清洁煤与油田绿色开发：
延长石油集团CCUS一体化项目
Clean Coal and Green Development of Oilfield:
The Integrated CCUS Project of Yanchang Petroleum Group

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引　言
Introduction

- 随着全球工业的快速发展，气候变化受到各国政府的高度重视.
- As the rapid development of global industry, climate change is getting rising concerns.
- CO_2捕集、利用与封存技术（CCUS）可有效降低碳排放量，是能源企业积极应对全球气候变化，实现碳减排的有效途径之一。
- As an important tool to reduce climate impact, CO_2 Capture Utilizing and Storage (CCUS) is a effective way that fossil energy business players take.
- 煤炭相关产业是当前二氧化碳排放的主要来源，开展CCUS项目将有助于推动煤炭的清洁化利用。
- Coal based industry is one major source of CO_2, CCUS project is founded to utilize coal in a cleaner way.
- 延长石油集团发挥自身优势，打造了全球首个集煤化工CO_2捕集、特低渗油田CO_2驱油与封存为一体的 CCUS项目，在技术创新方面积累了一些经验，愿与全球煤炭行业专家分享。
- With its core competencies, Yanchang Petroleum Group has built the very first integrated CCUS project, which combined coal chemical CO_2 capture and low permeability reservoirs CO_2 EOR and storage together, and our experiences in technology innovation will be shared here.

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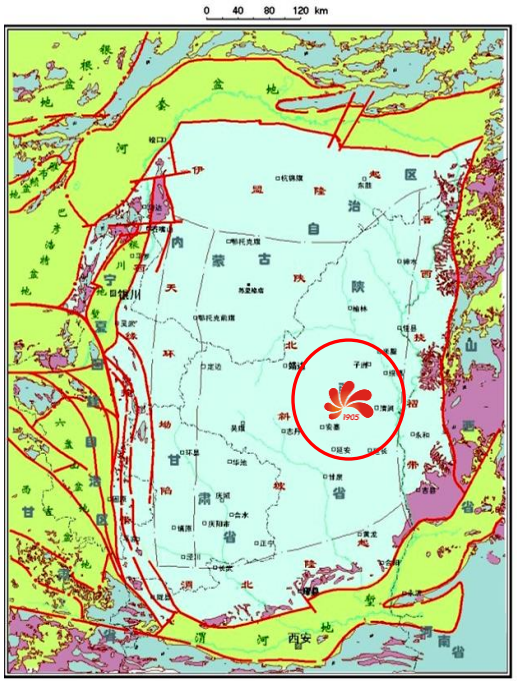
（一）延长石油集团概况
Overview of Yanchang Petroleum Group

- 延长石油地处中国鄂尔多斯盆地，是中国陆上发现最早的油田，成立于1905年；
- Yanchang Petroleum was founded in 1905, and it is located in Ordos basin, which is known as the first onshore oil field of China.
- 2015年原油产量1241万吨，连续9年稳产千万吨以上；
- In 2015, total oil production is approximate 100MMbbl, and this capacity has been maintained for 9 years.
- 业务涵盖油气勘探开发、煤矿开采、油气煤综合化工及科技研发等；
- Its business includes oil and gas E&D, coal mining, chemical industry, and R&D etc.
- 世界企业“500强”最新排名325位。
- Rank 325 in Global Fortune Top 500 (latest).




油田开发 **Oilfield**


综合化工 **chemical industry**


科技研发 **R&D**

（一）延长石油集团概况
Overview of Yanchang Petroleum Group

延长石油拥有多个煤矿、煤化工企业和油气田，可自主开展全流程一体化CCUS项目

Yanchang petroleum owns several coal mines ,coal-chemical plants and oil-gas fields, and can independently carry out the whole process of CCUS projects.

煤矿 **Coal Mine**

煤化工企业 **Coal-Chemical Plants**

特低渗油田 **Oil Fields with Low Permeability**

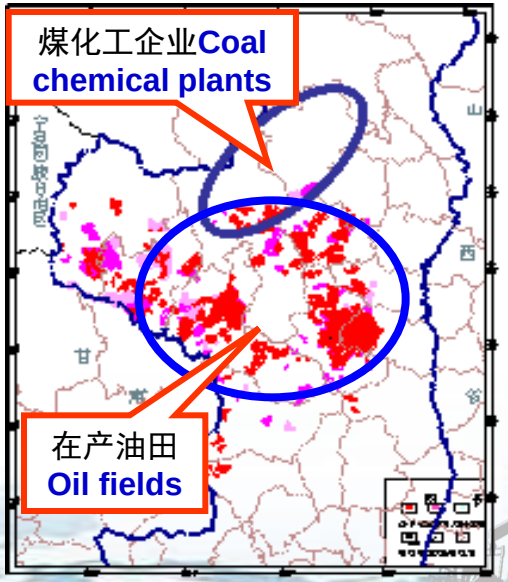
（二）延长石油开展CCUS项目的有利条件

Core competencies of Yanchang Petroleum to have CCUS

1、具有充足的碳源和较低的捕集、输送成本

Abundant carbon supply and low cost in CO_2 capture and transportation.

- **碳源充足**：相对集中的煤化工企业提供了充足的碳源；
- **Abundant carbon supply from** relatively concentrated coal chemical plants.
- **捕集成本低**：煤化工企业产生的CO_2浓度高，捕集成本约20美元/吨；
- **Low cost** of high concentration CO_2 from coal chemical plants **(approx. 20 USD per ton)**
- **输送成本低**：在产油田与煤化工企业处于同一区域，输送距离小于150公里
- **Low pipeline cost**, less than 150 km between coal chemical plants and oil fields.



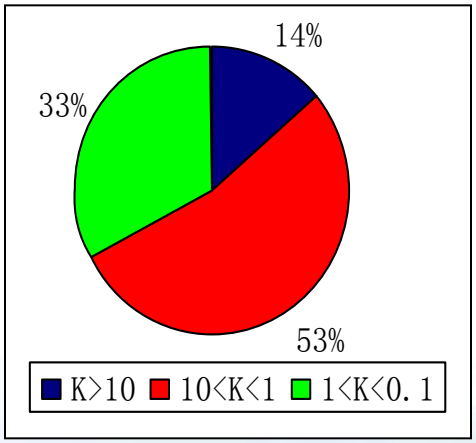
（二）延长石油开展CCUS项目的有利条件

Core competencies of Yanchang Petroleum to have CCUS

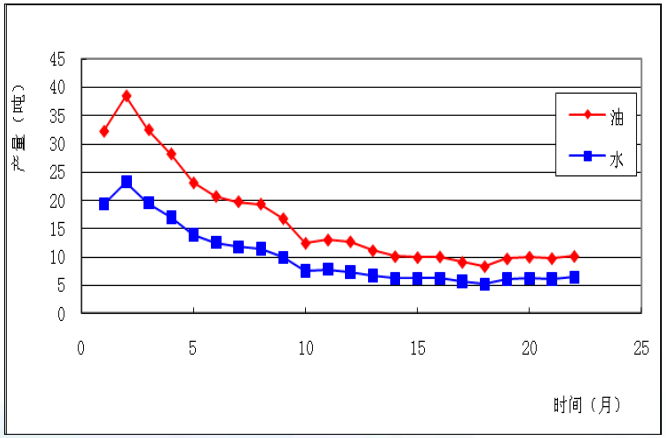
2、有大量低渗透油藏适合开展CO_2驱油

Large amount of oil reservoirs suits CO_2 flooding.

- **有助于油田长期稳产**：延长油田属于特低渗透油藏，产量递减较快，储层特征和温压条件适合开展CO_2驱油，可大幅度提高采收率；
- Yanchang oilfields are low permeability reservoirs, reservoir characteristics, formation temperature, and pressure are ideal to launch CO_2 flooding, which greatly improve the recovery factor.
- **有利于节约水资源**：陕北地区水资源匮乏，用CO_2驱油代替注水开发可节约水资源。
- Shanbei region suffers water shortage, so CO_2 flooding saves more water than water flooding.



不同渗透率级别储层储量分布图
Reserve Distribution for low, ultra-low, permeability reservoirs



单井月产量递减较快
Well production rate change

地表干旱缺水
Droughty land

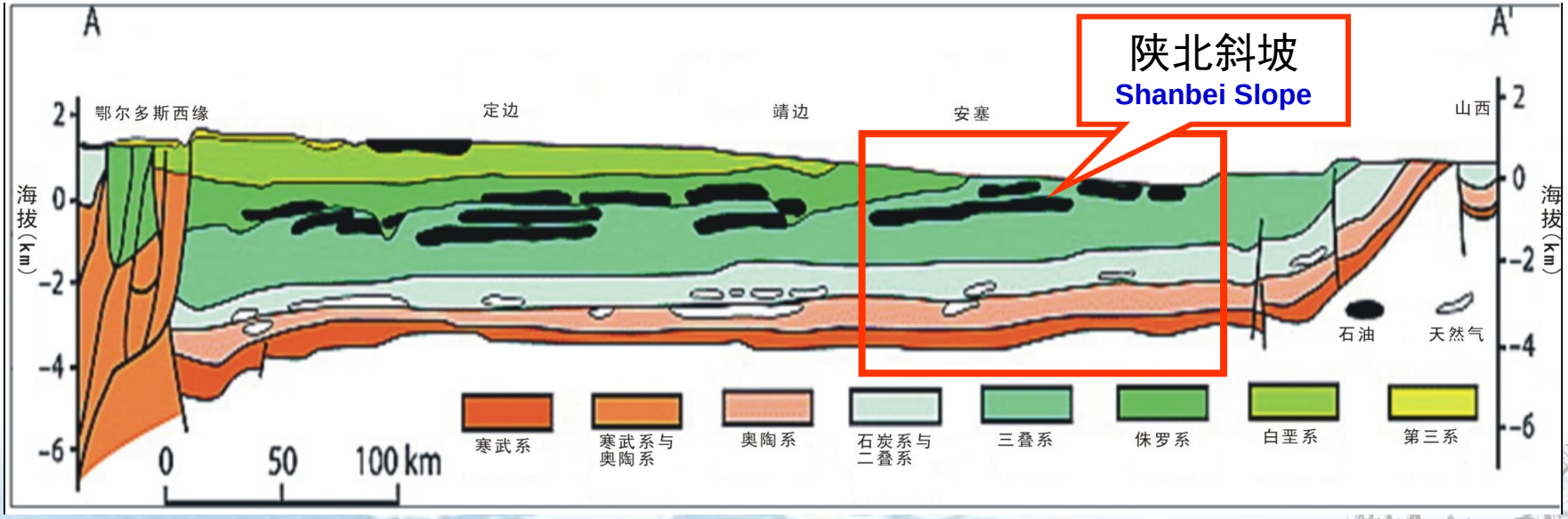
（二）延长石油开展CCUS项目的有利条件

Core competencies of Yanchang Petroleum to have CCUS

3、地层条件有利于CO_2长期封存

Geological condition benefits long-term CO_2 storage

- **封存条件好**：陕北斜坡构造简单，地层稳定，断层不发育，CO_2封存安全可靠；
- Shanbei Slope has simple structure, stable formation, and fault development, so CO_2 sequestration is secured and reliable.
- **封存空间大**：有大量需要提高采收率的油藏和盐水层，适宜于CO_2封存。
- There is plenty of low permeability reservoirs and saltwater layers to store CO_2.



（三）延长石油CCUS项目现状

Current Status of Yanchang CCUS Project

历时8年，投资近5000万美元。

Lasts 8 years & invested almost 50 million USD.

- 形成了碳捕集、利用与封存技术系列。
- Developed a series of CCUS technologies.
- 建成13万吨/年CO_2捕集装置。
- Established CO_2 capture plant with 130K ton per year capacity.
- 建成两个CO_2-EOR与封存先导试验区。
- Built two pilot test zones for CO_2-EOR and storage.
- 开展了非常规油气井CO_2压裂矿场试验。
- Developed CO_2 fracturing technologies and conducted tests in unconventional oil & gas wells.

通过开展CCUS项目，将**“碳捕集—提高油田采收率—碳封存—碳减排”**融为一体，是延长石油**实现低碳、可持续发展**的必然选择。

CCUS project integrates **CO_2 capture**, **enhanced oil recovery rate**, CO_2 storage and reduced CO_2 emission together, and it will help Yanchang Petroleum.to realize **low carbon and sustainable development**

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（一）形成煤化工低成本CO_2捕集技术

Developed low-cost CO_2 capture technology from coal chemical plant.

1、 实现高浓度CO_2低成本捕集。

CO_2 Capture with High Concentration and Low-cost.

- 2012年延长石油榆林煤化公司建成5万吨/年的CO_2捕集装置，采用**低温甲醇洗技术**，捕集成本仅20美元/吨。
- In 2012, Yanchang Yulin Coal-Chemical Company completed the capture plant with 50K tons p.a capacity by **Rectisol process**. The capture cost is only $20 per ton.

（一）形成煤化工低成本CO_2捕集技术

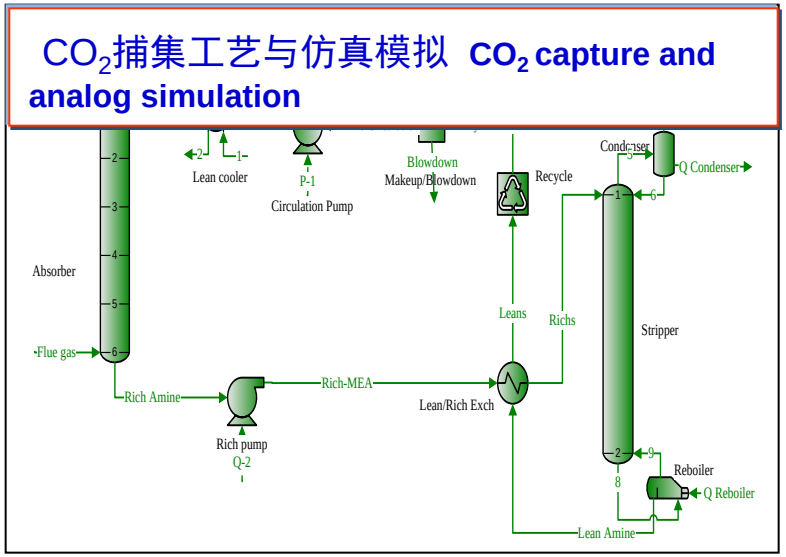
Developed low-cost coal chemical plant CO_2 capture technology

2、针对低浓度CO_2，采用氨吸收技术捕集，已完成工艺包开发和中试装置建设。

Industrialized process package and pilot plants have been developed for CO_2 capture with low concentration.

多功能中试装置multifunctional pilot plants

CO_2捕集工艺与仿真模拟 **CO_2 capture and analog simulation**



CO_2捕集能力近期将达到50万吨/年

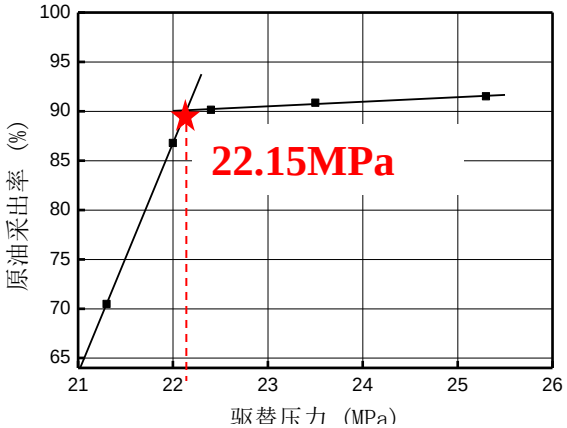
CO_2 capture capacity will reach 500K tons per year recently.

（二）形成特低渗油藏CO_2驱油与埋存技术
Developed CO_2-EOR and storage technology in ultra-low reservoir

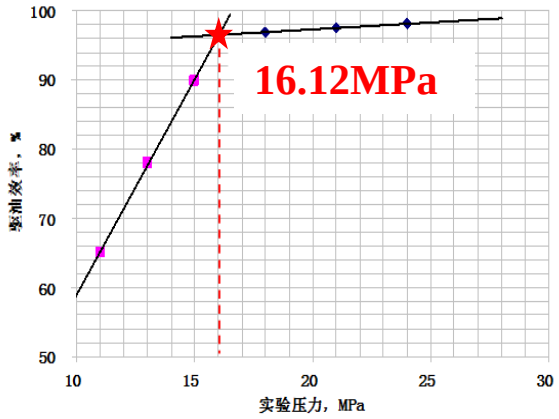
1、建立了完整的CO_2驱油室内实验评价方法
Completed the experimental evaluation method of CO_2-EOR.

- 微观和宏观有机结合，开展了CO_2驱油室内实验评价，对**CO_2驱油机理及驱替特征**进行研究
- Integrated micro and macro analysis methods are applied, the experimental evaluation for mechanism and characteristics of CO_2-EOR has been done

自动岩心流动实验仪
Experiment device of core displacement



靖边乔家洼长$_6$油层最小混相压力
Miscible pressure of Jinbian oilfield



吴起油沟长$_6$油层最小混相压力
Miscible pressure of Wuqi oilfield

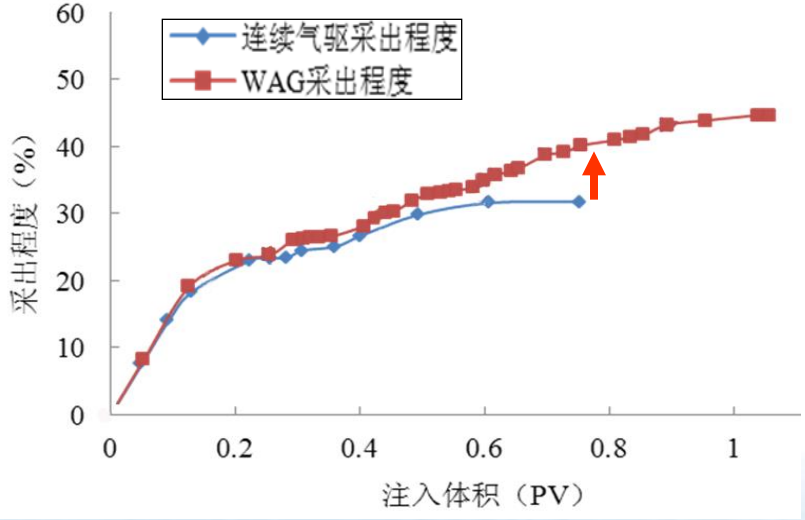
（二）形成特低渗油藏CO_2驱油与埋存技术

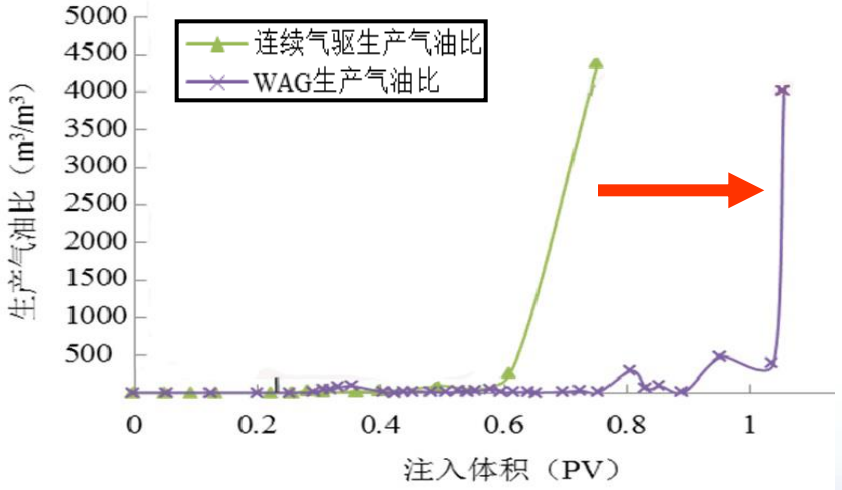
Developed CO_2-EOR and storage technology in ultra-low reservoir

模拟研究不同CO_2注入方式的采油效果，优选水气交替注入（WAG）

Determine the CO_2 injection mode by indoor simulation, WAG is the optimum way.

- 连续气注入最终采出程度为**33.73%**，提高采出程度**8.41%**；
- For continuous gas injection, ultimate recovery rate is 33.73%, increased by 8.41%.
- 水气交替注入（WAG）最终采出程度为**44.7%**，提高采出程度**20.95%**，较连续气驱的采出程度提高了**12.54%**。
- For WAG, ultimate recovery rate is 44.7%, increased by 20.95%, exceed continuous gas injection by 12.54%.





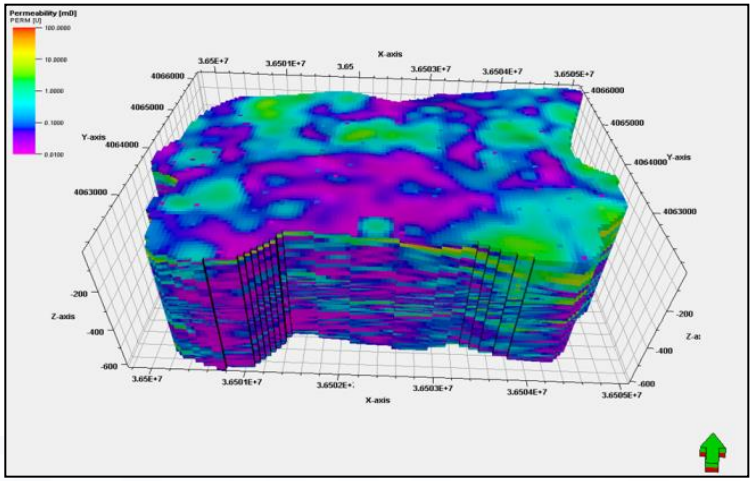
WAG与连续气驱驱油动态曲线

The dynamic curve of WAG and Continous Gas Injection

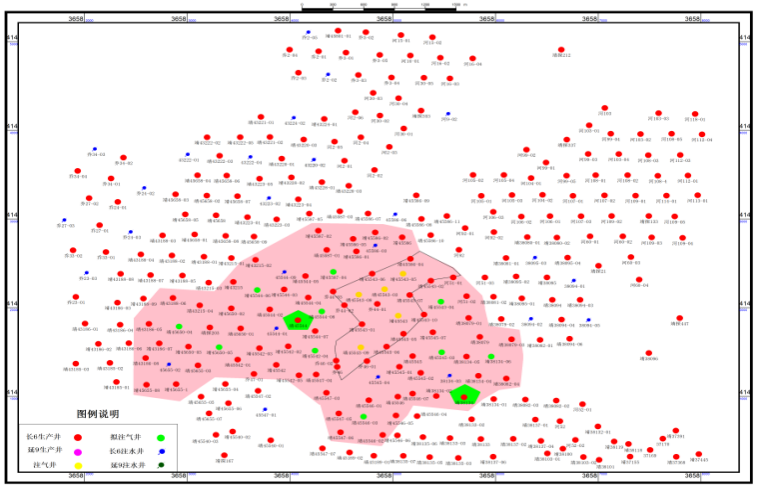
（二）形成特低渗油藏CO_2驱油与埋存技术
Developed CO_2-EOR and storage technology in ultra-low reservoir

2、优化了CO_2驱油油藏工程设计
Optimized reservoir engineering design for CO_2-EOR

- 通过油藏精细地质研究，优化了**注采井网、注气方式、注气压力**和**初期开发指标**等关键参数。
- Optimized parameters, such as injection-production pattern, gas injection method, gas injection pressure and initial development parameters by detailed geological studies.



油藏渗透率三维模型
3D model of reservoir permeability



CO_2驱注采井网
CO_2 injection-production pattern

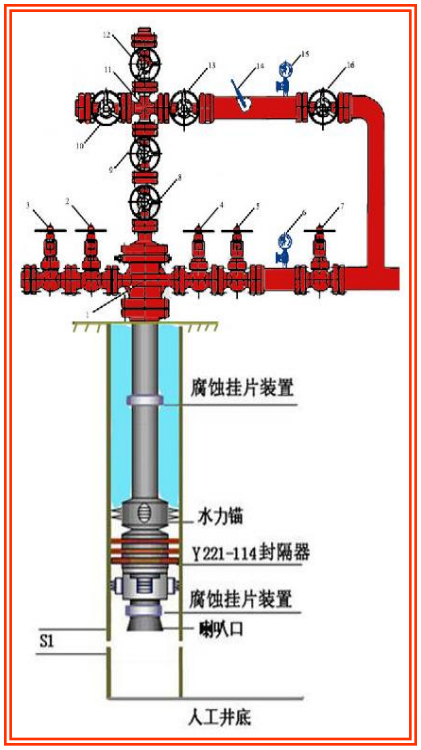
（二）形成特低渗油藏CO_2驱油与埋存技术
Developed CO_2-EOR and storage technology in ultra-low reservoir

3、形成了注采工艺配套技术及防腐技术

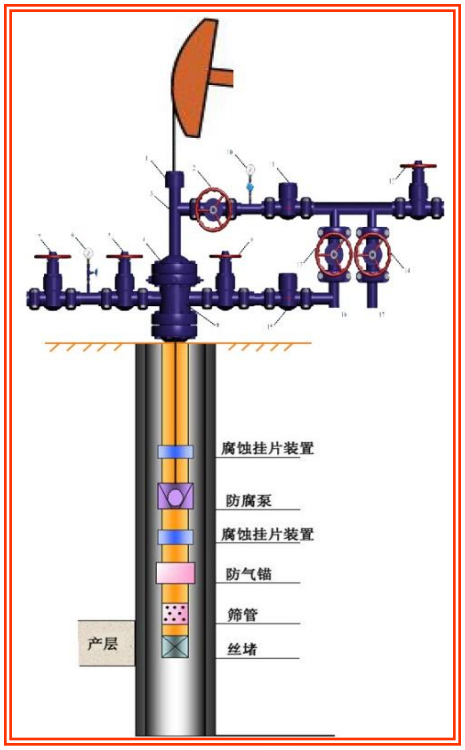
Formed the related techniques of CO_2 injection and oil production, and the anti-corrosion technologies.

优化了注采管柱设计，优选了**“普通碳钢+缓蚀剂”**防腐配套工艺，现场应用效果良好。

Injection & production string design has been optimized by a number of tests, and “ordinary steel+ inhibiter” has been selected as the best anti-corrosion approach. It performs excellent in field application.



注入工艺系统
Injection system

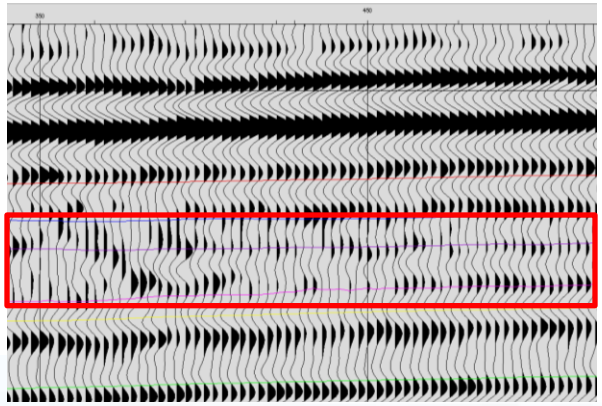


采油工艺系统
Production system

（二）形成特低渗油藏CO_2驱油与埋存技术
Developed CO_2-EOR and storage technology in ultra-low reservoir

4、初步形成CO_2安全监测技术
Developed CO_2 monitoring technology prototype.

- 从油藏监测、地表监测、大气监测三个角度，形成了**CO_2地质埋存安全风险评价和预警方法。**
- Has set up CO_2 storage risk assessment and warning technology in three aspects: reservoir monitoring, surface monitoring and atmospheric monitoring.
- 首次创立了利用**^{13}C同位素**监测CO_2前缘流动位置和近地表CO_2泄露的监测方法。
- Has initiated utilizing ^{13}C isotop in CO_2 flow front and surface leakage detection.



油藏监测 ——四维地震
Reservoir monitoring
—4D Seismic

地表监测——植被监测
surface monitoring
—Vegetation monitoring

大气监测——采出气组分分析
Atmospheric monitoring
—Gas sample testing

（二）形成特低渗油藏CO_2驱油与埋存技术
Developed CO_2-EOR and storage technology in ultra-low reservoir

5、开展了CO_2再捕集与循环利用技术研究
Carried out research on CO_2 recapture and recycling technologies .

根据气油比高低，开展了**低能耗CO_2胺吸收法**和**油气分离压缩直接回注**室内研究和技术开发，实现了再捕集和循环利用。

The low energy consumption amine absorption and gas-oil separation and recycling method can be used respectively for high and low gas-oil ratio reservoirs, which can realize the recapture and recycling.

低能耗CO_2胺吸收法

The equipment of amine absorption

（二）形成特低渗油藏CO_2驱油与埋存技术
Developed CO_2-EOR and storage technology in ultra-low reservoir

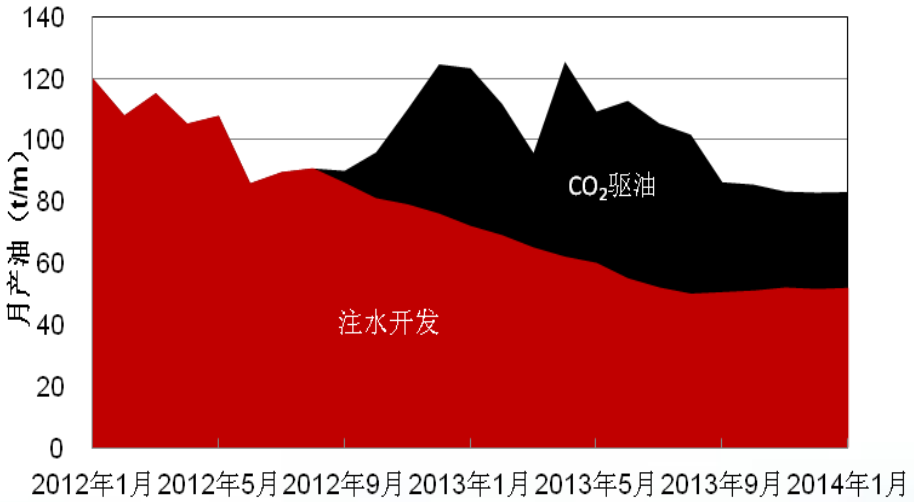
现场应用效果:

Field application performance:

- 建成两个试验区，目前10口注气井，累计注入7万吨液态CO_2，单井产量提高50%，预计可提高原油采收率8%，实现动态封存CO_2 7万吨。
- Two pilot test zones with 10 gas-injecting wells have been built. About 70K tons of CO_2 have been injected and sealed, the current performance of EOR meet the expectation.

驱油现场

CO_2 flooding site



一线受效井产量变化曲线

Production change of Affected well

（三）形成非常规油气藏CO_2压裂技术

Developed unconventional hydrocarbon reservoirs CO_2 fracturing technology

针对非常规油气储层特征，开发了CO_2增能压裂技术、VES-CO_2泡沫压裂技术、纯液态CO_2压裂技术

CO_2 energized, VES-CO_2 foam and pure liquid CO_2 fracturing technologies have been developed for each type of unconventional oil & gas reservoirs.

1）提高了单井产量。实施致密气井CO_2压裂12井次，平均单井产量提高30%以上；实施致密油井CO_2压裂12井次，产量提高2.8倍，返排率提高70%。

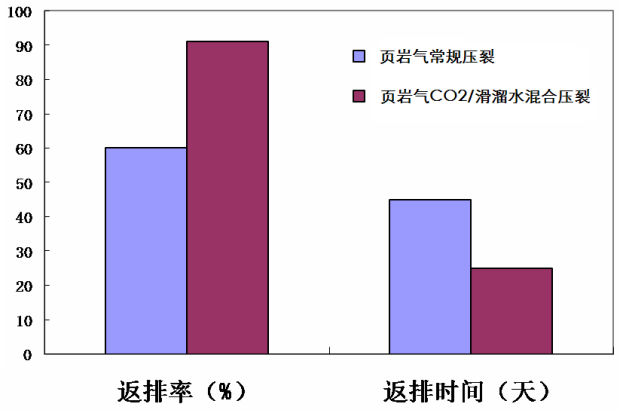
Tight gas average well output has been increased by over 30%. Tight oil average well has been 2.8 timed, and flowback rate has been increased by 70% after 12 times CO_2 fracturing.

2）提高了返排效率和速度。在页岩气井实施CO_2压裂47井次，返排率提高35%，排液周期缩短1/3。

Shale gas flowback rate has been increased by 35%, the fluid flowback period has been shortened by 1/3 after 47 times CO_2 fracturing in shale gas wells.

压裂现场

Fracturing Site



页岩气井CO_2压裂返排率对比

Comparison of the fluid flowback rate.

（三）形成非常规油气藏CO_2压裂技术

Developed unconventional hydrocarbon reservoirs CO_2 fracturing technology

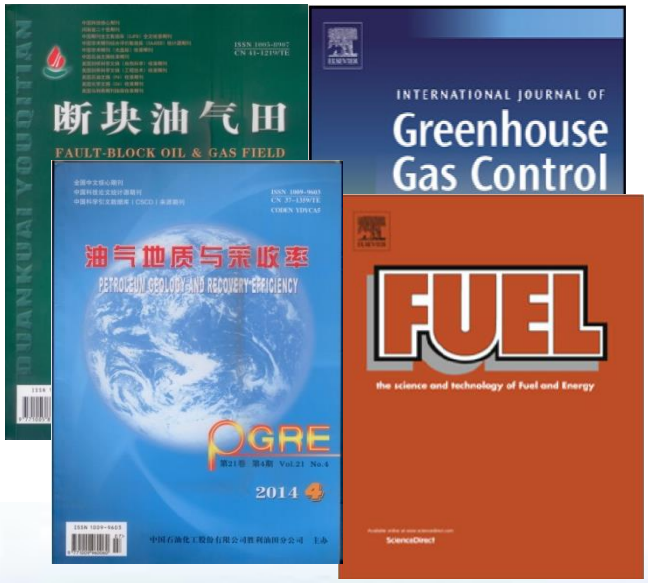
2015年10月19日，自主设计的**无增稠干法二氧化碳压裂技术在云页4井**成功实施，对于陕北缺水地区实现页岩气开发与环境保护具有重要推广意义。

On 19th October, 2015, the first Chinese pure CO_2 fracturing was carried out in YY4 well, which was designed and operated by Yanchang Petroleum independently. It means significantly to environmental protection and shale gas development in Shanbei water shortage regions.

（四）取得的科技成果
S&T Achievements

在国内外期刊发表学术论文**41**篇（国外期刊**8**篇），获国家专利**12**项，相关成果荣获科技奖励**8**项。

Until so far, Yanchang has got many S&T achievements in the field of CCUS, including 41 academic papers, 12 patents, and 8 S&T awards.



学术论文
Academic papers

发明专利
Patents

科技成果奖励
S&T Awards

（五）获得广泛国际认可
International Recognition

- **中-澳碳捕集、利用与封存（CCUS）一体化国际合作示范项目：**获得技术与资金支持；
- Sino-Australia International Cooperation on CCUS: Acquired technologies and funds support;
- **中-美气候变化工作组合作项目：**与美国西弗吉尼亚大学、怀俄明大学等共同开展合作研究。
- US-China Climate Change Working Group Cooperation Project: signed the memorandum with West Virginia University and University of Wyoming, aiming at the study of Yanchang CCUS project.

与澳大利亚全球碳捕集与封存研究院签署合作协议

Cooperation with GCCSI

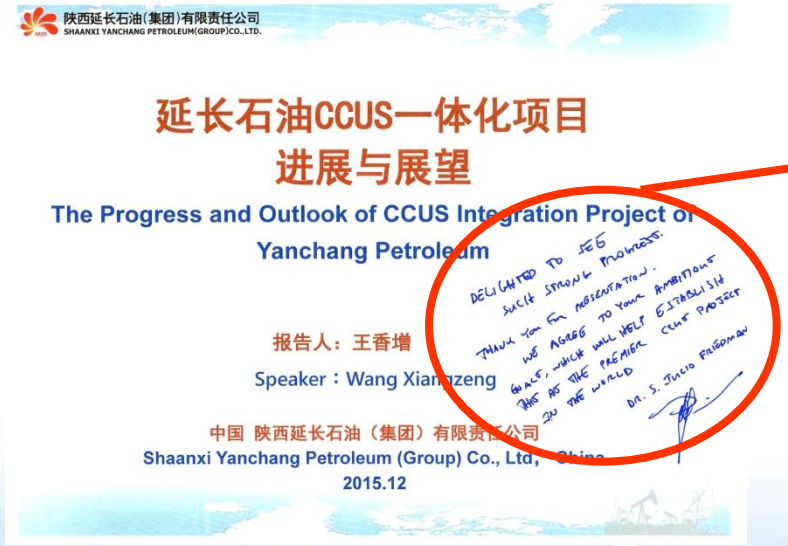
与西弗吉尼亚大学、怀俄明大学签署合作备忘录

Cooperation with WVU and UW

（五）获得广泛国际认可
International Recognition

■ 十分高兴看到延长CCUS项目取得如此大的进展，感谢您的报告。我们赞成您的远景目标，这将有助于将延长项目建设成**世界一流的CCUS 项目**。

-----胡里奥.弗里德曼博士
前美国能源部助理部长

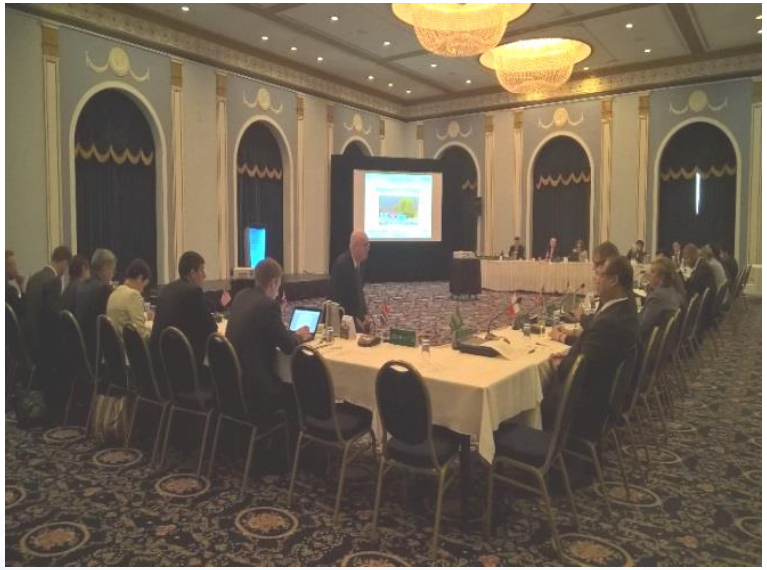


Delighted to see such strong progress, thank you for presentation. We agree to your ambitious goals, which will help establish this as **the premier CCUS project** in the world.

-----Dr. S. Julio. Friedmann

（五）获得广泛国际认可
International Recognition

- 2015年6月，靖边CCS项目获得全球碳封存领导人论坛（CSLF）认证，成为**发展中国家第一个**得到国际认证的CCS项目。
- In June 2015, Jingbian CCS Project was recognized as the first internationally certified CCS project from a developing country by Carbon Sequestration Leadership Forum.



认证会现场（加拿大里贾纳）
CSLF meeting at Regina

靖边CCS项目认证书
Certificate of Recognition from CSLF

（五）获得广泛国际认可
International Recognition

- 2015年9月，习近平主席访美期间，在《中美元首气候变化联合声明》中，提到**“关于2014年中美气候变化联合声明中所提的碳捕集、利用和封存项目，两国已选定由陕西延长石油公司运行的位于中国陕西省延安 - 榆林地区的项目场址。”**
- In September 2015, “U.S.-China Joint Presidential Statement on Climate Change” mentioned that “On the CCUS project agreed to in the 2014 Joint Announcement, the two countries have identified the project site in Yan’an-Yulin, Shan’xi Province, China, operated by Shaan’xi Yanchang Petroleum”

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U.S.-China Joint Presidential Statement on Climate Change

13. Building on the robust bilateral cooperation initiatives that support the achievement of ambitious domestic actions, the two sides commit to further deepen and enhance these efforts through the U.S.-China Climate Change Working Group (CCWG), the premier mechanism for facilitating constructive U.S.-China dialogue and cooperation on climate change. The two sides have made concrete progress in each of the initiatives, including heavy-duty and other vehicles, smart grids, carbon capture, utilization, and storage (CCUS), energy efficiency in buildings and industry, collecting and managing greenhouse gas emissions data, climate change and forests, industrial boilers efficiency and fuel switching, and climate-smart/low-carbon cities, and will continue to work together on green ports and vessels and zero emission vehicles, as well as the enhanced policy dialogue and cooperation on HFCs. Furthermore, a new Domestic Policy Dialogue was established this year to share information on respective domestic actions. The two sides will continue to devote significant effort and resources to the existing initiatives. On the CCUS project agreed to in the 2014 Joint Announcement, the two countries have identified the project site in Yan'an-Yulin, Shan'xi Province, China, operated by Shan'xi Yanchang Petroleum. The two sides will continue to collaborate to demonstrate the utilization of CO2 for enhanced water recovery.

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挑战一：全球首个由企业独立承担的CCUS全流程一体化项目，无成熟经验可借鉴。

Challenge 1: This project is the very first integrated CCUS project operated by just one company alone, so there is no reference to learn from.

煤化工
低成本CO_2捕集
Low-cost CO_2 capture from coal chemical plant

CO_2管输
CO_2 Pipeline

CO_2二次捕集
CO_2 recapture

CO_2综合利用
CO_2 utilization

CO_2埋存
CO_2 storage

驱油
EOR

压裂
Fracturing

技术？
Technology?

经济？
Economic?

安全环保？
HSE?

挑战二：项目区地形复杂，CO_2输送管网建设难度大。

Challenge 2: Terrain brings more difficulties to CO_2 pipeline construction

CO_2输送管网在温压控制、计量方式、增压站建设等方面与北美CCUS项目差异较大，需克服复杂地形带来的影响。

Yanchang CO_2 pipeline have to conquer geographic difficulties that result in temperature and pressure control, measurement and construction difficulties compared with North America CCUS projects.

延长石油CCUS项目区地形
——沟壑纵横
Terrain of Yanchang project region

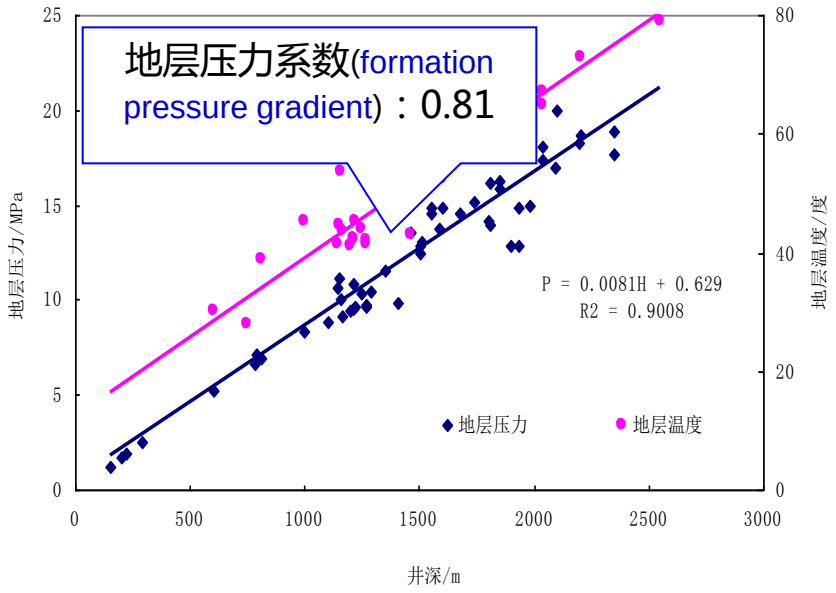
北美CCUS项目区地形
——平原为主
Terrain of America CCUS Region

挑战三：油田地层压力低于最小混相压力，难以实现CO_2混相驱油。

Challenge 3: Formation pressure of oilfield lower than minimum miscibility pressure makes CO_2 flooding miscibility harder

地层压力与埋深交汇图

Formation pressure and depth graph



原始地层压力与最小混相压力对比表

Comparision of IFP and MMP

项目区 Region	原始地层压力 IFP **(MPa)**	最小混相压力 MMP **(MPa)**
靖边项目区 Jinbian	**12.1**	**22.15**
吴起项目区 Wuqi	**15**	**16.12**

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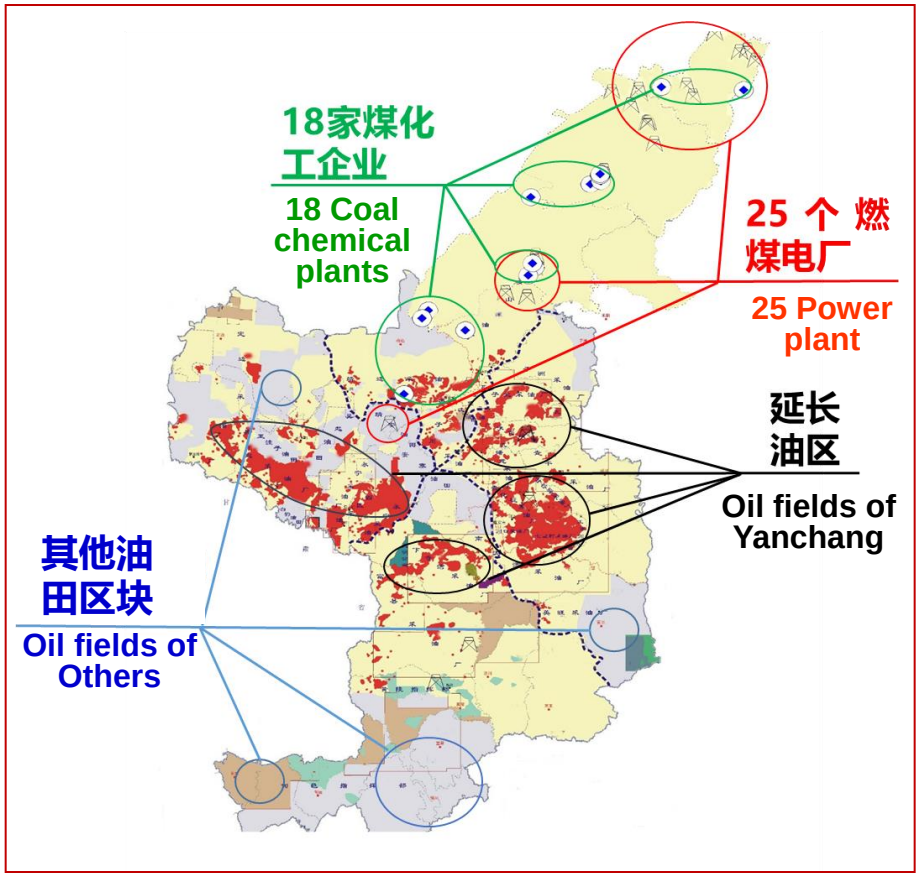
项目具有良好的发展前景

Project future is prospected to be bright

- **充足的碳源**：项目区二氧化碳年排放量超过1亿吨。
- **Abundant carbon resources:** annual CO_2 production is more than 100 million tons in the project area.
- **油气田封存潜力**：延长石油有12.5亿吨石油地质储量适合CO_2驱油与封存，可封存$CO_2$6.5亿吨
- **Storage capability of oil and gas fields:** Yanchang has 1.25 billion tons of OOIP for CO_2 flooding and storage. It can store 650million CO_2.
- **盐水层封存潜力**：奥陶系的盐水层可封存CO_2数十亿吨，其它地层封存量可达数百亿吨
- **Storage capability of saline water layers:** Ordovician saline water layers can store billions tons of CO_2. Other formations can store tens billions tons of CO_2.



陕北油区、煤化工、燃煤电厂分布图

The map of Oil field, Coal chemical and Power plant

制定了中、长期发展规划

Development strategy has been done

近期目标：2017年建成36万吨/年CCUS示范区；

Short-term goal: By the end of 2017, finish construction of integrated CCUS demonstration zone with 360K ton/year capacity

中期目标：2020年建成100万吨/年CCUS示范工程；

Medium-term target: By the end of 2020, finish construction of CCUS demonstration project with 1 million tons/year capacity;

远期目标： 2030年建成400万吨/年能力CCUS示范基地。

Long-term goals: By 2030, finish construction of CCUS demonstration base with 4 million tons/year capacity.

最终目标：Ultimate goal:

形成完整的煤化工CO_2捕集、驱油、封存技术体系与标准，探索CCUS商业运作模式，为中国碳减排和CO_2资源化利用起到示范引领作用。

Complete formatting CCUS technology system and standard, explore CCUS commercial operating mode, and provide relevant experiences for other domestic regions.

结束语
Finally

二氧化碳捕集、利用与封存（CCUS）是能源企业积极应对气候变化，实现碳减排和循环发展的有效途径。将煤化工与碳捕集相结合，将驱油与碳封存相结合，可以降低成本，保障CCUS项目可持续发展。延长石油愿与国际同行进一步加强交流与合作，积极倡导低碳理念，为全球化石能源的高效、清洁、低碳利用做出积极的贡献。

For energy enterprises，CCUS is an positive response towards climate change, and an effective way to achieve low CO_2 emission and recycle. Combined coal chemical industry and carbon capture together, displacement and storage together, cost will be remarkably down, and CCUS projects will be sustainably developed. Yanchang Group is open to knowledge exchanges and work collaborations with worldwide researchers on advocating low carbon style, making contribution to utilizing fossil energy in a more efficient, cleaner way with lower CO_2 emission.

谢 谢 关 注

Thanks for Your Attention