MEMORANDUM OF AGREEMENT

BETWEEN

CHINA ADVANCED COAL TECHNOLOGY CONSORTIUM

AND

U.S. ADVANCED COAL TECHNOLOGY CONSORTIUM

中方洁净煤技术联盟

与

美方洁净煤技术联盟

合作协议

WHEREAS China's Ministry of Science and Technology will extend the research collaboration between the two consortia named above; and

WHEREAS the U.S. Department of Energy has extended the research collaboration between the two consortia named above for the period 2016-2020; and

WHEREAS the two consortia named above are the lead consortia for coal research activities under the U.S.-China Clean Energy Research Center (CERC-ACTC); and

WHEREAS the leadership of each consortium named above desires to identify joint areas of collaboration to be performed during the renewal period of 2016-2020; and

WHEREAS the leadership of each consortium entered into a Memorandum of Agreement (the Agreement) dated August 19, 2014 in which five (5) themes were identified as appropriate to a renewal or extension period, and these themes are: Advanced Power Generation; Knowledge Sharing on large demonstration projects; CO_2 Utilization; Advanced Coal Conversion; and System Analysis of the cyclic operation on large base-load power plants;

NOW THEREFORE, the two consortia named above agree to joint collaboration in each of the above-mentioned themes as follows:

鉴于，中国科技部将延长以上两大联盟之间的研究合作；

鉴于，美国能源部已批准延长以上两大联盟之间的研究合作至 2016- 2020 项目二期；

鉴于，以上两大联盟是中美清洁能源研究中心框架下有关清洁煤煤项目合作的旗舰联盟；

鉴于，联盟双方领导希望明确 2016- 2020 年项目二期共同合作领域；

鉴于，联盟双方领导于 2014 年 8 月 19 日签订备忘录，明确了项目二期五大研究领域的合作意向，包括：先进发电；大型示范项目与知识共享；CO2 利用与埋存；清洁转化；系统分析与建模。

因此，本谅解备忘录的签署双方同意就以上研究领域开展具体合作：

Theme 1 Advanced Power Generation:

任务 1 先进发电 ：

Research and demonstration of advanced power generation including pressurized oxygen combustion (POC) and chemical looping combustion (CLC), including the reaction kinetics and heat transfer properties of pressurized oxy-combustion, the low cost and high quality oxygen carriers preparation for chemical looping combustion including life and physical/chemical stability of iron oxide based oxygen carriers and the interaction of iron oxide with multiple impurities, such as S, Cl, N; studies related to 700°C advanced ultra-supercritical coal-fired power generation technology including the coupling characteristics between combustion and hydrodynamics, the effect of ash deposition on the thermal safety of heating surfaces, and calculations, design methods and pressure part configurations for a 600MW USC 700°C boiler.

先进发电研究和示范包括压力富氧燃烧（POC）和化学链燃烧（CLC），增压富氧燃烧反应的动力学和热传递性质，以及化学链燃烧的低成本高性能氧载体制备 – 包括寿命和氧化铁基氧载体的物理/化学稳定性和氧化铁与杂质(S, CI, N 等)的相互作用； 有关 700℃先进超超临界燃煤发电技术研究，燃烧与水动力耦合作用特性、灰沉积对高温耐热材料热力安全影响、600MW 700℃高参数超超临界锅炉计算和设计方法，为研发新一代 700℃超超临界机组服务。

POC operating under pressure can increase plant efficiency. Conceptual power plants have been previously proposed and modeling results have indicated that an increase in overall plant efficiency of approximately 3 percentage points can be attained by pressurized oxy-combustion. The primary benefits of pressurized oxy-combustion include: 1) the moisture in the flue gas condenses at higher temperature, and thus the latent heat of condensation can be utilized to improve the overall cycle efficiency; 2) the gas volume is greatly reduced; therefore, the size and cost of equipment can be reduced; 3) the convective heat transfer to the boiler tubes is increased for a given mean velocity; and 4) air ingress, which normally occurs in induced-draft systems, is avoided, thereby increasing the CO_2 concentration of the combustion products and reducing purification costs.

增压富氧燃烧可以提高工厂的运行效率。概念性发电厂先前已经提出并有模拟结果证明，增加压力后的富氧燃烧可以实现整体效率提高约 3 个百分点。加压富氧燃烧的主要优点包括：1）烟道气中的水分冷凝在较高温度，从而冷凝潜热可以被利用来改善整体循环效率；2）气体体积大大降低； 因此，可以降低设备尺寸和成本；3）相对于给定的平均流速，锅炉管道对流传热增加了；4）避免了通常发生在感应系统的空气进入，从而提高燃烧产物的 CO 2 浓度和降低纯化成本。

The feasibility of applying chemical looping combustion (CLC) to coal-fuel for large-scale power generation is heavily hinged on the suitability and sustainability of the oxygen carrier (OC).

Researchers are proposing a systematic study of two advanced OCs in coal-fueled CLC including red mud-based and calcium-based OCs. In this project, it is proposed to conduct extensive experimental and computational studies to fully understand the deactivation of these target OCs, the fuel flexibility and the reduction reaction kinetics, the interaction among OCs and coal ash or other impurities such as sulfur, the pressure effect, reactor CFD and scale-up, system (process) evaluation and phase diagram construction including the thermodynamic and experimental kinetics of OC/flyash interaction under real reactor operating condition. The success of the proposed project will result in a detailed understanding of the performance of the cost-effective OCs utilizing rare earth elements as reaction rate promoters and their behavior in a coal-fueled CLC process.

氧载体（OC）颗粒的适宜性和可持续性是煤燃料用于大规模发电中施加化学链燃烧（CLC）的可行性的关键。研究人员提出系统研究燃煤化学链燃烧的两种氧载体， 即红土和钙基氧载体颗粒。在这个项目中，建议进行广泛的实验和计算研究，以充分了解氧载体失活，燃料灵活性和还原反应动力学， 了解这些氧载体颗粒与煤灰或其它杂质如硫之间的相互作用，压力作用，反应器 CFD 模型模拟及大规模制备，了解系统（过程）评估和绘图施工包括实际反应器操作条件下 OC /粉煤灰相互作用的热力学和实验动力学。拟建项目的成功将会对利用稀有元素加快反应速度的富氧燃烧过程成本效益进行详细了解。

Research on a 600 MW, USC 700 °C boiler will include: Transformation of mineral substance in coal during combustion; Ash adhesion behavior on interface surfaces under multi-parameter influences; Effects of ash adhesion behavior on thermal resistance properties; Improvements in coal quality, and ash deposition reduction, and control methods; Design and implementation of experiment platforms for key components; Verification of super alloy materials for key components; High temperature corrosion behavior under multi-parameter influences; Determination of super alloy composition; Mastering material manufacturing and welding process; Verification of turbine materials by using or transforming the experiment platform.

600 兆瓦，700 ℃高参数超超临界锅炉设计研究包括以下工作：煤粉燃烧过程中矿物质转化；多参数影响下的接口表面煤灰附着沉积行为；灰沉积对热阻性能的影响；煤质改良，减少灰沉积和防控方法；关键部件验证实验平台的设计与建设；高温合金材料及关键部件的实炉验证；多参数影响下耐热材料的高温热腐蚀行为；高温合金组合物的测定和选材。掌握优化材料部件的加工和焊接工艺；利用并改造实验平台完成对汽轮机材料的验证。

Theme 2 Knowledge Sharing on large demonstration projects:

任务 2 大型示范项目合作与知识共享

Facilitating collaboration and knowledge sharing on existing and planned CCUS demonstrations in both the US and China, including pre- and post- combustion; Knowledge-sharing regarding the planning, construction, commissioning, operation and performance improvement of large CCS demonstrations; a Compendium of operating data describing simultaneous capture, storage, utilization, and electricity generation, comparison on the performance of the demonstration system operation; Improved performance of CO_2 capture systems (higher efficiencies, lower cost) through technical modification and system optimization.

中美两国就现有的和计划运行的 CCUS 示范项目促进合作和知识共享，包括：燃前和燃后碳捕集;分享有关规划，建设，调试，大型 CCS 示范运行的性能提升等方面数据和信息；整合有关捕集，储存，利用和发电系统化，和系统运行性能比较数据；通过技术改造和系统优化，加强二氧化碳捕集系统的性能（效率更高，成本更低）。

For pre- and post-combustion capture, technical exchange and cooperation in the following key domains will be conducted: key Data comparison on the commissioning, operation and modification of large scale CCS demonstration; the comparison on similar IGCC based pre-combustion CO_2 capture systems of China and US, the techno-economic analysis of the pre-combustion and post combustion capture system; the evaluation of the integration strategy between capture and power units, modification of the power unit or whole system; the optimization of the integration between CO_2 utilization and capture unit, meeting the standards on CO_2 production rate and purity, while making the energy cost lowest; techno-economic evaluation on the application of new absorbents/adsorbents for post- and pre-combustion CO_2 capture, energy-saving technology and process modification to the exiting demonstration units, in terms of cost, energy penalty and power efficiency; Information and experience sharing on technical modification and improvements on system currently on operation.

For oxy-combustion capture, data sharing can be carried out to semi-industrial facilities, such as China HUST 35MW facility in Yingcheng and the 15MW oxy facility in Alstom, and execute experimental and numerical study on such facility on common interested issue, such as radiative heat transfer during oxy-combustion process, so as to accumulate design experience on large scale facilities. The theme will try to leverage the knowledge sharing between large scale oxy demonstration projects, and further explore the system integration and optimization of such projects, eg. the influence of new oxygen production and CPU technology on thermo-economics of oxy-combustion.

对燃烧前和燃烧后碳捕集，技术和经验交流合作的主要内容包括：大型 CCS 示范项目调试、运行、改进主要技术参数比较，中美两国基于 IGCC 的燃烧前捕集项目参数的比较，燃烧前、燃烧后项目技术和经济性比较；燃烧前、燃烧后捕集系统涉及的发电端改造及与系统深度深度整合和优化的策略和评价；优化驱油和封存端与捕集系统的集成关系，保证捕集端 CO2 产率和纯度满足注入标准前提下，使 CCS 系统整体能耗最低；燃烧前、燃烧后捕集相关的新型吸收剂/吸附剂、节能技术和新工艺改造的技术经济评估以及对成本、能耗和发电效率的影响；在运行的示范系统技术改进方面信息和经验交流。

对富氧燃烧碳捕集，就 35MW 富氧燃烧示范项目与美方阿尔斯通公司的 15MW 富氧燃烧示范项目进行数据及经验共享，并在该平台上就共同感兴趣的富氧燃烧过程辐射传热开展试验和数值模拟研究，以期为该技术的大型化积累设计经验；结合双方正在进行和拟开展的富氧燃烧大型示范工程推动项目信息和经验的分享，在此基础上开展大型富氧燃烧机组的系统集成和优化设计分析，并探讨未来新型制氧和压缩纯化方法对系统经济性的影响。

Theme 3 CO_2 Utilization and Storage:

任务 3 CO2 利用与埋存

If CO_2 captured from power plant is injected into a saline aquifer, brine water of low salt concentration could be recovered and could be purified and used by industry or to supply domestic use. Besides the benefit of low salt concentration in the brine water, the purification cost of the recovered water could be lowered as it was produced with high initial pressure, making separation using membrane easier. Also, it may be possible to manage the CO_2-water pressure front and increase the storage capacity of the aquifer. Thus it is of multiple benefits to apply CO_2-EWR. Such a study could involve researchers from both China and the US and would establish what technologies are available, what limitations exist for those technologies, what markets exist for the production of clean water from saline sources, and general economics of such solutions, as well as to make key findings on CO_2-EWR in real scenario. The collaboration if successful would help win support from the public for clean coal technology and CCUS. Thus cooperation will also drive the adoption of policies in both countries to further promote R&D and educational exchanges in these relevant fields.

如果从发电厂捕获的CO2被注入咸水层，低盐浓度的淡盐水可以被回收，被纯化然后使用到工业用途或饮用水。除盐度较低以外，由于淡盐水源具备一定压力（有利于反渗透分离），可使净化成本大大降低。此外，有可能实现预控二氧化碳水压力和增加含水层的存储容量。因此，CO2驱水具有多重效益。相关研究将有助于双方了解在应用CO_2强化采水技术流程中已经有的技术，技术的成熟度和限制，技术潜在的市场，全流程应用的主要经济性指标，以及新的重要发现。此次合作如果成功，将有助于赢得公众对清洁煤技术和CCUS的支持。这样的合作也将推动在这两个国家和这些相关领域采取措施，进一步促进研发和教育交流。

Low permeability and ultra-low permeability oil reservoirs have very strong heterogeneity, combined with the characteristics of low pressure, low production, so it is difficult to recover these reservoirs. At present, most of the low permeability and ultra-low permeability reservoirs are developed by injecting water. However, sometimes it is very difficult to inject water or there are no effects after injecting water because of low permeability. Conventional water flooding development also leaves a large amount of residual oil retention in tiny pores. The arid or semi-arid region like Shaanxi Province has a shortage of water resources, and water injection development and hydraulic fracturing will produce a large amounts of waste. Improving the low permeability and extra-low permeability reservoirs' withdrawal efficiency posts a critical technical challenge. Based on the CO_2 flooding characteristics and displacement effect analyses, quantitative evaluation will focus on the key factors that control CO_2 displacement effects. The research will establish fine geological models, carry out numerical simulations of CO_2 displacement and combine with experimental results, then optimize parameters, such as injection cycle, injection rate and MVA.

低渗透和特低渗透油藏具有很强的非均质性，加上低压，低产量的特点，难以形成自然产能，开发的难度很大。目前，大部分低渗透和特低渗透油藏需要注水开发。然而，有时这是非常困难的，低孔低渗储层存在难以注入水，和注水后无产能的现象。常规传统的水驱开发还导致大量残余油滞留在细小的孔隙内，难以采出。像陕西省干旱或半干旱地区水资源短缺，注水开发和水力压裂后油井会产生大量的废弃物，造成环境污染。如何提高特低渗与超低渗致密储层的开发效益成为关键的技术难题。基于对 CO2 驱替特征和驱替效果分析，定量对比评价制约 CO2 驱替效果的关键因素。这项研究将建立精细地质模型，开展 CO2 排量的数值模拟，并与实验结果相结合，然后优化参数，如注入周期，注入速率和 MVA。

Built on the success in the first five years, the proposed work for the next five years will focus on the commercialization of CO_2 capturing technology using microalgae. A demonstration of large scale waste CO_2 utilization using selected algal strains previously developed will be conducted at a 3-acre cultivation facility co-located with a Coal Gasification Plant. By achieving long-term stable operation, the annual carbon fixation capacity for the demonstration facility will reach 80 metric tons. Secondly, development will be undertaken on multiple algal products, including crude algal oils for biofuels, defatted algal biomass for high-protein animal feeds, as well as other types of high value products (e.g. EPA, DHA, pigments etc.). The development and utilization of the downstream products will increase the economics and sustainability of this technology, which ensures the viability for its commercialization.

本项目将基于上一个五年计划的研发成果，开展大规模微藻固碳示范及其产品开发应用的研究。所选示范养殖基地养殖面积约 3 英亩，通过实现长期稳定运行，固碳能力预计达到 80 吨/年。在规模化示范的同时，生产高品质的微藻生物质，并通过多联产技术开发出包括生物柴油和高蛋白动物饲料在内的多种产品，提高微藻固碳的经济效益，从而加速技术的产业化进程。

Theme 4 Advanced Coal Conversion:

任务 4 清洁转化 ：

Based on the research work in the first phase of ACTC, the partners from China team and USA team will focus on the research and development of the new coal stage conversion poly-generation technologies combined pyrolysis, gasification and combustion, advanced coal gasification processes (Chemical Looping gasification with CO_2 capture, Direct SNG production from coal, stage oxygen injecting entrained flow gasification and underground gasification), coal/biomass or coal/low grade oil co-conversion process and utilization of coal DCL residue and waste water. The design theory and methods for demonstration of these new coal conversion technologies will be developed and part of developed technologies will be demonstrated successfully at industrial scale for development and installation in both countries. This project will pursue high conversion efficiency with low cost footprint reductions, low carbon emission, and pollution control at large coal conversion plants.

中美双方研究团队将在第一阶段的研究工作基础上，重点开展煤炭热解气化燃烧分级转化、先进煤气化（煤炭化学链气化、煤炭直接气化制天然气、分级供氧气流床气化以及煤炭地下气化）、煤炭与生物质或劣质油共转化以及煤直接液化残渣及废水的综合利用等技术的研究与开发，在对关键过程的实验与理论研究基础上，提出所研发技术的设计理论与方法，具备工业化示范条件，同时实现部分技术在中美两国进的工业示范，并促进所研发的技术在两国的发展与推广，实现煤炭高效低成本转化、碳捕集以及低污染物排放。

Theme 5 System Analysis and Modeling:

任务 5 系统分析与建模 ：

Coal-fired power plants used mainly to provide base-load power, and rarely used for peak-load power generation, have operating and control problems during periods of intermittency. With increasing capacity of intermittent renewable power in the power fleet, coal-fired power plants will be used more for load adjustment. Study of power plant performance during rapidly changing loads will be a major task in the next five to ten years. In summary, performance study and operation optimization of coal fired power plants with a wide range of generation loads are of interest to both China and the US.

燃煤电站在过去基本承担基本负荷发电任务，较少参与电网调峰。随着间歇式可再生发电的装机不断增加，燃煤电站在新时期将不得不承担起更多的调峰任务。研究燃煤电站变工况运行特性是燃煤发电领域未来五到十年内的主要方向之一。综上所述，燃煤电站宽负荷范围内的机组特性及运行优化研究是中美两国共同的研究兴趣。

Compared with conventional coal-fired power plants adding the relatively independent but still associated carbon capture, utilization, and storage (CCUS) system and other chemical production or environmental control systems, overall plant performance will be heavily determined by sub-system performance and the integration between different sub-systems, which will make the processes more complicated. Due to the lack of actual operating data and experience at this level of sophistication, it is difficult to evaluate some new design effects in practical operation. Thus it will be better to run those designs first in a dynamic simulator for verification. The designs can also be modified according to the simulation results. The design and analysis resources database based on the dynamic simulator may facilitate system design, design validation, auto-tuning of control system parameters. Information developed in this theme can be used to retrofit existing control systems in order to improve load response, and minimize stresses resulting from cyclical operation.

与传统燃煤电厂相比，集成电厂是一个多种设备、多项技术集成的复杂系统，整个系统的性能取决于子系统的性能及各子系统间的匹配，使工艺过程更加复杂，如果再加入相对独立，但仍相关的 CCUS 和化工产品生产或环境控制系统等既关联而又相对独立的子系统，将会使过程更复杂。由于这个级别的复杂运营缺乏实际运行数据和经验，难以评估一些新设计的实际操作效果。因此，先在仿真机上进行模拟运行可很好地帮助设计方案，还可根据仿真效果随时修改设计方案。仿真机上储存有设计、分析资源库，可方便系统设计，验证设计方案，自动整定系统参数，为现场调试参数的设定提供参考。

A Statement of Project Objectives, written by West Virginia University, dated June 22, 2015, and a Collaboration Plan for Phase II (China Side Draft), dated 2015-08-05 are both attached to this Memorandum for guidance and as source documents related to the five (5) themes, and the agreements reached in this Memorandum of Agreement.

本协议附录包括，2015 年 6 月 22 日由西弗吉尼亚大学草拟之项目目标声明，和 2015 年 8 月 5 日中方项目第二阶段合作计划草案，作为本备忘录五大合作任务的相关源文档。

Agreed July, 1, 2016 in Beijing, People's Republic of China:

双方同意签署协议， 2016 年 7 月 1 日，中国北京

For China Advanced Coal Technology Consortium:

洁净煤联盟中方签署人：

Dr. ZHENG Chuguang- Director

郑楚光博士，联盟中方主任

For U.S. Advanced Coal Technology Consortium:

洁净煤联盟美方签署人：

James F. Wood- Director

詹姆斯-伍德先生 ，联盟美方主任