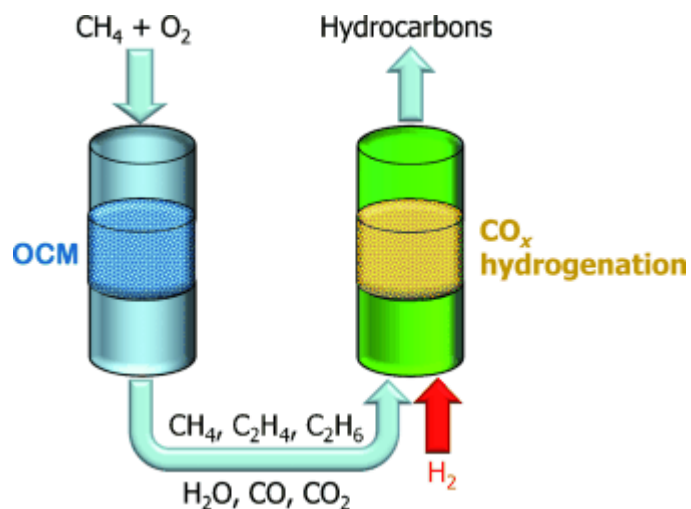


CHALLENGE OF METHANE ACTIVATION

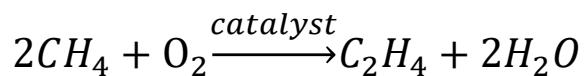


CURRENT RESEARCH STATUS

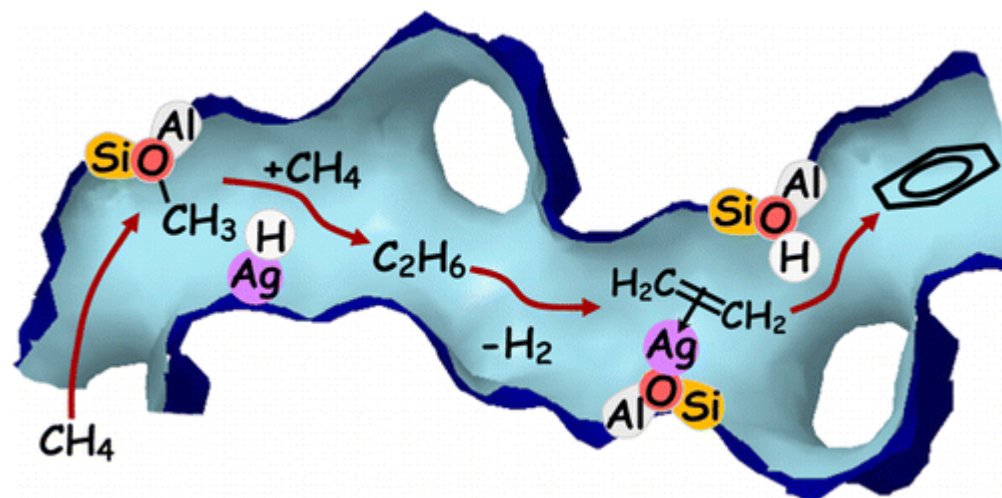
Oxidative Methane Activation



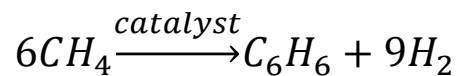
E. Kondratenko, et al., ChemCatChem, 2013, 5 (3), 697



Nonoxidative Methane Activation



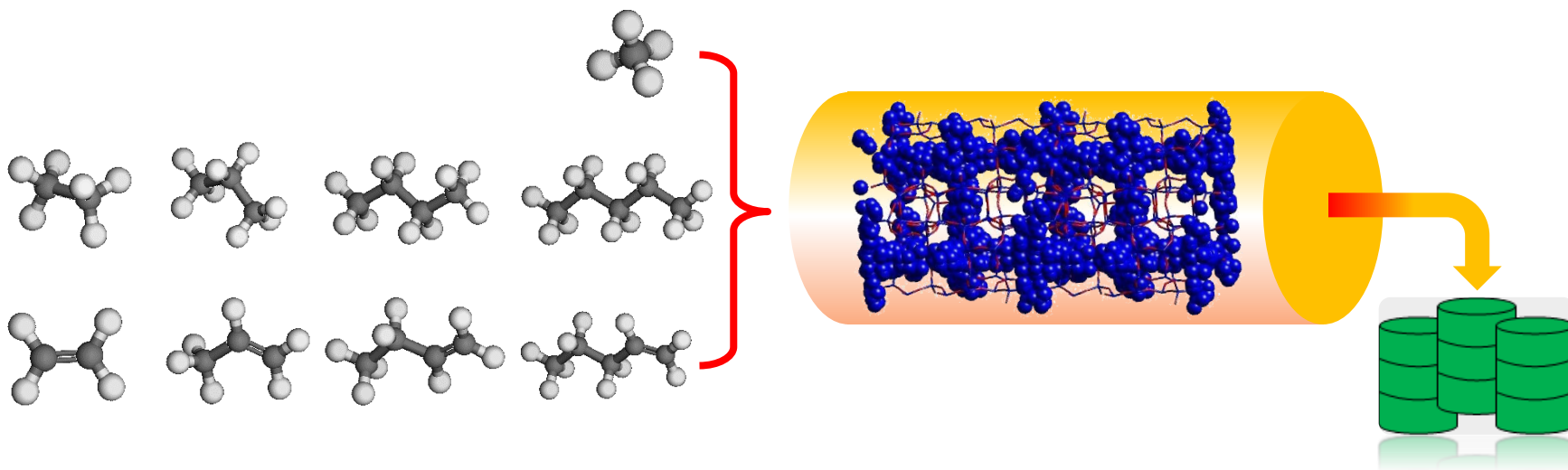
A. Gabrienko, et al., J. Phys. Chem. C, 2013, 117 (15), 7690



- ❖ Severe reaction conditions have to be employed to overcome activation barrier.
- ❖ Specially tailored catalyst has to be present to lower down the activation energy.
- ❖ No effective catalyst has been identified until now for methane activation.

THEORETICAL METHODOLOGY

- ❖ Methane can be more easily activated in the presence of higher hydrocarbons especially unsaturated hydrocarbons^[1] and even oxygenated hydrocarbon like alcohol^[2] and converted to liquid at temperature of 400 ~ 600 °C and atmospheric pressure.
- ❖ The synergetic effect should happen when natural gas reacts with naturally available fuels like coal, biomass, and heavy crude oil.
- ❖ The addition of steam or originally present moisture will further facilitate methane activation^[3].

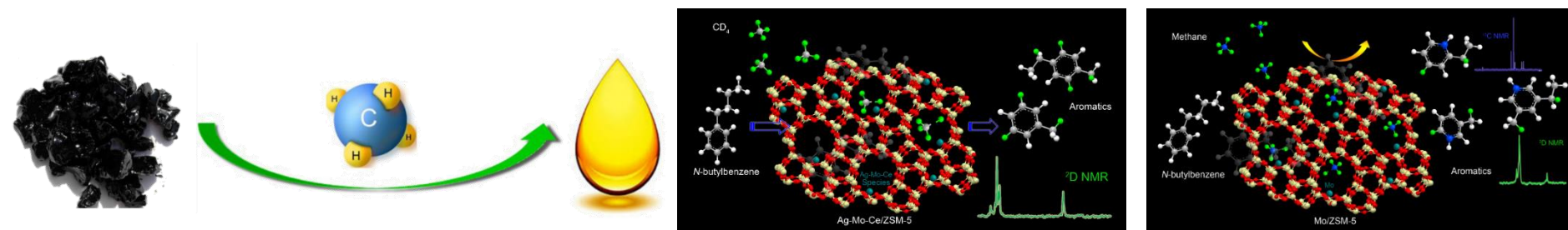


¹ Choudhary, V.R.; Kinage, A.K.; Choudhary, T.V. *Science* **1997**, 275, 1286-1288

² Choudhary, V.R.; Mondal, K.C.; Mulla, S.A.R. *Angew. Chem. Int. Ed.* **2005**, 44, 4381-4385

³ Ovelles, C.; Hamana, A.; Rojas, I.; Bolívar, R. *Fuel*, **1995**, 74, 1162-1168

ACHIEVEMENTS IN BITUMEN UPGRADING AT LAB SCALE



Upgrading Performance and Liquid Product Properties

Oil Sample	Viscosity (cP)	Coke Yield (wt.%)	H/C Atomic Ratio	G&D Fraction (wt.%)	Asphaltene Content (wt.%)	Density (g/cm ³)	Molecular Weight (g/mol)	TAN (mg KOH/g)
Bitumen	848,080	---	1.52	12.15	22.04	1.0275	700	2.59
N ₂	2083	0.60	1.53	27.69	16.81	0.9957	527	0.51
CH ₄	1617	0.55	1.51	30.69	16.15	0.9871	541	0.24
N ₂ + Catalyst	1276	0.86	1.58	32.47	12.32	0.9755	468	0.39
CH ₄ + Catalyst	278	0.80	1.72	43.51	9.48	0.9523	289	0.02

- ❖ Upgrading of bitumen under methane environment is technically feasible at lower pressure when suitable catalyst is charged.
- ❖ Incorporation of methane molecule into carbon chain of upgraded oil was experimentally evidenced.
- ❖ Compared to thermal cracking, methanotreating can obtain more upgraded oil with better quality.

ACHIEVEMENTS IN HEAVY CRUDE UPGRADING AT LAB SCALE

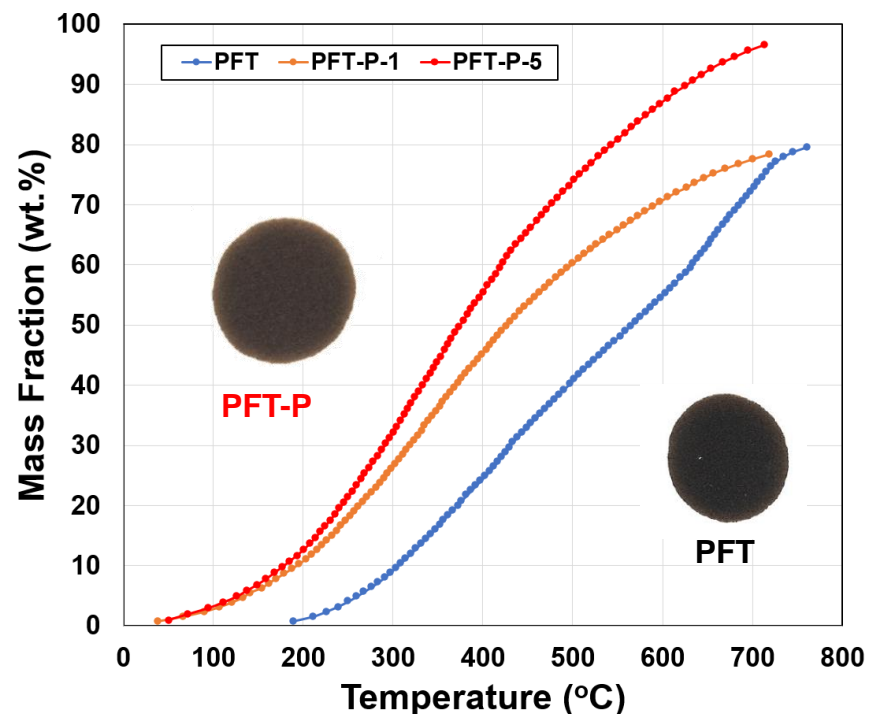
Oil Sample	Upgrading Performance and Liquid Product Properties							
	Coke Yield (wt.%)	Viscosity (cP @ 60 °F)	Olefin content (wt.%)	Density (API °)	Density (g/cm ³)	Asphaltene Content (wt.%)	TAN (mg KOH/g)	Stability (ASTM D4740)
Crude A	---	1,203	BDL [#]	16.7	0.954	16.2	1.21	1
Product A	0.10	56	2.4	22.8	0.916	4.2	0.85	1
Crude B	---	2,249	BDL	15.6	0.961	17.7	2.09	1
Product B	0.20	98	2.3	22.4	0.918	12.7	1.00	1
Crude C	---	7,770	BDL	13.6	0.974	19.9	2.08	1
Product C	0.50	45	1.9	19.4	0.937	10.3	0.88	1
Crude D	---	89,628	BDL	12.0	0.985	24.7	3.03	5
Product D	1.80	143	2.0	16.3	0.956	8.3	0.79	1
Crude E	---	110,000	BDL	12.3	0.983	23.2	2.96	5
Product E	0.90	658	2.1	16.1	0.957	9.3	1.05	1

Reaction conditions: 400 °C, 30 bar CH₄, 40 mins with 1 wt.% catalyst HOU-3

[#]Below detection limit

CATALYTIC UPGRADING OF EXTRA HEAVY CRUDE FROM PFT UNIT

Properties	PFT	PFT-P-1	PFT-P-5
Viscosity(15.6°C) /cP	125,769	185±4	109±5
Density (15.6°C) /g/ml	0.998	0.973	0.965
Liquid Yield / wt%	N.A.	95.4	93.3
Gas Yield / wt%	N.A.	4.0	5.54
TAN (mg KOH/g)	3.22	0.52	0.17
Olefin Content / wt%	0.054	0.152	0.342
Gasoline content /wt%	0	5.6	8.2
Diesel content /wt%	6.3	34.5	41.5
AMW / g/mol	617	400	317
Solid Content / %	0.76	0.7	0.68
Coke Yield / %	N.A.	0.15	0.80
Sulfur Content / %	4.36	2.86	1.97
Asphaltene Content / wt%	6.45	2.5	1.5

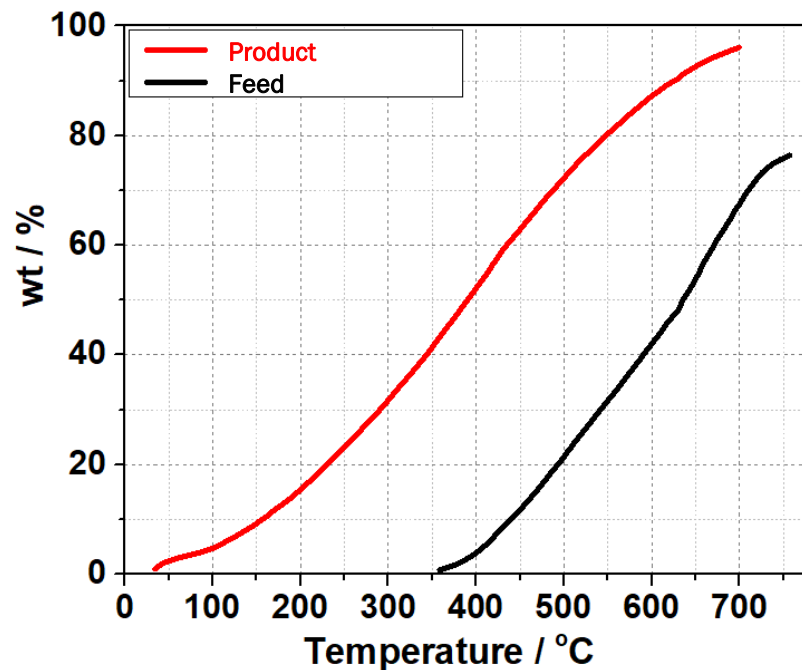


- ❖ Our technique can also effectively upgrade extra heavy crude like the one derived from paraffinic froth treatment process.
- ❖ Better upgrading performance can be achieved at lower space velocity.

Reaction conditions: 400 °C, 5 bar N₂, 25 bar CH₄, 1 hour with 1 wt.% and 5 wt.% catalyst

CATALYTIC UPGRADING OF VACUUM RESIDUE (VR) UNDER METHANE

Oil Sample	Upgrading Performance and Liquid Product Properties						
	Liquid Yield (wt.%)	Coke Yield (wt.%)	Viscosity (cP @ 60 °F)	Olefin content (wt.%)	Density (g/cm ³ @ 60 °F)	Asphaltene Content (wt.%)	TAN (mg KOH/g)
Feed	---	---	>1 million	BDL	1.048	15.6	1.89
Product	96.0	1.8	110	0.46	0.9615	6.5	0.64

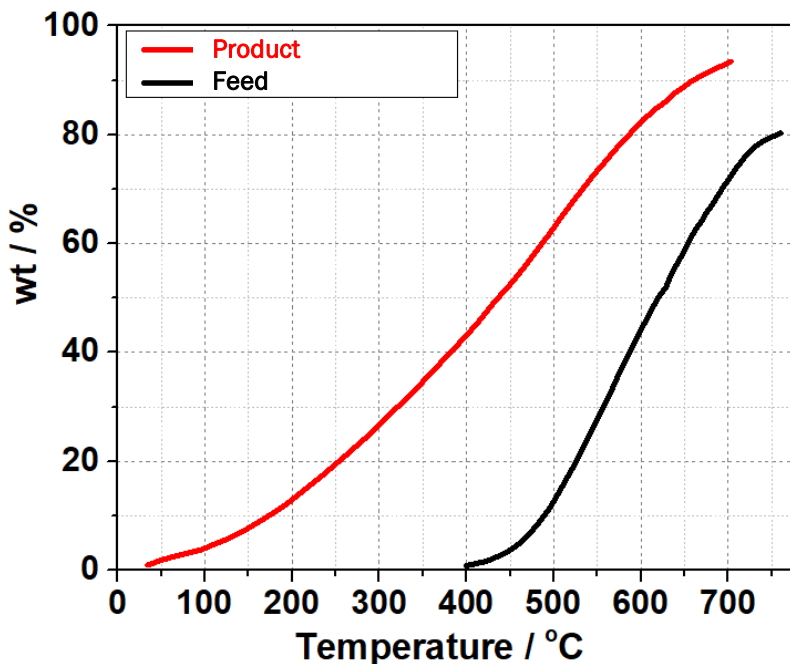


Samples	Upgrading Performance and Liquid Product Properties		
	S Content (wt.%)	Ni Content (ppm)	V Content (ppm)
Feed	5.53	115	220
Product	3.02	39	65

- ❖ Vacuum residue could be largely converted into light fraction with our technique, accompanied with significantly reduced density and viscosity.
- ❖ This technique will be highly beneficial and profitable for the treatment of VR and similar heavy residue.

CATALYTIC UPGRADING OF VACUUM RESIDUE (VR) UNDER METHANE

Oil Sample	Upgrading Performance and Liquid Product Properties						
	Liquid Yield (wt.%)	Coke Yield (wt.%)	Viscosity (cP @ 60 °F)	Olefin content (wt.%)	Density (g/cm ³ @ 60 °F)	Asphaltene Content (wt.%)	TAN (mg KOH/g)
Feed	---	---	>1 million	BDL	1.030	15.0	2.10
Product	98.2	0.7	177	0.45	0.9545	5.4	0.77



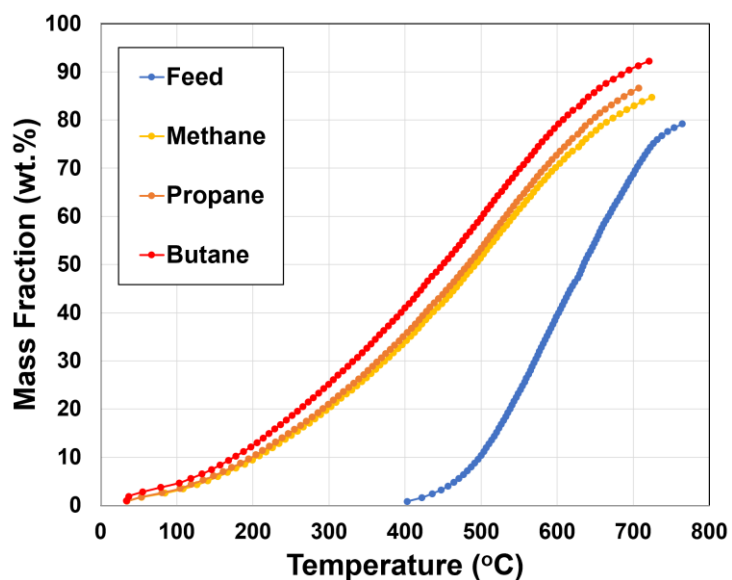
Samples	Upgrading Performance and Liquid Product Properties		
	S Content (wt.%)	Ni Content (ppm)	V Content (ppm)
Feed	4.34	117	245
Product	1.86	33	49

- ❖ Vacuum residue could be largely converted into light fraction with our technique, accompanied with significantly reduced density and viscosity.
- ❖ This technique will be highly beneficial and profitable for the treatment of VR and similar heavy residue.

EFFECT OF REACTIVE GAS ENVIRONMENT UNDER BATCH MODE

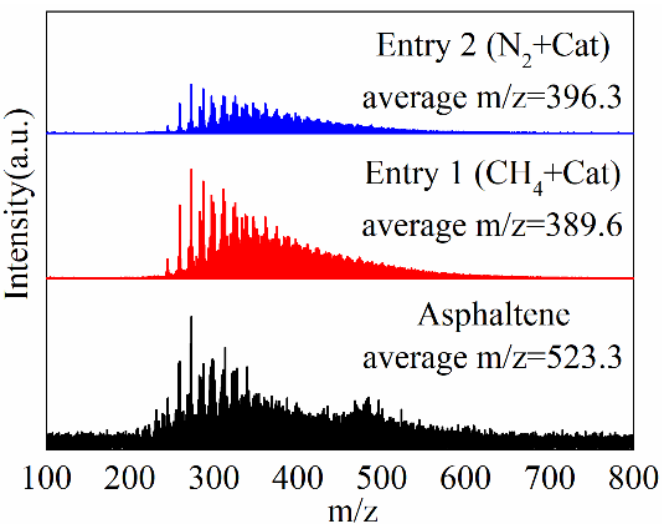
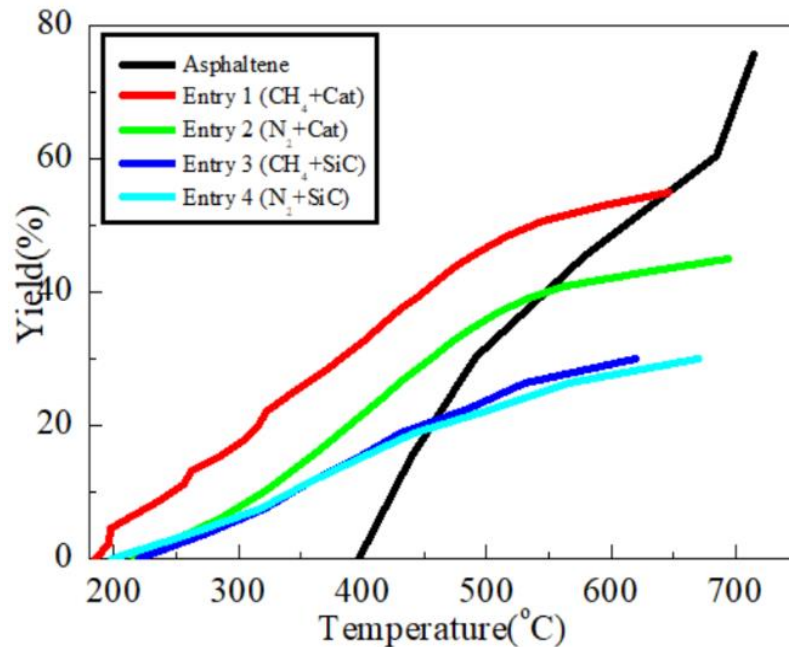
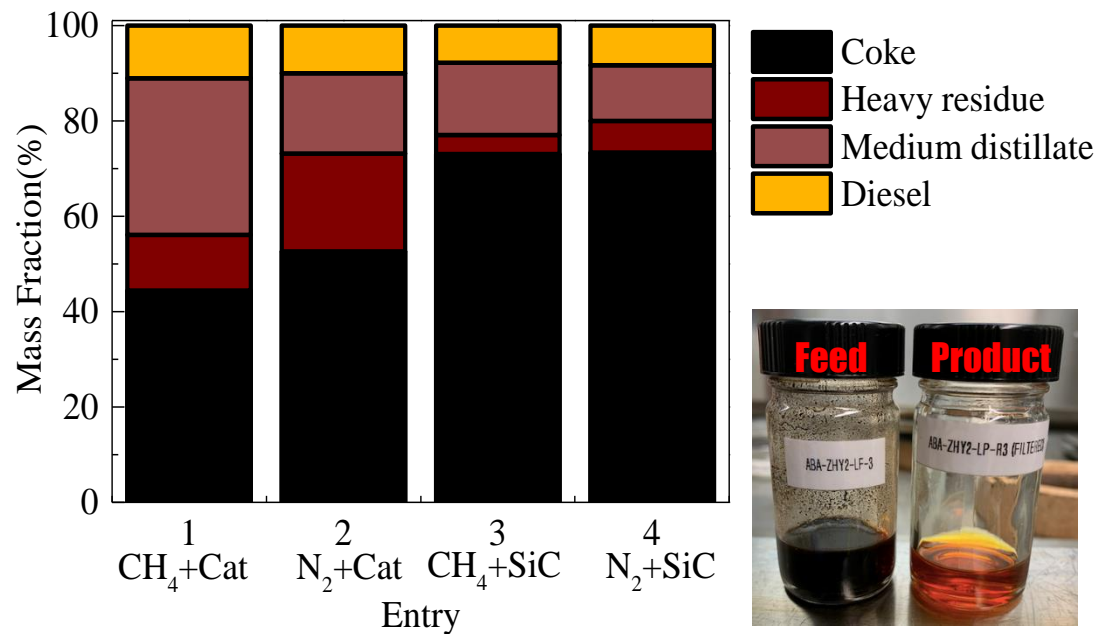
	Temperature (°C)	Charged catalyst	Catalyst to oil ratio	Gas to oil ratio	Duration (h)
Conditions	410	HOU-2	1:100	60:1	1

Reactive Gas	Upgrading Performance and Liquid Product Properties						
	Viscosity (cP @ 60 °F)	Olefin content (wt.%)	Sulfur Content (wt.%)	Density (g/cm ³)	Asphaltene Content (wt.%)	TAN (mg KOH/g)	Liquid Yield (wt.%)
Feed	587,000 @45°C	BDL	3.40	1.01002	11.6	1.76	---
Methane	1,610	0.29	2.17	0.95766	7.43	0.74	98.1
Propane	750	0.38	1.96	0.94180	6.12	0.57	98.3
Butane	154	0.47	1.83	0.93701	4.02	0.47	98.8



Reactive Gas	Feed	CH ₄	C ₃ H ₈	C ₄ H ₁₀
Naphtha Fraction (<180 °C, wt.%)	0	8.0	8.5	10.5
Middle Distillate Fraction (180~360 °C, wt.%)	0	20.0	21.0	23.7
Gas Oil Fraction (360~500 °C, wt.%)	10.5	23.5	24.0	25.5
Heavy Residue Fraction (>500 °C, wt.%)	89.5	48.5	46.5	40.3
Averaged Molecular Weight (g/mol)	849	497	485	467

CATALYTIC UPGRADING OF ASPHALTENE UNDER METHANE



Sample	Asphaltene	Entry 1	Entry 2
Reaction	/	CH_4+Cat	N_2+Cat
TAN (mg KOH g^{-1})	2.80	BDL*	BDL
Sulfur content (wt%)	6.77	3.02	5.00

- ❖ Asphaltene (the heaviest component in heavy crude) could be effectively converted into light fraction with our technique.
- ❖ Light fraction yield can be doubled while coke yield is halved in our technique, leading to notable asphaltene valorization.

EFFECT OF SOLVENT ON METHANOTREATING OF ASPHALTENE

PROPERTIES	FEEDSTOCK	REACTIONS	
	ABA-LF ¹	R1	R2
Liquid Yield ² (wt%)	N/A	89.0	89.7
Gas Yield (wt%)	N/A	9.5	5.9
Coke Yield (wt%)	N/A	2.3	5.3
Overall Mass Balance (wt%)	N/A	100.8	100.9
Asphaltene Conversion (%)	N/A	99.9	99.9
Methane Conversion (%)	N/A	8.5	8.6
Sulfur Content (ppmw)	6,580 ± 40	705 ± 2	1,417 ± 26
TAN (mg KOH/g)	0.27 ± 0.02	BDL	BDL

Asphaltene+Paraffin



Asphaltene+Aromatic



Xu. H., et al., *Fuel*, (2021) 291, 120157

Compared to aromatic based solvent, usage of paraffinic solvent can notably reduce coke formation, accompanied with better sulfur removal upon asphaltene upgrading.

Note:

- 1) ABA-LF means 10% asphaltene diluted with 90% solvent; R1 indicates the reaction using paraffinic solvent diluted asphaltene as the feed; R2 represents the reaction using aromatic solvent diluted asphaltene as the feed;
- 2) All yields are based on the total liquid feedstock mass.

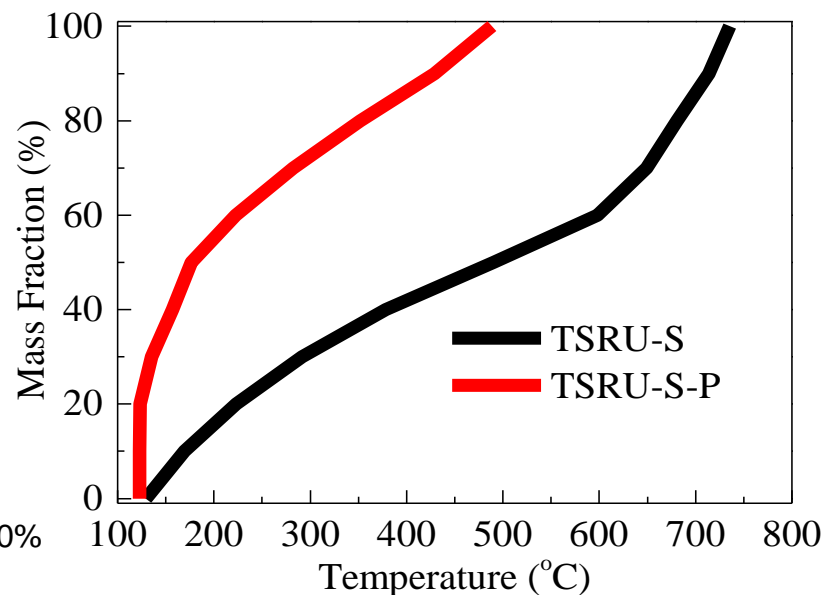
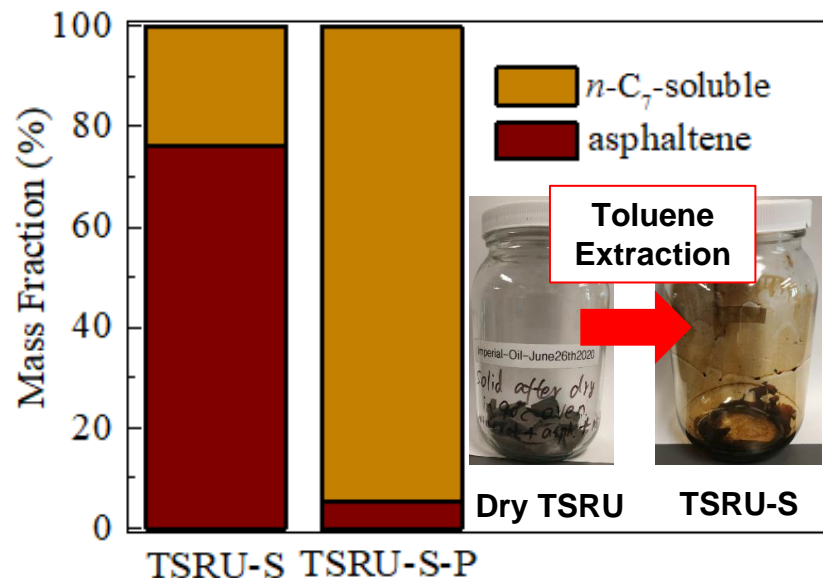
Reaction conditions: batch mode; catalyst: ZHY2 at 1 wt.%; gas feed: 90% methane + 10% N₂; temperature: 400 °C; Pressure: 30 bar; duration: 1 h.

CATALYTIC UPGRADING OF DRY TSRU TAILING RESIDUE

Reaction	CH ₄ +Cat
Overall mass balance (wt%)	100.3
Asphaltene conversion (%)	93.5
Methane conversion (%)	1.7
Gas yield (wt%)	4.8
Coke yield (wt%)	2.7
Liquid yield (wt%)	92.8

Sample	Initial boiling point (°C)	Final boiling point (°C)	Average molecular weight (g/mol)
TSRU-S	129.5	735.3	627
TSRU-S-P	122.9	488.4	242

❖ Upon upgrading, almost all asphaltene rich solid residue is successfully converted into high value-added light fractions

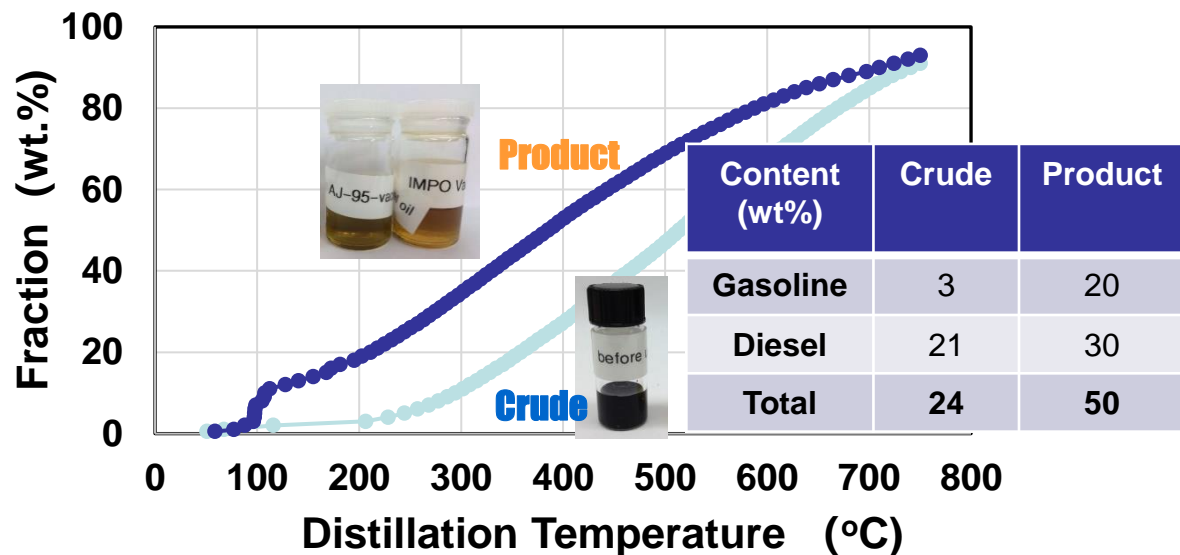


Reaction conditions: batch mode; catalyst: HOU-2 at 1 wt.%; gas feed: 90% methane + 10% N₂; temperature: 400 °C; Pressure: 30 bar; duration: 1 h.

ACHIEVEMENTS IN HEAVY OIL UPGRADING AT PILOT SCALE (20 L/D)

	Temperature (°C)	Pressure (MPa)	WHSV (h ⁻¹)	Liquid Yield (wt.%)	Coke Formation Rate (g/g _{cat} -h)	Duration (h)
Conditions	430	5	1	101	0.00145	240

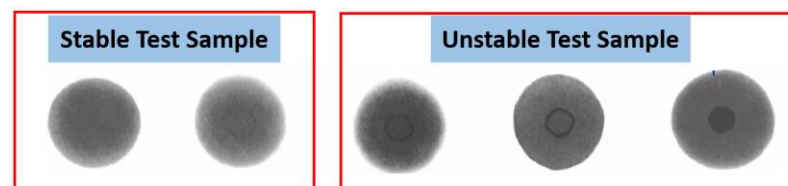
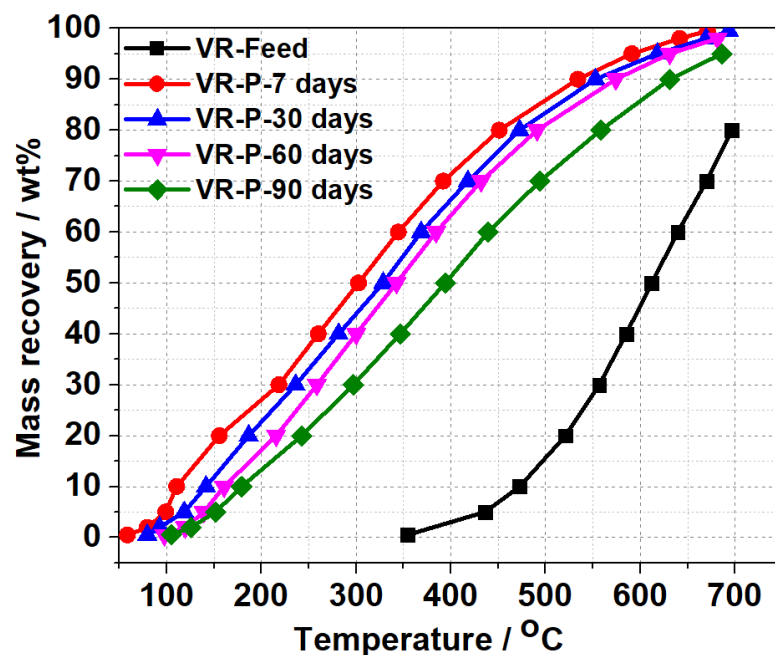
Oil Sample	Upgrading Performance and Liquid Product Properties						
	Viscosity (cP @ 60 °F)	Olefin content (wt.%)	Sulfur Content (wt.%)	Density (g/cm ³)	Asphaltene Content (wt.%)	TAN (mg KOH/g)	Stability (ASTM D4740)
Crude	12,315	---	3.05	0.9791	10.4	2.28	1
Product	128	1.2	0.98	0.9430	3.1	0.43	1



wt.%	Crude	Product
Paraffins	1.3	3.4
Naphthenes	26.8	21.2
Mono-aromatics	8.8	38.3
Bi-aromatics	13.2	10.6
Poly-aromatics	5.3	2.3

ACHIEVEMENTS IN VR UPGRADING AT PILOT SCALE (20 L/D)

	VR Feed	Product Oil			
		1-w	1-m	2-m	3-m
Viscosity (cP @ 60 °F)	> 1 million	187	202	207	217
Density (g/cm ³)	1.026	0.906	0.947	0.958	0.962
Asphaltene Content (wt.%)	17.1	2.1	7.2	9.0	9.4
Sulfur Content (wt.%)	4.10	0.64	2.45	2.81	3.00
Nitrogen Content (wt.%)	0.63	0.14	0.27	0.44	0.51
TAN (mg KOH/g)	1.88	0.03	0.11	0.15	0.21
Freezing point (°C)	>50	-51	-49	-47	-48



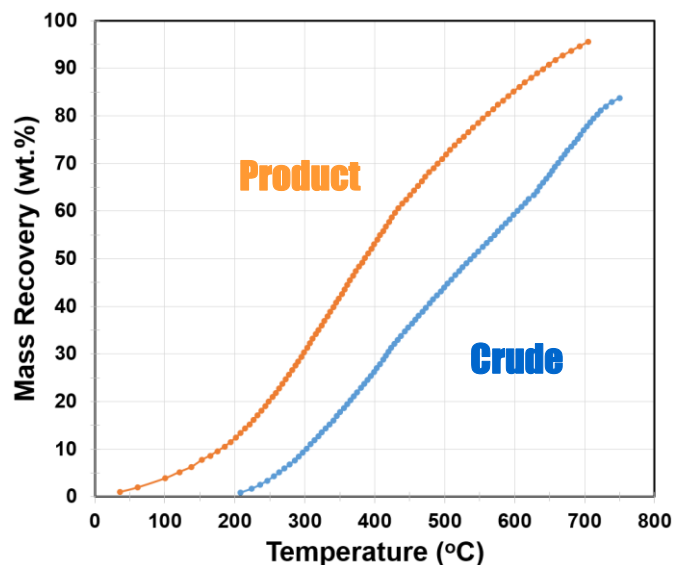
- ✓ The **vacuum residue** got significantly upgraded even after 3-month continuous run.
- ✓ The charged catalyst remains active even after 3-month continuous run.



ACHIEVEMENTS IN HEAVY OIL UPGRADING AT PILOT SCALE (1 B/D)

	Temperature (°C)	Pressure (MPa)	WHSV (h ⁻¹)	Liquid Yield (wt.%)	Coke Formation Rate (g/g _{cat} -h)	Duration (h)
Conditions	430	5	0.5	98	0.0017	360

Oil Sample	Upgrading Performance and Liquid Product Properties						
	Viscosity (cP @ 60 °F)	Olefin content (wt.%)	Sulfur Content (wt.%)	Density (g/cm ³)	Asphaltene Content (wt.%)	TAN (mg KOH/g)	Stability (ASTM D4740)
Crude	154,730	BDL	4.08	1.0096	12.44	2.10	1
Product	204	0.25	2.02	0.9552	5.13	0.51	1



	Crude	Product
Naphtha Fraction (<180 °C, wt.%)	0	10
Middle Distillate Fraction (180~360 °C, wt.%)	19	34
Gas Oil Fraction (360~500 °C, wt.%)	25	27
Heavy Residue Fraction (>500 °C, wt.%)	56	29
Averaged Molecular Weight (g/mol)	616	416

ACHIEVEMENTS IN JET FUEL UPGRADING UNDER METHANE

Sample Name	Contents of different species (wt %)							
	Paraffins	Naphthenes	Olefins	Aromatics	Benzene	Toluene	E-Benzene	Xylene
Jet Fuel	53.19	14.92	1.05	30.84	0	0	0	2.74
Jet Fuel Product	21.11	15.82	1.61	61.45	2.35	9.13	2.73	12.62

Sample Name	C9-aromatics (wt%)	C10-aromatics (wt%)	C11-aromatics (wt%)	C12-aromatics (wt%)	Polycyclic-aromatics (wt%)
Jet Fuel	8.92	7.72	3.67	2.31	5.48
Jet Fuel Product	12.89	7.04	4.57	1.74	8.38

❖ Upon upgrading, aromatics amount can be doubled with remarkable increase of BTEX, especially xylene.

Reaction conditions: continuous fixed bed mode; catalyst: HOU-2; light hourly space velocity: 2 h⁻¹; gas feed: 90% methane + 10% N₂; temperature: 400 °C; Pressure: 30 bar; time-on-stream: 6 h.

MARINE DIESEL OIL (MDO) DESULFURIZATION UNDER METHANE

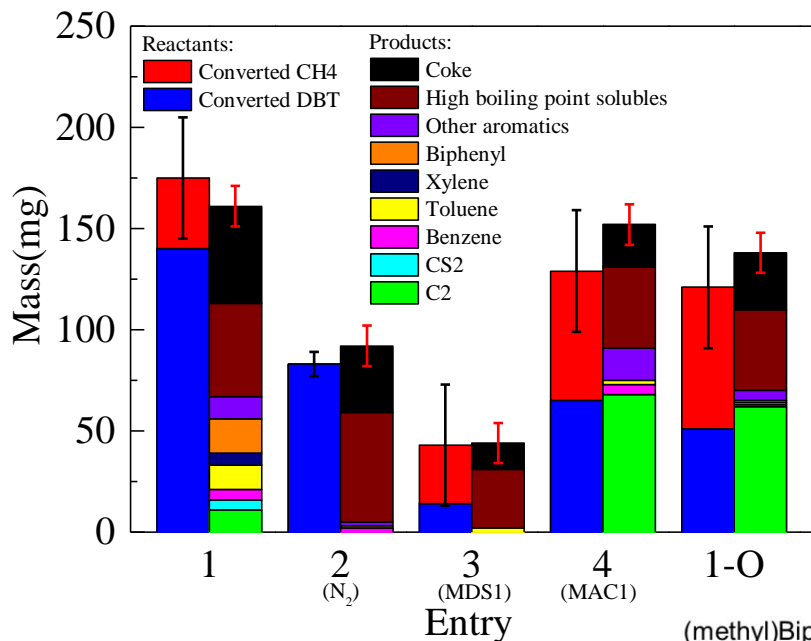
Entry	Gas Yield (wt%)	Liquid Yield (wt%)	Coke Yield in 6 hours (wt%)	Coke Formation Rate [g coke(h*g catalyst)]	Overall Yield (wt%)	Methane conversion (%)
SC-001; CH ₄	2.56	96.09	1.20	0.011	99.85	1.81
SC-001; N ₂	2.82	95.40	0.96	0.008	99.18	N/A

Entry	Density (g/cm ³ , at 15.6°C)	TAN (mg KOH/g)	Sulfur Content* (ppm)	Sulfur content reduction (%)
Feed (MDO)	0.85239 ± 0.00002	0.24	2153 ± 13	N/A
SC-001; CH ₄	0.84176 ± 0.00002	0.03	887 ± 1	58.8
After vaporization at 50 °C for possible CS ₂ removal			636 ± 2	70.5
SC-001; N ₂	0.83456 ± 0.00001	0.05	1231 ± 9	42.8
After vaporization			1251 ± 8	

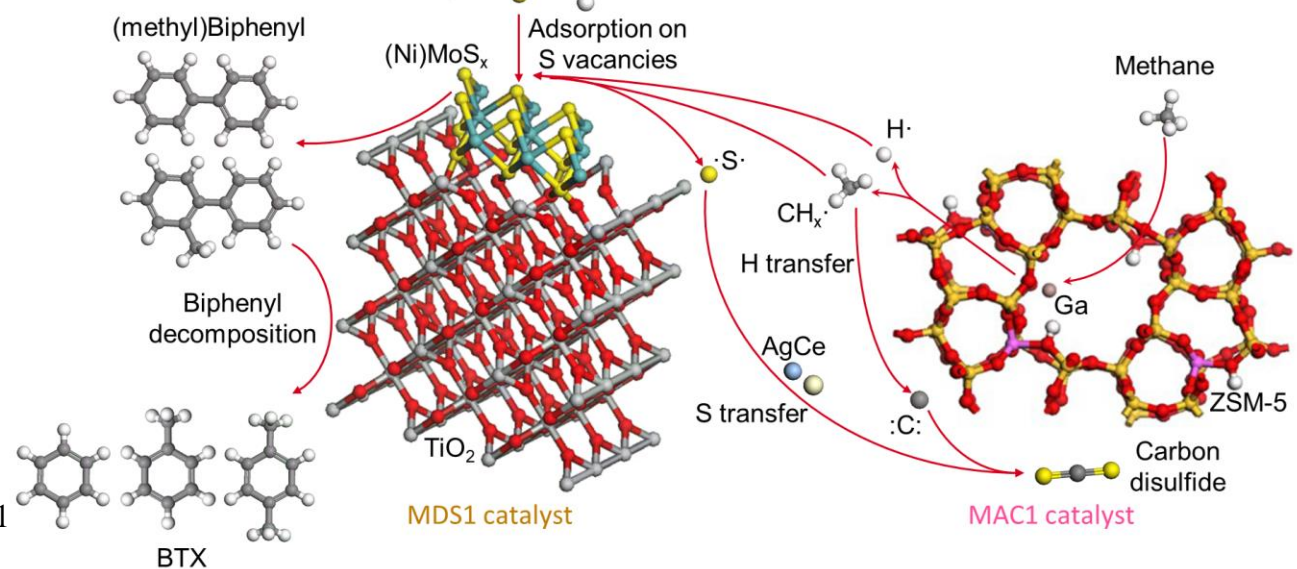
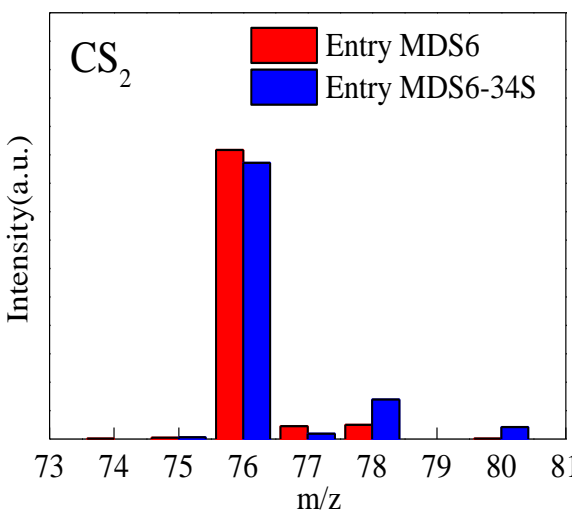
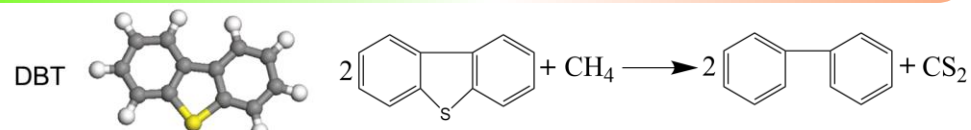
❖ Upon engaging suitable catalyst under methane environment, the quality of the MDO can be notably improved in terms of reductions of density, total acid number (close to 90%), and sulfur content (over 70%);

Reaction conditions: continuous fixed bed mode; catalyst: SC-001; light hourly space velocity: 1 h⁻¹; gas feed: 90% methane + 10% N₂; temperature: 400 °C; Pressure: 30 bar; time-on-stream: 6 h.

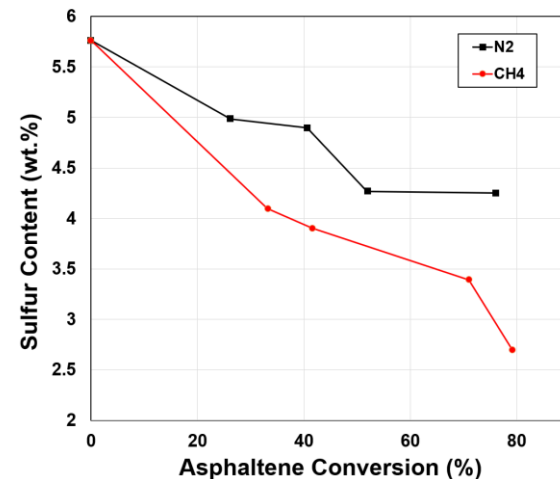
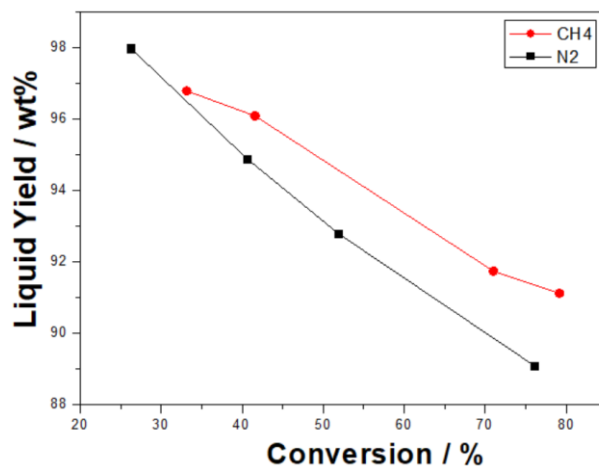
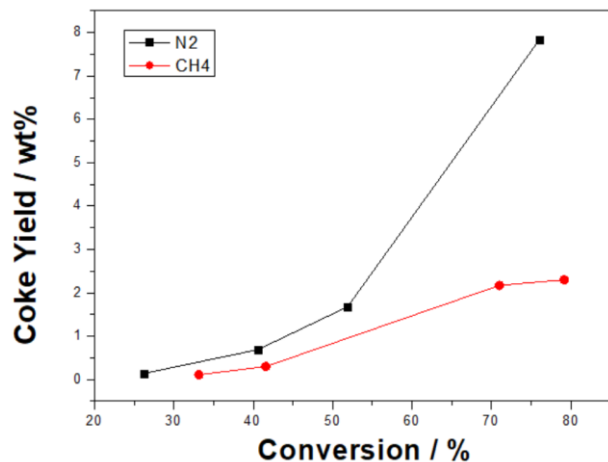
METHANE ASSISTED CATALYTIC DESULPHURIZATION



- ❖ DBT desulfurization are technically feasible under methane environment;
- ❖ CS₂ is identified as a new product under MDS process, which is not previously detected in HDS process;
- ❖ Sulfur surface transfer between two physically mixed catalysts are clearly observed;
- ❖ Methane and dual catalyst system (MDS1 and MAC1) are observed to be indispensable for DBT desulfurization process.

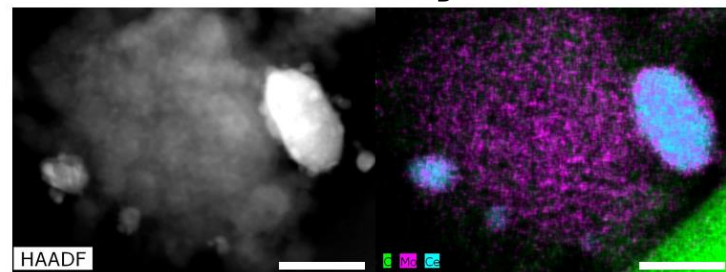


METHANE ROLE INVESTIGATION FOR HEAVY OIL UPGRADING



Catalyst	BET surface area (m ² g ⁻¹)	Total pore volume (mL g ⁻¹)	Micropore surface area (m ² g ⁻¹)	Micropore volume (mL g ⁻¹)
Fresh	179.8	0.205	82.7	0.043
Spent-CH ₄	88.5	0.063	36.5	0.021
Spent-N ₂	69	0.058	16.3	0.005

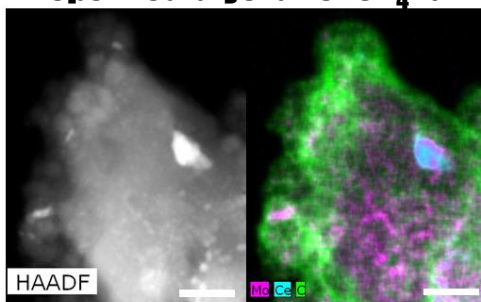
Fresh Catalyst



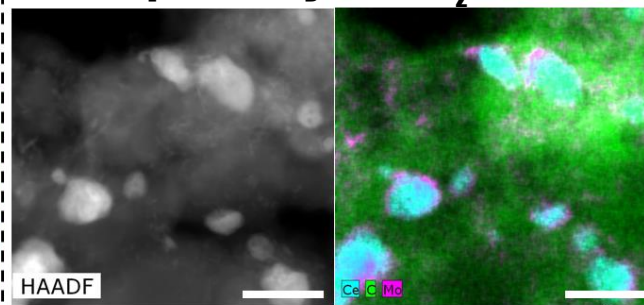
❖ Methane presence can effectively suppress thermal cracking and promote desulfurization, leading to reduced coke yield and sulfur content;

❖ Methane presence prevent coke formation onto the internal surface due to the preferable adsorption of methane molecules.

Spent Catalyst after CH₄ run



Spent Catalyst after N₂ run



CONCLUSIONS

- ❖ The technical feasibility of the developed heavy oil targeted hi-grading technology is verified over various heavy feeds, and units from lab scale to pilot scale.
- ❖ The developed technology has been successfully applied to the valorization of versatile light crudes in terms of sulfur reduction, oxygen removal, TAN reduction, monoaromatics formation.
- ❖ The roles played by methane during crude upgrading process have been better understood as followings:
 - Effective suppression of thermal over-cracking;
 - Efficacious inhibition of polymerization for coke formation.
 - Selective promotion of heavy residue conversion to light fraction;
 - Efficient prevention of heavy residue deposition/adsorption on catalyst surface, particularly internal surface through enhancing monoaromatics formation (solvent effect) and preferable adsorption of methane molecules;
 - Novel desulfurization pathway generation through forming highly volatile sulfur containing liquid species such as CS_2 as good solvent for heavy residue dissolution;
 - Possible incorporation into the formed liquid product for liquid yield enhancement and varied properties of the upgraded oil;
 - Facilitation of deoxygenation and desulfurization reactions;

FUTURE WORK

- ❖ The heavy oil upgrading performance is in the process of being further verified at a scale of 1 barrel/d on the fabricated research prototype.
- ❖ The developed technology will be tuned to a wider spectrum of oil feed to evaluate its application generality.
- ❖ More sample characterizations will be performed to get an even better understanding of the involved catalytic reaction mechanism, beneficial for the rational design of the engaged catalyst.
- ❖ More catalysts will be synthesized to achieve optimized performance in terms of reduced viscosity, increased oil yield, and higher paraffin content.
- ❖ More model compounds will be reasonably selected to represent crude oil for better mechanistic study of the involved upgrading reactions.
- ❖ Long term stability test will be conducted at larger scale and catalyst deactivation mechanism will be better identified for its potential commercialization.



Thanks for your attention! Welcome for questions and comments

Governmental Funding Agencies



N SERC
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