

出國報告（出國類別：開會）

## 2024 年地熱崛起研討會出國報告

服務機關：台灣中油股份有限公司

姓名職稱：地熱開採工程師 張瑋倫

派赴國家/地區：美國/夏威夷大島

出國期間：113 年 10 月 26 日至 11 月 1 日

報告日期：113 年 11 月 19 日

## 摘要

地熱崛起會議是地熱界最大的年度聚會亦是地熱產業的旗艦年會。會議討論內容包含鑽井技術、發電技術、區域供暖、直接利用等方面。2024 年地熱崛起會議在夏威夷大島的希爾頓威克洛亞村舉辦，其位置如下圖 1，個人主要行程如下表 1 所示，圖 2 為個人註冊登記時拍攝照片，圖 3 為個人在會場與地熱專家宋聖榮教授合影照片。與會過程收穫的新知很多，包含管材、塗層、除垢、鑽頭及發電等技術。參展商攤位亦相當盛大，其中發現 cladtek 公司已將耐腐蝕合金內襯複合管成功商業化，其展示海報如圖 4 所示。很榮幸有機會參加這個會議，除了結交地熱專家外也學習到很多新的技術。後續個人也會持續精進，為國內提高地熱能源占比努力。

表 1、2024 GRC 主要行程

日期	主要行程摘述
10/26(六)~10/26(六)	去程 (台灣桃園→日本福岡→美國夏威夷檀香山→美國夏威夷科納→希爾頓威克洛亞村)
10/27(日)	註冊登記、技術海報
10/28(一)	研討會第一天、技術會議、技術海報、參展商攤位
10/29(二)	研討會第二天、技術會議、技術海報、參展商攤位
10/30(三)	研討會第三天、技術會議、技術海報、參展商攤位
10/31(四)-11/1(五)	返程 (希爾頓威克洛亞村→夏威夷科納→夏威夷檀香山→日本東京→台灣桃園)



圖 1、Geothermal Rising Conference 2024 舉辦地點



圖 2、Geothermal Rising Conference 2024 會議現場進行註冊



圖 3、會議現場與宋聖榮教授合影



圖 4、cladtek 展示 CRA 合金內襯複合管產品海報

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## 目的

夏威夷當地沒有生產石化燃料，幾乎所有石油都來自利比亞和阿根廷，這造成夏威夷的能源價格昂貴，且容易受到天氣和地緣政治干擾。目前夏威夷積極往減碳及再生能源方面努力，承諾 2023 年前完全無煤，並製定法律要求在 21 年內實現 100%清潔能源。夏威夷擁有豐富的風能、太陽能 and 地熱能，目前夏威夷 6.25% 的電力來自七個風電場，在大島上，約 30%的能源來自地熱發電廠，該發電廠從基拉韋厄火山(Kilauea volcano)附近獲取熱量，對火山型地熱發電的經驗豐富。

國內目前有 24 處地熱案場，規劃總裝置容量 61.75 MW。台灣中油在地熱開發積極投入，在宜蘭仁澤打造 0.84 MW 地熱電廠；在土場有二期及三期計畫。探採研究所目前進行火山型酸性地熱田開發相關技術研究，編列「酸性地熱井中和系統可行性研究」及「完井管材篩選與耐蝕監測技術研究」期待未來對國內大屯山區地熱開發有所助益。

夏威夷能源發展條件和台灣相似，可作為我國綠能發展的參考，其在火山型地熱的開發經驗相信也對國內大屯山開發有幫助。2024 年地熱崛起國際研討會選擇在夏威夷大島的威克洛亞村舉辦，地熱崛起國際研討會是地熱界重要的年度聚會，當地的地熱學者及專家相信也不會缺席這個重大的會議。參加地熱崛起國際研討會將有益火山型地熱開發技術的交流與學習，幫助我們掌握國際最新技術，並提升年度研究計畫的廣度與深度。

## 過程

本次出國計畫行程自 10 月 26 日至 11 月 1 日，其中會議時間為 10 月 27 日至 10 月 30 日，共計四天，會議區域位於希爾頓威克洛亞村大廳階梯後方，圖 5 為會議區地圖。大型討論會安排在 Grand Ballroom，技術研討會安排在 Kohala 1~4 及 King' s 1~3 會議室，海報區設置在 Grand Promenade 右側，參展商攤位則設置在 Kona 及 Queens，圖 6 為本次會議取得的參展廠商型錄資料。本次會議的技術研討會安排在 10/28~10/30 進行，報告的重點如表 2 所示。

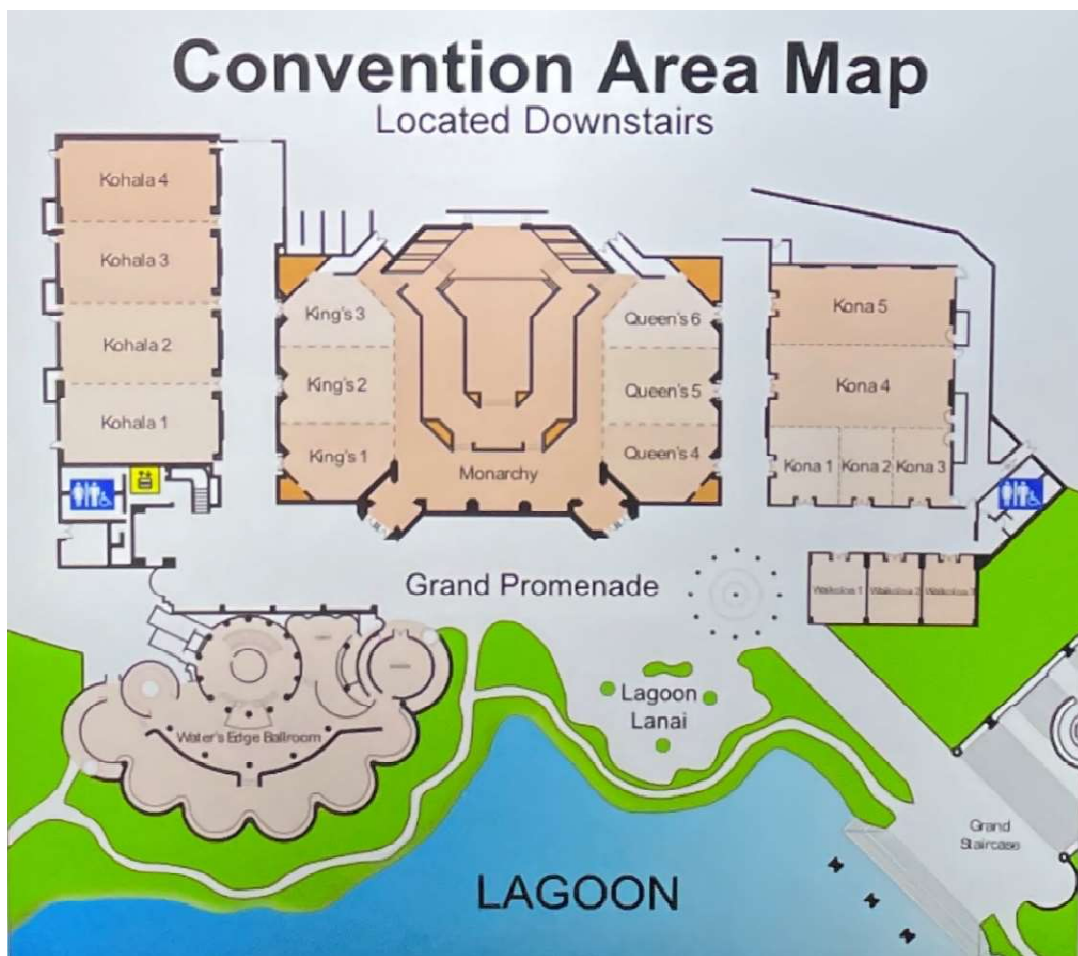


圖 5、會議區地圖



圖 6、會議參展商型錄

表 2、技術研討會重點題目  
2024/10/28(一)

**Session 1C: Drilling**

📍 Kohala 3-4

- 1. Breaking the 200C Barrier – Development of an Integrated High Temperature Directional Drilling System (3:00 PM - 3:20 PM)
- 2. Managed Temperature Drilling: Real-Time Damage Monitoring of Insulated Drillpipes and an Automatic Controller to Mitigate Effects of Temperature Increase (3:20 PM - 3:40 PM)
- 3. Effect of Hydrostatic Pressure on Mechanical Specific Energy and Interfacial Friction Angle in Hard Rock Drilling (3:40 PM - 4:00 PM)
- 4. Driving Down Exploration Costs in Geothermal (4:00 PM - 4:20 PM)
- 5. Enhanced Weight on Bit Application in Hard Rock Drilling Through Innovative Anchoring Technology (4:20 PM - 4:40 PM)
- 6. Optimizing Hard Rock Geothermal Drilling Efficiency with PDC Bits: A Comprehensive Study (4:40 PM - 5:00 PM)

**Session 1E: Closed Loop/Advanced Geothermal Systems**

📍 King's 2 (Grand Ballroom)

- 1. Techno-Economic Viability of Flexible Dispatch of Unconventional Geothermal Systems (3:00 PM - 3:20 PM)
- 2. Geomechanical Modelling for Closed-Loop Geothermal Development in Geretsried, Germany (3:20 PM - 3:40 PM)
- 3. Exploring Thermal Efficiency: Accurately assessing K-Values of Vacuum Insulated Tubulars for Geothermal Applications (3:40 PM - 4:00 PM)
- 4. Influence of reservoir convection on heating in closed-loop geothermal (4:00 PM - 4:20 PM)
- 5. Optimizing Geothermal Borehole Number and Positioning through Simulated Annealing Algorithm (4:20 PM - 4:40 PM)
- 6. On the potential of closed-loop long horizontal wells for heat storage (4:40 PM - 5:00 PM)

2024/10/29(二)

**Session 2B: Enhanced (or Engineered) Geothermal Systems**

📍 Kohala 1-2

- 1. Experimental investigation of the flow behavior of Ionic Liquids for use as working fluids in Enhanced Geothermal Systems (7:30 AM - 7:50 AM)
- 2. EGS Reservoir Modeling for Developing Geothermal District Heating at Cornell University (7:50 AM - 8:10 AM)
- 3. Geopressured Geothermal System: An Efficient and Sustainable Heat Extraction Method (8:10 AM - 8:30 AM)
- 4. Operation Strategies to Avoid Thermal Short-circuit in EGSs with Horizontal Wells (8:30 AM - 8:50 AM)
- 5. Experimental Analysis of Fluid Hydraulics in Enhanced Geothermal Systems (8:50 AM - 9:10 AM)
- 6. Understanding Thermal Effects on In-Situ Stress Estimations Through Post-Peak Pressure Analysis from High-Temperature True-Triaxial Block Fracturing Experiments (9:10 AM - 9:30 AM)



### Session 2C: Drilling

📍 Kohala 3-4

- 1. High-Temperature Characterization and Drilling Simulation of Rock from Utah FORGE (7:30 AM - 7:50 AM)
- 2. Severe Lost Circulation Mitigation using Temperature Activated Materials (7:50 AM - 8:10 AM)
- 3. Expandable LCMs: An Effective Solution for Plugging Fractures (8:10 AM - 8:30 AM)
- 4. The Characteristics of the Overpressured Sedimentary Formation in Ulubelu Geothermal Field, Indonesia (8:30 AM - 8:50 AM)
- 5. Enhancing Geothermal Drilling Performance: A Stuck-Pipe Risk Advisor Leveraging Causal-AI and Semantic Web for Explainable Decision Support (8:50 AM - 9:10 AM)
- 6. Drilling Innovation Enables Faster Delivery of Geothermal Wells in Indonesia (9:10 AM - 9:30 AM)

### Session 3B: Enhanced (or Engineered) Geothermal Systems

📍 Kohala 1-2

- 1. Influence of hydraulic fracturing on induced seismicity based on a combined flow and geomechanical model (10:00 AM - 10:20 AM)
- 2. Analysis of the Stimulated Volume and Seismicity Migration in Utah FORGE Stimulations (10:20 AM - 10:40 AM)
- 3. Scaling and Thermal Penetration Depth in Enhanced Geothermal Energy Production (10:40 AM - 11:00 AM)
- 4. Learning curve of seismic risk mitigation for EGS since Basel 2006 to Utah FORGE 2024 from the perspective of a project developer (11:00 AM - 11:20 AM)
- 5. Interpretation of Stimulated Permeability by Model Calibration with Data from Circulation Program at FORGE (11:20 AM - 11:40 AM)
- 6. Integrated Life Cycle Simulation Study and Recommendations for Utah FORGE (11:40 AM - 12:00 PM)

### Session 3C: Reservoir/Production

📍 Kohala 3-4

- 1. Temporal Evolution of Kamojang Reservoir Pressure: Unraveling Upflow Dynamics in a Dry Steam Geothermal System Through Multidisciplinary Analysis (10:00 AM - 10:20 AM)
- 2. Coupled multi-segment wellbore and thermal modeling in a deep sedimentary geothermal field -- a case study for the DEEP Geothermal Project, Saskatchewan, Canada (10:20 AM - 10:40 AM)
- 3. Numerical Modeling and Reservoir Behavior of the Puna Geothermal Venture (10:40 AM - 11:00 AM)
- 4. Updates of Numerical Reservoir Model for Sorik Marapi Geothermal Field (11:00 AM - 11:20 AM)
- 5. A Wellbore Model Approach for Scaling Prediction and Condition Assessment (11:20 AM - 11:40 AM)
- 6. Enhancing Reservoir Performance Insight: A Comprehensive Monitoring Approach with Steam Allocation Lumut Balai (SALB) Application (11:40 AM - 12:00 PM)

### Session 3D: Energy Conversion/Utilization

📍 King's 1 (Grand Ballroom)

- 1. Generating Value in Non-Condensable Gas Emissions from Geothermal (10:00 AM - 10:20 AM)
- 2. Monetizing Low-Moderate Enthalpy Reservoirs: Lessons Learned (10:20 AM - 10:40 AM)
- 3. A study of deep geothermal energy feasibility for "behind the fence" power at the Calgary International Airport. (10:40 AM - 11:00 AM)
- 4. Grid Resilience Analysis on Geothermal District Heating and Cooling Implementation Alongside Four Existing Oil and Gas Wells in Tuttle, Oklahoma (11:00 AM - 11:20 AM)
- 5. Greenhouse Gas Emissions Reduction: Global Geothermal Power Plant Catalog (11:20 AM - 11:40 AM)
- 6. Geothermal Power for Green Hydrogen Production (11:40 AM - 12:00 PM)

### Session 4B: Super Hot Geothermal

📍 Kohala 1-2

- 1. Ideal Thermal-Hydraulic Performance of Geothermal Power Systems Above 300 °C (4:30 PM - 4:50 PM)
- 2. Increased Structural Integrity of Casings of High-Temperature Geothermal Wells using Novel Technologies (4:50 PM - 5:10 PM)
- 3. Optimizing Energy Production for Large Scale Superhot Rock Geothermal (5:10 PM - 5:30 PM)
- 4. The Superhot Opportunity for New Zealand- Joining the Ends Together (5:30 PM - 5:50 PM)
- 5. Heat Harvester: Mazama Energy's Full-System Power Generation Optimizer for Superhot Rock EGS (5:50 PM - 6:10 PM)
- 6. Superhot Geothermal - Experience and Outlook in Iceland (6:10 PM - 6:30 PM)

### Session 4C: Reservoir/Production

📍 Kohala 3-4

- 1. Development and Evaluation of Preformed Particle Gels for Preferential Fluid Flow Control (4:30 PM - 4:50 PM)
- 2. Dynamic Modeling of Fracture Networks to Optimize Geothermal Reservoir Performance (4:50 PM - 5:10 PM)
- 3. Characterization of Flow in Induced Fractured Networks Using Tracers in Enhanced Geothermal Systems (5:10 PM - 5:30 PM)
- 4. Power Outputs from the Field Tests of Thermoelectric Generators at Different Temperatures (5:30 PM - 5:50 PM)
- 5. Unlocking the Full Production Potential of Geothermal Wells in Indonesia using a Novel In-situ Generated Acid Fluid Technology (5:50 PM - 6:10 PM)
- 6. Textural Analysis of Sedimentary Rocks: Implications for Geothermal Reservoir Characterization (6:10 PM - 6:30 PM)

#### Session 4D: Economics

📍 King's 1 (Grand Ballroom)

- 1. Probability of Discovery as a useful concept for communicating exploration drilling uncertainty (4:30 PM - 4:50 PM)
- 2. Assessing the Economic Value of Underground Thermal Storage for Hybrid Geothermal Power (4:50 PM - 5:10 PM)
- 3. Whispers of a New Frontier for Safe and Profitable Geothermal Anywhere (5:10 PM - 5:30 PM)
- 4. Geothermal Power Systems Analysis: Outcome of Industry Stakeholders Workshop (5:30 PM - 5:50 PM)
- 5. Geothermal Reserves Standards: A Study of the Applicability of the SPE Petroleum Resources Management System, a Proposed Classification Framework for Geothermal Reserves and Resources (5:50 PM - 6:10 PM)
- 6. Collaboration and Continuous Improvement Makes Utah Geothermal Project Economic and Successful (6:10 PM - 6:30 PM)

2024/10/30(三)

#### Session 5C: Reservoir/Production

📍 Kohala 3

- 1. Casa Diablo IV: A case study for cooperative baseline analysis to mitigate environmental impacts (10:00 AM - 10:20 AM)
- 2. Geothermal Resource Management: Insights from Stock Modeling Analysis in Icelandic Fields (10:20 AM - 10:40 AM)
- 3. Conceptual Model of the Hydrothermal System at the Salton Sea KGRA (10:40 AM - 11:00 AM)
- 4. Improving Geothermal Well Production through Scale Removal: A Lakeview, Oregon Case Study (11:00 AM - 11:20 AM)
- 5. Puna Geothermal Venture Flow Testing: Facility Design Upgrades and Results (11:20 AM - 11:40 PM)
- 6. Hot springs and geysers: Exploring historical and modern impacts of geothermal energy production on surface thermal features and standardizing management practices. (11:40 AM - 12:00 PM)

#### Session 5E: Transition from Oil & Gas

📍 King's 2 (Grand Ballroom)

- 1. Geothermal Reservoir Simulation Analysis in Support of Electricity Co-Production Feasibility Study at the Blackburn Oil Field, Nevada (10:00 AM - 10:20 AM)
- 2. Impact of Geothermal Energy Production from Four Inactive Oil and Gas Wells in Tuttle, Oklahoma for District Heating and Cooling on Grid Flexibility (10:20 AM - 10:40 AM)
- 3. Modeling a Hybrid Renewable Energy System for Bowman County, North Dakota: Assessing the Feasibility of Transitioning from Coal to Wind, Solar, and Geothermal Power (10:40 AM - 11:00 AM)
- 4. DeepStor - District heating from high-temperature heat storage in a depleted hydrocarbon reservoir (11:00 AM - 11:20 AM)
- 5. Optimizing Design and Operation of Closed Loop Geothermal Using Integrated Asset Simulation (11:20 AM - 11:40 AM)
- 6. Geothermal Prospecting in Oil and Gas Basins (11:40 AM - 12:00 PM)

#### Session 6E: Well Construction & Completion

📍 King's 2 (Grand Ballroom)

- 1. Zonal Isolation Concept for FORGE Geothermal Wells (1:30 PM - 1:50 PM)
- 2. Development and Qualification of an Elastomer Based Retrievable Packer for Effective Annular Isolation in Enhanced Geothermal Systems (1:50 PM - 2:10 PM)
- 3. Alkali-activated Gibbsite Cement for Use in Supercritical and CO<sub>2</sub>-rich Geothermal Wells (2:10 PM - 2:30 PM)
- 4. Integration Well Construction, Value to Reduce Overall West Java Geothermal Development Cost (2:30 PM - 2:50 PM)
- 5. REVOLUTIONISING GEOTHERMAL WELL DESIGN AND OPERATIONS WITH HIGH-TEMPERATURE METAL EXPANDABLE PACKER TECHNOLOGY: A NOVEL APPROACH IN DRILLING AND WORKOVER (2:50 PM - 3:10 PM)
- 6. A Summary of the FORGE Project for the Development of Multi-Stage Fracturing System and Wellbore Tractor to Enable Zonal Isolation During Stimulation and EGS Operations in Horizontal Wellbores (3:10 PM - 3:30 PM)

#### Session 6F: Mineral Extraction|Regional Updates

📍 King's 3 (Grand Ballroom)

- 1. Quantifying the Impact of Water Needs for Lithium Production from Geothermal Brines in the Salton Sea KGRA (1:30 PM - 1:50 PM)
- 2. What's in Your Brine - a Case for Critical Minerals Co-production from Geothermal Brines (1:50 PM - 2:10 PM)
- 3. Initial Simulations of Lithium Production from Geothermal Brines (2:10 PM - 2:30 PM)
- 4. REVIEW OF LITHIUM EXTRACTION SUITABLE FOR INDONESIA GEOTHERMAL BRINE (2:30 PM - 2:50 PM)
- 5. How can the EU's post-communist countries use geothermal to achieve energy independence? (2:50 PM - 3:10 PM)
- 6. Exploring the Past, Present, and Future: Geothermal Energy on the 100th Anniversary of the Turkish Republic (3:10 PM - 3:30 PM)

## 具體成效

具體成效依據會議參展商資料、海報資料及技術報告資料中重要的部分進行介紹。

### 1. 參展商資料

會議參展商的數量非常多，其中和防蝕技術和管材製造有關的廠商和個人研究最為相關，以下針對相關收穫進行報告。

首先是一家名為 Cladtek 的廠商，其展示產為機械式襯管(Mechanically Lined Tubular, MLT)，是一種以耐蝕合金作為內襯的複合管材。Cladtek 是一家專門製造和銷售抗腐蝕合金(Corrosion Resistance Alloy, CRA)機械內襯管的公司，他們為 CRA 複合管材提供全面的解決方案，包括管件、配件、法蘭、壓力容器、閥門及彎頭。Cladtek 支援廣泛的應用，包括陸上、海上、海底、地下、地熱、氫氣儲存和運輸、碳捕獲、利用和封存 (CCUS) 以及碳捕獲和封存(CCS)。Cladtek 在印尼、巴西和沙烏地阿拉伯設立製造工廠，並計劃 2025 年在卡達擴張，保證具有成本效益、高品質和及時的全球交付。

在本會議上其展示的機械內襯管(Mechanically Lined Tubular, MLt)為該公司最新的發明。複合管使用碳鋼製外管，配有耐腐蝕合金襯裡和適用於井下應用的優質接箍，圖 7 為 MLT 產品的示意圖。外管可選擇 API 5CT 規範的管材，包含 K55、L80、T95 及 P110，內襯的部分可選擇材質包含 316L 不銹鋼、317Mn、6Mo、22Cr 雙相不銹鋼、25Cr 雙相不銹鋼、鈦金屬及鈦合金。由於機械磨損的原因，內襯厚度最少為 1.5 mm，可依需求增加，當然價格會因內襯厚度增加而變貴。現場 cladtek 的銷售員拿出一塊實體切片向我展示，其照片如下圖 8 所示。表 3 為 CRA 管、GRE 內襯複合管、高分子內襯複合管、碳鋼管及 MLT 的比較表。GRE 內襯複合管和高分子內襯複合管在耐高溫及耐機械損傷部分表現較差，在高溫地熱應用較困難；碳鋼耐腐蝕性不佳；CRA 管則是價格較高。

過去川崎重工曾致力於井下複合管材的製造，但井下金屬複合管的製作並不容易，必須克服：內外層的接合強度、接合後的母管強度、內襯合金抗蝕性維持及接箍問題。因此有很長一段時間都無商業化產品。其中接箍是最困難的部分，克服接箍設計後才陸續有金屬複合油管出現。Grant Prideco 曾發表過複合油管

的產品，抗腐蝕合金板材（2~8 mm 鎳基合金）經過裁切、自動焊接、缺陷檢測、插入碳鋼管內及液壓成型。管串兩端以焊接密封防止流體滲透，接箍設計允許使用聚四氟乙烯（PTFE）增加密封性，不過 Grant Prideco 的產品資料顯示其僅有管徑小的油管。目前 Cladtek 已經可以提供 4”~20” 內徑的複合套管，可用來作為地熱生產管材，這個產品提供未來酸性地熱完井材料更多的選擇。

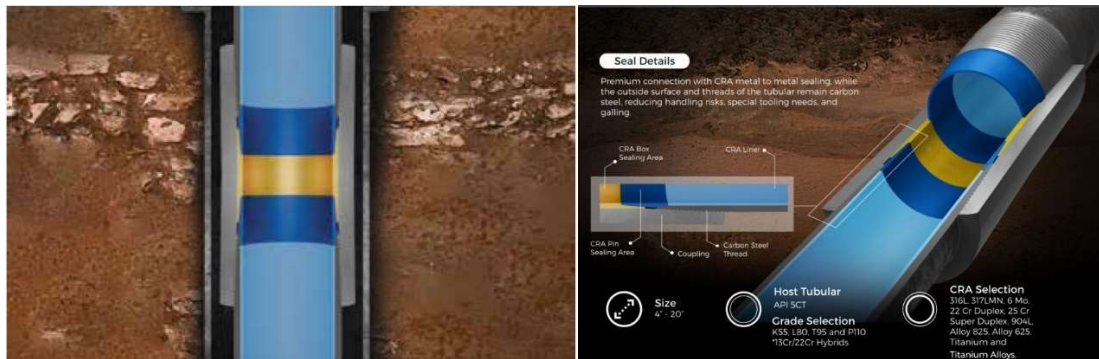


圖 7、cladtek 耐腐蝕合金機械內襯管材剖面示意圖

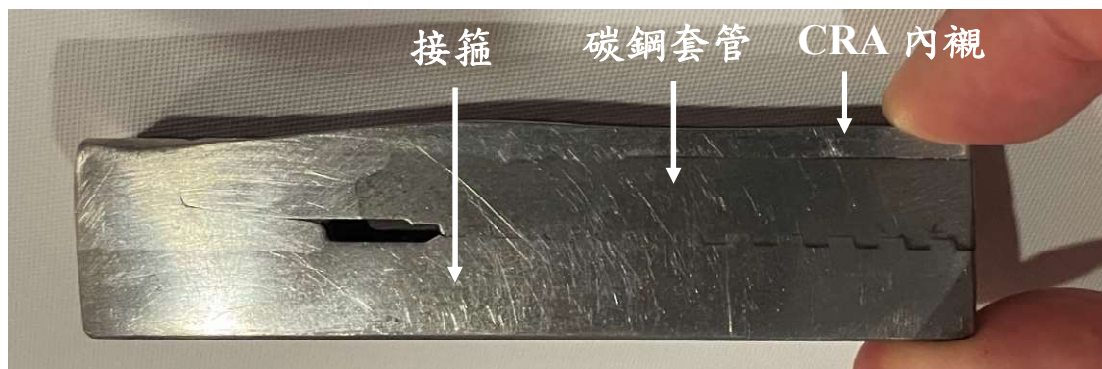


圖 8、cladtek 耐腐蝕合金內襯套管實體切片照片

表 3、CRA、GRE 複合管、高分子複合管、碳鋼管及 MLT 比較。

Material Comparison	Cost	Corrosion Resistance (ID)	Corrosion Resistance (OD)	Temperature	Handling	Intervention & Mechanical Damage
Solid CRA	✗	✓✓	✓✓	✓✓	✗	✓✓
GRE Lined	✓	✓	✗	✗	✓	✗
Polymer Lined	✓	✗	✗	✗✗	✓	✗
Carbon Steel	✓✓	✗✗	✗	✓✓	✓	✓✓
Cladtek MLT	✓	✓✓	✗	✓✓	✓	✓

除了 cladtek 外，會場還有三家管材製造商，分別是 BUTTING、HUNTING 及 vallourec。BUTTING 於 1777 年在奧德河畔克羅森成立，最初是一家銅匠店，目前已是一家在不銹鋼加工方面聞名的公司，其在成型、焊接加工和材料技術方面具領先地位，可提供各種適用於特殊腐蝕性應用的高性能材料。BUTTING 製造生產優質不銹鋼焊管(有縫管)在世界各地已廣泛應用，例如食品工業管件、製藥工業管件和生物化學管件。員工具備所有現行焊接程序的資格和認證，保證焊接的不銹鋼管符合要求。可提供外徑 15~ 2032 mm、壁厚最大 70 mm 的耐腐蝕有縫管。管件符合多種國際標準，包括 API、ISO、ASTM 及 NORSOK 等。因應地熱的腐蝕環境，BUTTING 提供 Alloy 625、S32205 雙相不銹鋼及 S32750 超級雙相不銹鋼材質的有縫套管。圖 9 為 BUTTING 在現場的展示攤位，圖 10 為其提供的型錄資料。

有縫管在腐蝕環境中，焊縫附近的熱影響區容易有材質不均及應力集中的問題，是腐蝕優先發生的區域。現場人員未能提供這部分更深入的資料，後續若要考慮有縫管，可針對熱影響區耐蝕性再進行評估。



圖 9、BUTTING 套管製造商展示攤位



圖 10、BUTTING 有縫管型錄

HUNTING 是一家歷史悠久的公司，1874 年發跡至今已 150 年，是全球能源、航空航太、醫療和發電行業的領先製造商和技術提供者。其產品包含射孔、井測、接箍、油套管、海底技術、修井設備及隨鑽量測等設備。其在地熱領域提供耐高溫高壓的管材及接箍，圖 11 為其現場展示的 SEAL-LOCK XD 產品。圖 12 左側為 SEAL-LOCK XD 剖面圖。SEAL-LOCK XD 是一種鉤式螺紋的接箍設計，非常適合應用於高彎曲、高壓及高壓縮應力的極端井應用，其底切負載側面可在極端負載下維持結構完整性。可提供的尺寸範圍為 2.375~14 吋，材質包含碳鋼、雙相不銹鋼、鎳合金及鈦合金，耐溫可達 350°C。另一種產品是針對疲勞強度進行最佳化的 TEC-LOCK™ Wedge，如圖 12 右側。可提供的尺寸範圍為 4~13.625 吋，材質包含雙相不銹鋼、鎳合金及鈦合金，耐溫一樣可達 350°C。HUNTING 公司的接箍產品令人印象深刻，其提供井下力學條件嚴苛時完井材料的解決方案，材質部分選擇也相當多，未來若有需求可參考該公司產品。



圖 11、HUNTING 展示攤位



SEAL-LOCK XD (SLXD)



TEC-LOCK™ Wedge (TLW)

圖 12、HUNTING 地熱管材解決方案

最後是國際知名管材製造商 vallourec，他是一家總部位於法國的跨國製造公司。該公司成立於 1957 年，從事熱軋無縫鋼管、汽車零件和不銹鋼等產品的

生產。vallourec 的產品主要供應給能源、建築、汽車和機械行業，致力於創新和可持續的管件解決方案，用以支持低碳能源的發展和減少碳排放。

原本以為其在地熱會議會展示其無縫的耐腐蝕管材，然而攤位桌上擺著一段雙層金屬管，如下圖 13 所示。經詢問，這個展品是 THERMOCASE VIT，VIT 是 Vacuum-insulated tubing 的縮寫。這個產品使用雙層管並將兩管間的空隙抽真空，最大限度的降低兩管間的熱傳導。這種管串在閉循環的地熱系統中扮演重要角色。某些地區地下岩石溫度足夠但少有裂縫，意味著井下沒有流體或滲透率非常低，無法使用傳統地熱的形式發電。利用閉循環系統，冷流體注入 THERMOCASE VIT 和套管之間的環孔並向下流入井中加熱，加熱後的流體再從井底沿著 THERMOCASE VIT 管內向上流動並用於渦輪機發電，圖 14 為閉循環系統管內流體流動示意圖。THERMOCASE VIT 的高隔熱性能可大幅減少冷水和熱水間的熱交換損失，增加發電量。

根據銷售員的說法，日本的一家地熱業者在井底溫度為  $230^{\circ}\text{C}$  的乾熱岩層中安裝閉環系統，以 THERMOCASE VIT 提供隔熱功能，該井的生產效率可接近 80% (即保持井下可用功率的 80%)，流量為  $4.2\text{ L/s}$ 。國內大屯山過去也曾發現某幾口探勘井地下水量不足的問題。若溫度夠高，將其改以封閉迴路方式發電，或許可增加一些可以開發的區域。

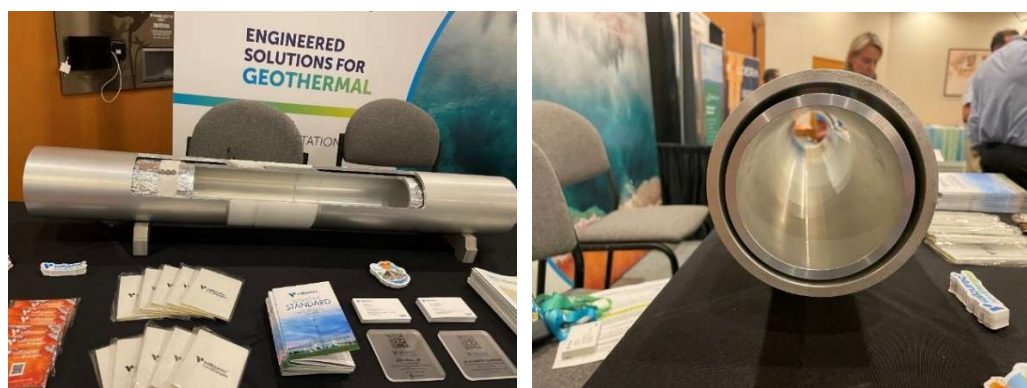


圖 13、Vallourec THERMOCASE VIT 展示品



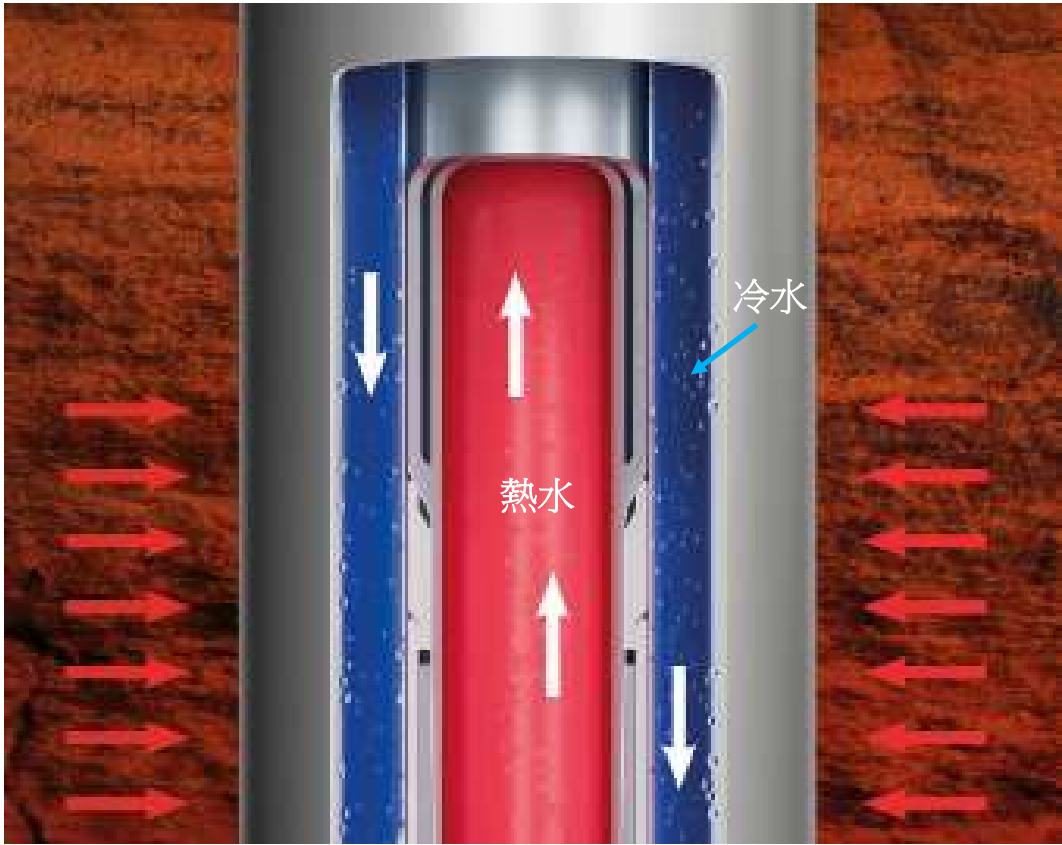


圖 14、Vallourec THERMOCASE VIT 展示品

## 2. 海報資料

會議在 Grand Promenade 右側每天皆有不同的海報展示，內容涉及範圍相當廣泛，其中冶金、鍍膜、結垢、固井水泥及二氧化碳管理相關的海報特別引起我的興趣，就以下針對海報區相關收穫進行報告。

海報題目：用於增強型地熱系統(EGS)的耐腐蝕、高強度管材：鎳基超合金的擠製和熱機械加工以增強機械性能

這是 Nippon Foundation-Deepstar Collaborative Technology Development Grant Program 有關的研究，單位是 Daido Steel of Japan。其目的是開發熱穩定、具優異高溫機械性質的耐腐蝕合金地熱發電組件。目前正在開發“Nano-Composite Expandable Element-Stack with Elastomeric-Core”，用於高溫高壓地熱井的封隔器。此外，也開發出導熱率接近零的經濟型奈米複合管原型。設計耐腐蝕合金以鎳為主體，加入鈦及鈮元素促進 $\gamma$ 相析出(鎳合金中的強化相)。可客製化添加鉻和鉬元素提高合金耐腐蝕性及耐孔蝕當量(PREN)，其發展出的合金 PREN 在 54~65 之間。

一個新的合金設計產品包含許多考量，成分、微結構、機械性質等，當其中一個環節有問題就必須重新開始，因此一個商業化產品常是歷經多年努力的成果。海報中雖沒有推出正式的商业化產品，不過其顯示地熱領域已有廠商開始往合金設計方向研發。或許，不久的將來就會有更多優質的地熱發電組件可以選擇。相關的海報如下圖 15 所示。

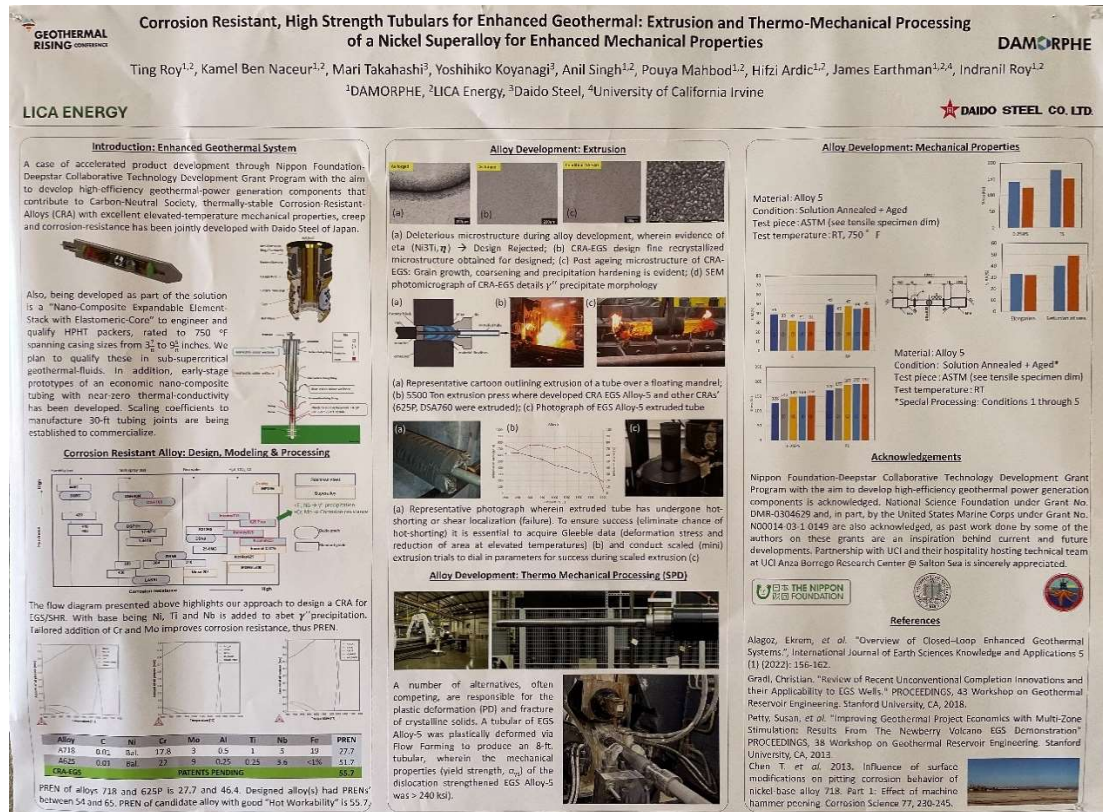


圖 15、GRE2024 海報，題目 Corrosion resistance, high strength tubular for enhanced geothermal: Extrusion and Thermo-Mechanical Processing of a Nickel Superalloy for Enhanced Mechanical Properties

海報題目：開發碳基塗層用以抑制管道內表面的矽垢積聚

矽垢是地熱發電廠最大的問題之一，例如熱交換器中的矽結垢會導致輸出下降。作者先前的研究中已發現類鑽碳膜塗層(Diamond like carbon, DLC)可以抑制矽垢在管件中沉積。但管件內部很難進行 DLC 鍍膜。此研究的目的是在開發出專門用於管件內部表面的 DLC 鍍膜方法。其開發出的新型鍍膜方式如下圖 16 所示。

實驗部分，該研究使用內徑 16 mm、長度 500 mm 的管件為基材，將 DLC 鍍在管道上。利用 XAFS 判斷 DLC 結構，利用 ERDA 量測鍍膜上的氫含量。預計氫含量高的鍍膜對結垢具有更好的抑制效果。現地結垢試驗，與無塗層管道相比，最優條件的 DLC 塗層可將二氧化矽積聚量減少至 0.5%。相關的海報如下圖 17 所示。

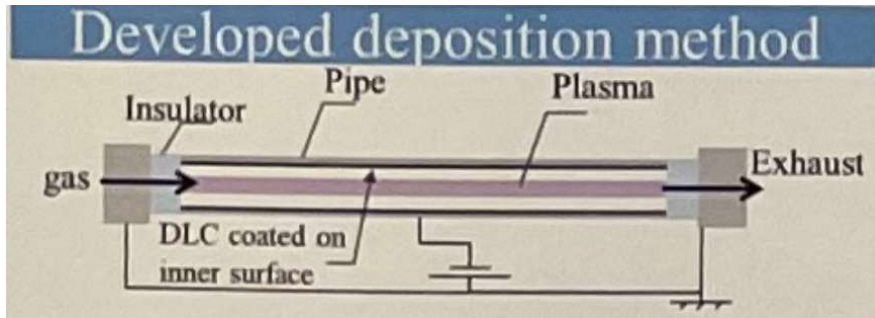


圖 16、此研究開發的管內鍍膜設備

**Development of Carbon-based coating to suppress silica scale accumulation on the inner surface of pipes**

Yuya Nakashima<sup>1</sup>, Shinya Uj<sup>1</sup>, Shigeto Yamada<sup>1</sup>, Risako Imai<sup>2</sup>, Hiroyuki Kousaka<sup>3</sup>

<sup>1</sup>Fuji Electric Co., Ltd., <sup>2</sup>Graduate school of Natural Science and Engineering, Gifu Univ., <sup>3</sup>Center of applied research of plasma, Faculty of Engineering, Gifu Univ.

**Summary**

- New deposition method of DLC (Diamond like carbon) coatings specialized for inner surface of pipes has been developed.
- DLC coating on the inner surface coating could suppress silica accumulation to 0.5 % compared with stainless steel pipes.

**Background**

- Silica scale is one of the biggest problem in the geothermal plant such as in the heat exchanger causes an output drop (Fig. 2).
- In our previous research, Carbon based coating (DLC) which could suppress the silica scale accumulation has been developed. However, it's difficult to deposit inside of pipes (Fig. 3).

**Aim**

- Development of low adherence DLC against silica scale on the inner surface of pipes

**Experiment procedure**

**Materials and coatings**

Stainless steel pipe (AISI 304, ID:16 mm, O.D.:19 mm, L:500 mm), plate (AISI 420, 10 × 10 × 1 mm, for structure analysis)  
 DLC coating: deposited by the inner pipe deposition equipment (Table 1)  
 DLC analysis for DLC: X-ray analysis fine structure (XA-FS)  
 Elastic recoil detection analysis (ERDA)

**Scaling test**

Geothermal brine had flowed into the coated/iron-coated pipes for 75 days with 0.65t/hr at the Takigami binary plant located in Kyushu area in Japan (Fig.4).  
 Accumulated silica amount: Detected Si atom composition by SEM-EDX

**Table 1 Deposition setting**

Average Voltage	~440 V
Duty rate	0.075 %
Deposition time	360 min
Pressure	33 Pa
Gas	Ar
Flow rate	75 sccm
Flow rate	CH <sub>4</sub> 18.5 sccm

**Results**

**1. DLC coating on the inner surface of pipes**

- Black colored coating was deposited at the whole length of the pipe (Fig.5).
- From XAFS spectrum, (a) (b): 0-250 mm had amorphous carbon structure. DLC was deposited at least more than half length of the pipe. (c)500 mm is thought as polymer like carbon coating since it had a periodic structure in the peak derived from  $\sigma^*$  structure (Fig.6).
- From ERDA analysis, (c):500mm had higher hydrogen content than (b):250 mm on the outer most surface at 1mm (Fig. 7). (c):500mm was expected to have lower scale accumulation since higher hydrogen content could reduce silica adhesion in our previous research.

**2. Silica accumulation through the scaling test**

- Even though silica scale got fractured, steel surface still had accumulated silica scale. It seems silica scale adhered to the steel strongly. In contrast, silica scale peeled off from the DLC surface (Fig.8)
- Accumulated silica amount eventually reduced to minimum 0.5 % compared with stainless steel pipe (Fig.9).

**Discussion**

**Suppression mechanism of silica scale accumulation by DLC coating**

- Inner surface of the pipe had rough surface and silica scale remained in the groove (Fig.10). Peeled silica scale had fractured portion which had correlated shape with silica scale in the groove in the inner surface of the pipe (Fig.11).  
 → Anchor effect mainly enhanced the scale accumulation, however DLC itself had few adhesion force with silica.

**Conclusion**

- Pipe with inner diameter 16mm, length 500mm was used for the inner surface coating substrate and the coating was deposited in the entire length of pipe. Polymer like carbon coating at the 0 mm from top of the pipe and DLC coating was deposited at 250, 500mm, it is distinguished by XAFS analysis.
- DLC coating at 250, 500mm of the pipe had hydrogen content of 11.27%, respectively. 500 mm of the pipe had higher hydrogen content than at 250mm and expected to have higher suppression effect for scale accumulation.
- After the scale test at site, amorphous silica scale was accumulated. DLC coating at 500 mm could reduce the amount of accumulated silica to 0.5 % compared with non-coated pipe made from SUS304.

**Future work**

- Chemical structure control to decrease silica accumulation on the whole length of the pipes
- Improvement of deposition method to adapt DLC coatings to longer pipes (final target should be 10 m)

**Acknowledgement**

The authors are grateful to involved in the Takigami binary power plant for their long-term proper maintenance and management of the scale accumulation test equipment and for their fruitful discussions.

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圖 17、GRE2024 海報，題目 Development of Carbon-based coating to suppress silica scale accumulation on the inner surface of pipes

海報題目：利用低導熱係數塗層的最新進展延長地熱井鑽具壽命

此海報指出，儘管地熱發電潛力巨大，但目前全球地熱發電量 16 GW 僅佔再生能源發電量的 0.5%。由於增強型地熱系統(EGS)等進步，全球地熱發電裝置容量在 2030 年預估將達到 32 GW。EGS 需要在乾燥、非常堅硬、炎熱的岩石中鑽探。這些條件超出原本為石油和天然氣開發的工具適用範圍。保持鑽井液冷卻可

避免井下工具(BHA)損壞，導熱係數(TC)控制是溫度管理的關鍵。TC 是衡量材料導熱能力的物理量。對於 EGS，低 TC 的鑽桿對於鑽井至關重要，較低的 TC 可確保較低的流體溫度並保護井下 BHA。該研究研發新型塗層，並在在儲層溫度 250 °C，用絕緣塗層管鑽 5 公里深的花崗岩地熱井進行測試。結果顯示新型塗層在整個鑽井過程中可使鑽井液溫度維持在 95°C 以下，並確保鑽柱溫度維持在 120°C 以下防止 BHA 損壞。相關的海報如下圖 18 所示。


GEO THERMAL  
RISING  
CONCEPT

## Extending drilling tool life in geothermal wells with recent advances in low thermal conductivity coatings

Michael Adams  
Tuboscope | NOV

### Introduction

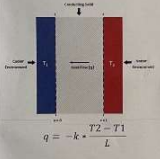
- Geothermal energy is the only large, inexhaustible renewable energy source that naturally produces heat and clean, reliable baseload power at scale
- Despite its potential, global geothermal power production is currently 16 gigawatts, just 0.5% of electricity generation from renewables (IEA, 2013)
- By 2030, global installed geothermal power capacity could reach 32 gigawatts, thanks to advancements like enhanced geothermal systems (EGS)
- Closed-loop EGS requires drilling multilaterals at depths of ~2+ miles into dry, very hard, hot rock (390°F+)
- These conditions exceed tolerances of directional and MWD tools originally developed for oil & gas
- Keeping drilling fluids cool is critical to keeping downhole tools cooler to avoid damage and downtime



Courtesy: US DOE (2018)

### Thermal conductivity controls the key to temperature management

- Thermal conductivity (TC) measures a material's ability to conduct heat
- For EGS, low TC drill pipe is critical for effective, efficient drilling
- Lower TC → Lower rate of heat transfer
- Lower rate of heat transfer → Improved T protection for cooler fluids and BHAs



$q = -k \frac{T_2 - T_1}{L}$


### Goal for EGS drilling at scale

- Insulate drill pipe to keep its TC at or below 0.5 W/mK
- Leverage Tuboscope's 70 years of plastic pipe coating for oil & gas
- Starting point: Internal coatings developed for long-term corrosion control, hydraulic efficiency, and deposit prevention on pipe surfaces
- Evaluate TC of current coatings
- Adjust coating formulation to reduce TC to target value
- Ensure new coating retains chemical, corrosion performance

### Testing methodology

Thermal conductivity testing

- ASTM E1530-19 → Industry standard for measuring thermal resistance for solids < 25 mm thick (-20 to 310°C)
- Accurate thermal conductivity measurements are calculated from thermal resistance values



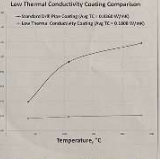
Thermal GEM-01 - Coated Heat Flow Meter

Physical properties/chemical/corrosion testing

- Abrasion resistance
- Impact resistance
- Flexibility
- Hydraulic improvement/surface roughness
- Chemical/corrosion resistance in immersion tests and in-house autoclave testing

### Identifying suitable coatings in the lab

- Per ASTM E1530-19, initial oil & gas coating's TC = 0.8360 W/mK, exceeding operator's TC target
- Iterative formulation adjustments produced a new coating with TC = 0.1808 W/mK
- The new coating maintained the same desirable properties for impact, chemical, and abrasion resistance as well as corrosion resistance
- The new coating applied smoothly to minimize surface roughness and improve hydraulic efficiencies



Type	Conventional coating	Low-conductivity coating
Liquid epoxy phenolic	5-9 (127-229)	26-30 (508-742)
Applied thickness, mil (micron)	0.6	0.32
Abrasion resistance (Fiber thickness mil/1000 cycles)	11.97	2.43
Surface roughness (Ra µm)	0.8168	0.1808
TC (W/mK)	50	108
Ring crush (mm distance)	51	185
Direct impact (m/s)	80	88

### Proving its potential in the field

Field testing conditions/setup

- Goal: drill a 5-km (3.1-mile) deep granite geothermal well with new insulating coated pipe at reservoir temperatures of 250°C (482°F)
- Local geothermal gradients in the region exceeded 50°C/km
- MWD tools measured temperature at the bit
- Temperature sensors along the drill string recorded annular fluid temperatures

Results

- New coating kept drilling fluid temperatures below 95°C (203°F) throughout the drilling run
- Drill string stayed below the temperature threshold of 120°C (248°F) to prevent BHA damage
- Downhole temperatures validated the operator's transient thermodynamic model, confirming that the coating could maintain the drilling fluid below 120°C (protecting downhole tools from temperature failures)

### Conclusions

- Drill strings with low TC can optimize geothermal drilling by keeping drilling fluid and tools cooler for longer
- Low conductivity coatings developed for oil & gas can be easily modified/refined to drill long multilaterals in deep, hot geothermal reservoirs
- Thorough testing and refinement delivered a low TC coating (0.1808 W/mK) that maintained superior corrosion, chemical, and hydraulic performance
- Field testing confirmed that the new coating kept mud below 120°C to protect BHA tools while drilling a 5-km geothermal well
- Operators are placing more insulated drill pipe orders for further field trials

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### Acknowledgments

- Thanks to our team for consistently designing/delivering low TC coatings that meet the demands of deeper, hotter reservoirs

圖 18、GRE2024 海報，題目 Extending drilling tool life in geothermal wells with recent advances in low thermal conductivity coatings

海報題目：利地熱系統中二氧化矽抑制劑與 pH 調節的比較研究

此海報指出，Geo Dipa Energi (GDE) 擁有印尼爪哇省的地熱發電廠。這座電站自 2002 年以來一直在運行，迄今地表和地下仍然存在結垢問題，二氧化矽含量非常高，約為±900 mg/L。兩相流體的溫度範圍 180~200 °C，透過單閃蒸系統發電，所有鹽水透過開放式運河系統冷卻，並以 40~60°C 的溫度重新回注

GDE 的許多井場採用 pH 調節來減輕二氧化矽結垢。硫酸可以透過放熱反應稀釋鹽水中的礦物質，包括單體二氧化矽。理論上，只要單體二氧化矽仍以矽酸的形式存在，其穩定性就會維持。然而，AFT(常壓閃蒸槽)後二氧化矽濃度值降低，導致該處形成非晶相二氧化矽沉澱。實際上使用 pH 調節方法要達到所需 pH 值是困難的。再者，注入過多硫酸導致 pH 值過低將導致設備腐蝕問題。

GDE 對 DPI-920(二氧化矽抑制劑)和 H<sub>2</sub>SO<sub>4</sub>的經濟性進行研究。化學抑制劑在操作和維護過程中更有效果，其減少頻繁的二氧化矽清潔成本和管道更換成本，並減少生產時間的損失。總結 1 年的總營運成本，井場中的化學抑制劑比 pH 調節方法的效率高 17%。相關的海報如下圖 19 所示。

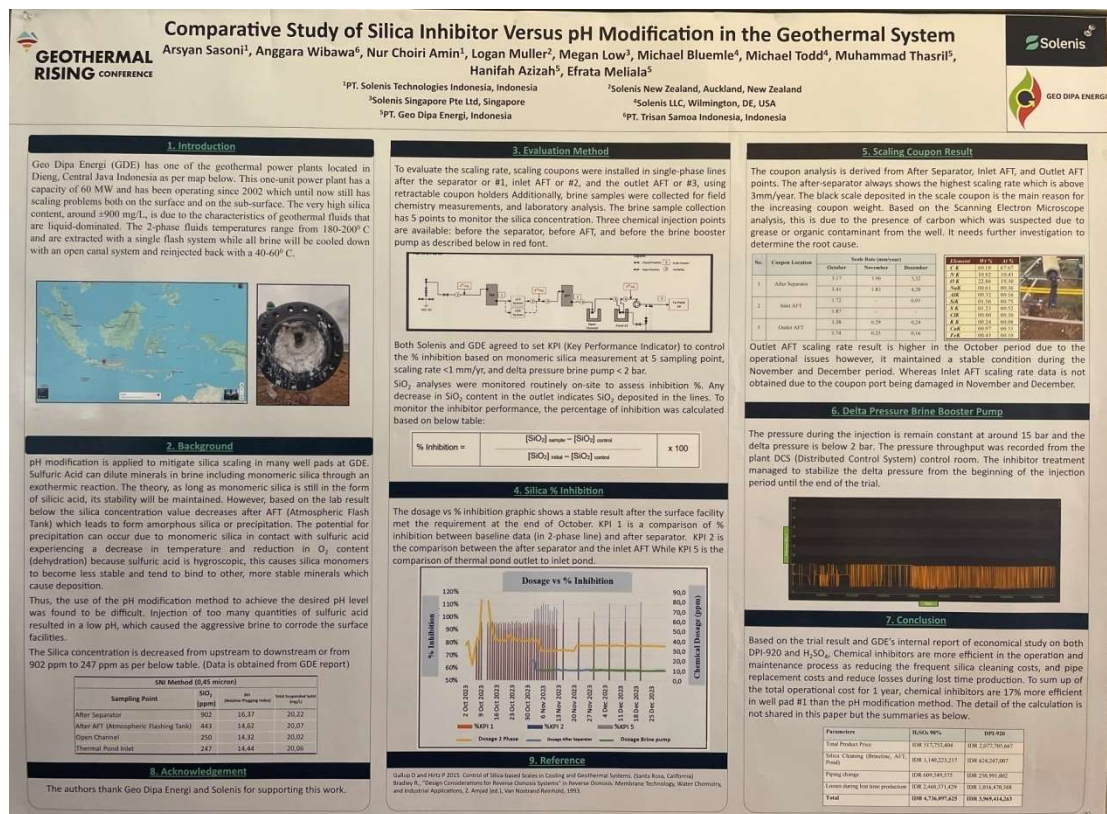


圖 19、GRE2024 海報，題目 Comparative Study of Silica Inhibitor Versus pH Modification in the Geothermal System

海報題目：常溫和高溫下 G 級與 H 級水泥套管-水泥界面接著剪切強度比較分析  
 海報指出，固井作業對於維持地熱井、石油井和天然氣井的完整性至關重要。隨著地熱能需求的成長，高溫的極端條件需要更高品質的固井。這些環境中水泥

的完整性取決於其物理、化學、熱和機械性質。熱負荷會導致水泥環收縮和膨脹，導致應力重新分佈並損害井的完整性。此研究評估 G 級和 H 級水泥與不同套管材料間的黏結強度，確定失效前的最大應力，並透過 DCS 測試評估機械性質。

結果顯示，G 級水泥因其初始黏結強度強而成為高溫地熱應用的首選。儘管隨著時間的推移，性能略有下降，但它仍可提供地熱井必要的完整性。G 級水泥是高溫下的理想選擇，而 H 級水泥在室溫下長期表現較好。相關的海報如下圖 20 所示。

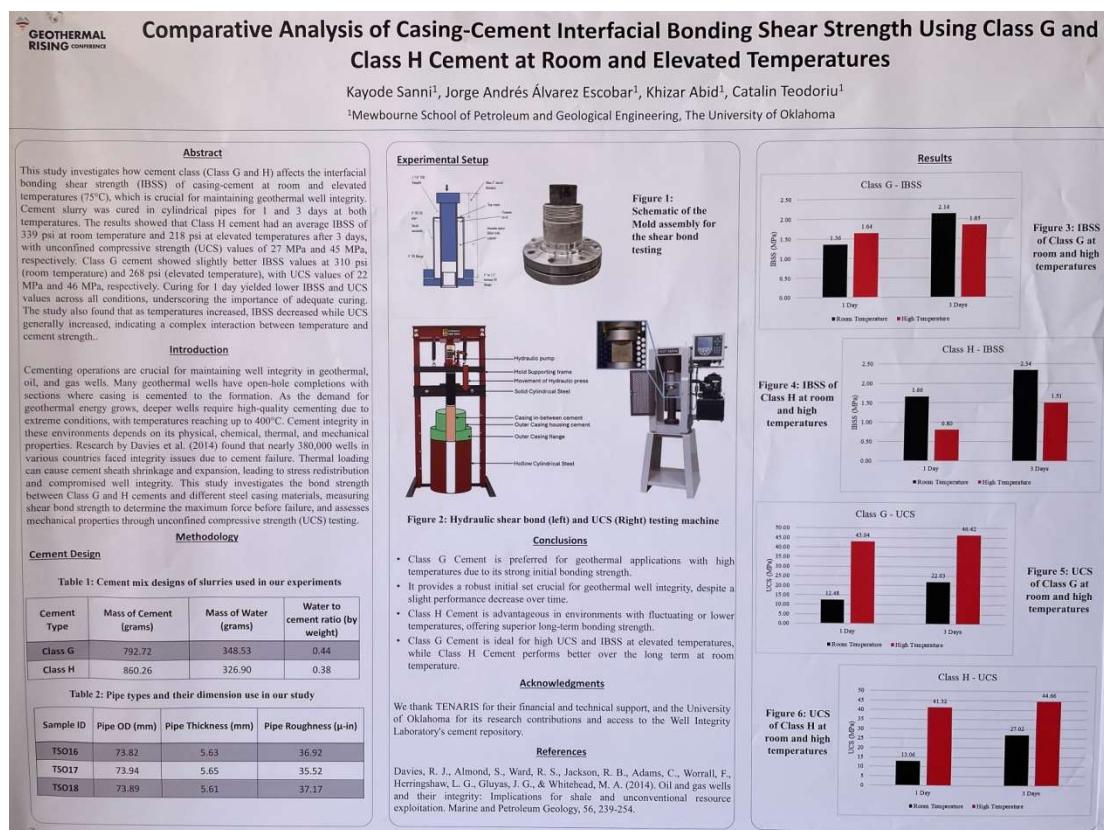


圖 20、GRE2024 海報，題目 Comparative Analysis of Casing-Cement Interfacial Bonding Shear Strength Using Class G and Class H Cement at Room and Elevated Temperatures

海報題目：地熱能和二氧化碳管理

海報指出，不凝結氣體(NCG)是地熱流體中存在的氣體，它們在發電廠冷凝器的溫度和壓力條件下不會凝結。這些氣體維持氣態，會影響地熱發電廠的效率。

地熱流體中常見的不凝結氣體包括：

1. 二氧化碳：地熱系統中最常見的不凝結氣體。它可以透過增加冷凝器壓力來影響發電廠的性能。
2. 硫化氫：經常存在於地熱流體中，尤其是在火山地區。它有毒且具有腐蝕性，需要特殊處理和處理。
3. 甲烷：雖然通常含量較少，但它也可能存在於地熱系統中。
4. 氮氣：地熱流體中另一種常見的不凝結氣體。
5. 氫氣：可能存在，特別是在高溫地熱系統中。
6. 可能含有苯和其他碳氫化合物。

此研究認為有效管理 NCG 是優化地熱發電廠性能和穩定生產的重要關鍵。NCG 可顯著影響地熱發電廠的效率及安全性。透過氣體提取系統、洗滌器和回注策略等技術對這些氣體進行適當的管理和緩解至關重要。相關的海報如下圖 21 所示。

The poster is titled "Geothermal Power and Carbon Dioxide Management" with a subtitle "Purification, Capture, Application" and a tagline "Advancing CO2 Technologies for a Low-Carbon World". It is organized into three main columns: "What are NCG's", "Management and Mitigation", and "Conclusion".

- What are NCG's:** Defines Non-Condensable Gases (NCGs) and lists six types: Carbon Dioxide (CO2), Hydrogen Sulfide (H2S), Methane (CH4), Nitrogen (N2), Hydrogen (H2), and Benzene/other hydrocarbons. It also discusses the impact on power plants, such as efficiency reduction, corrosion, and environmental concerns.
- Management and Mitigation:** Lists options like Gas Extraction Systems, Scrubbers and Abatement Systems, and Reinjection. It also mentions NCG Mitigation Solutions for beverage and industrial grade CO2.
- Conclusion:** States that effective management of NCGs is key to optimizing performance and sustainability.

The poster includes a diagram of a geothermal power plant cycle showing the geothermal reservoir, separator, power station, and reinjection process. It also features a photograph of a typical CO2 plant and a quote: "Harnessing Earth's Power, Purifying Its Breath: Geothermal NCG Mitigation for a Sustainable Future".

圖 21、GRE2024 海報，題目 Geothermal power and CO<sub>2</sub> management



### 3. 技術報告資料

會議的技術報告時間安排在 10/28(一)~10/30(三)三天，總共有五個會場同時進行發表(不包含大廳的討論會議)。會議的主題包含 1. 低溫/直接使用、2. 鑽井、3. 能源轉換/利用、4. 閉環/先進的熱系統、5. 地球化學、6. 增強型(或工程型)地熱系統、7. 地質學、8. 區域更新、9. 油藏/生產 10. 部落社區、11. 超熱地熱、12. 經濟學、13. 多元化、公平、包容性和歸屬感、14. 地球物理、15. 機器學習/計算、16. 從石油和天然氣轉型、17. 井下測井、18. 非技術、19. 建井和完井及 20. 礦物開採。總計 179 篇論文發表，相關的論文題目已列於上述表 2。會議期間無法同時兼顧，以下就其中幾篇重要的報告進行說明。

題目：溫度控制鑽井：絕緣鑽桿的即時損壞監測和減輕溫度升高影響的自動控制器

鑽探高熱地熱井的熱管理對於成功鑽井至關重要。鑽井液與岩石之間傳熱的準確建模可用於井底循環溫度 (BHCT) 預測。這些結果使井下工具和鑽頭能夠在其溫度限制內運作，防止鑽井時高溫暴露而過早失效。這研究使用 thermos-hydraulic model 來模擬 BHCT 的瞬態行為及鑽柱和泥漿溫度剖面。結果顯示，提高鑽井流量、使用泥漿冷卻器、使用某些流體類型及增加孔徑都可以作為有效降低淺層地熱井 BHCT 的策略。深層地熱井的情況，泥漿冷卻和其他普遍接受的冷卻措施有效性降低。對於此類井，使用絕熱鑽桿 (Insulated Drilling Pipe, IDP) 結合鑽井流量可有效地進行熱管理。

IDP 可以透過在傳統 5 吋鑽桿內焊接 3.5 吋外徑、3.068 吋內徑襯管來製造。隨後，將絕熱材料插入管體與內襯間的環形空間(詳見圖 22 第 2 張投影片)。然而，這些絕熱材仍可能隨時間發生問題，因此，研究亦提出鑽桿絕緣塗層狀況線上診斷方並利用控制策略減輕塗層損壞對井下循環溫度升高的影響。報告部分投影片如下圖 22。

# Managed Temperature Drilling: Real-Time Damage Monitoring of Insulated Drill Pipes and an Automatic Controller to Mitigate Effects of Subsequent Temperature Increase

Ningyu Wang, Pradeepkumar Ashok, Eric van Oort  
The University of Texas at Austin

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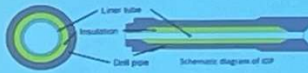
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## Insulations are Very Effective

Well Type A (FORGE): The BHCT is reduced from 114 °C to 64 °C with Insulated Drill Pipe (IDP)  
Well Type B (West Texas): The BHCT is reduced from 178 °C to 120 °C with IDP

### Well Type A

Reservoir T = 220 °C  
GT gradient = 70 °C/km  
Reservoir MD = 2.7 km  
8 3/4" vertical hole  
Circulation rate = 600 GPM



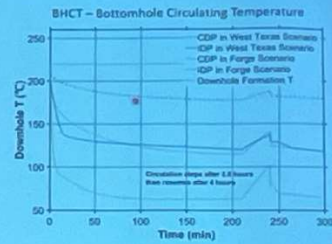
IDP Schematic, source: Ando R., and Haganawa S. (2020)

	CDP	IDP
Outside diameter (inch)	5	5
Inside diameter (inch)	4.3	3.1
Thermal conductivity (W/m.k)	45.3	3.1

SPE-212550-PA\* Khaled et al. 2023

### Well Type B

Reservoir T = 220 °C  
GT gradient = 24 °C/km  
Reservoir MD = 8.6 km  
8 3/4" vertical hole  
Circulation rate = 600 GPM



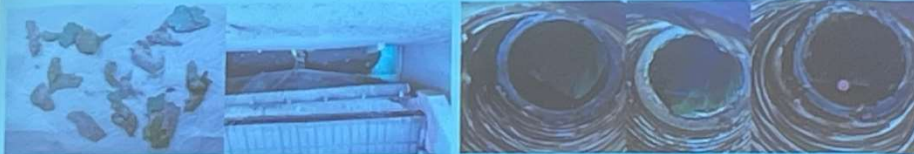
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## Issue With Insulations



- Photos from Eavor's FORGE Report (2023)
- Type of damage to expect
  - Peeling/Flaking
  - Thinning

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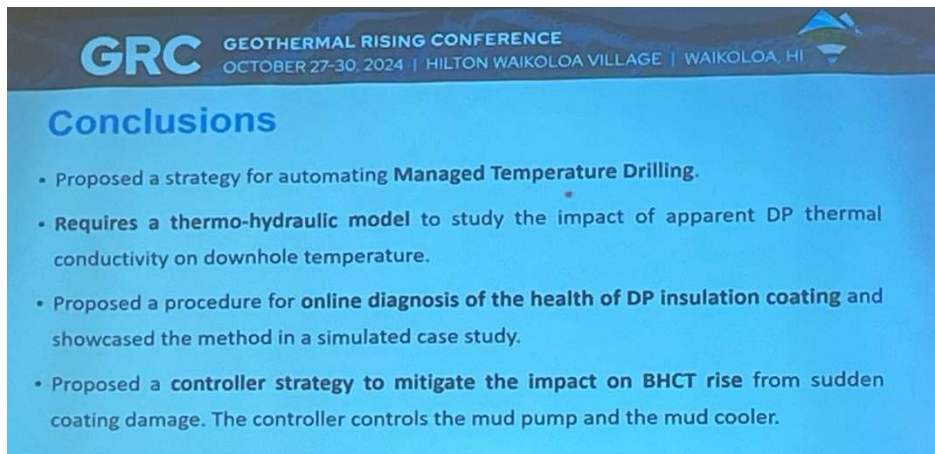
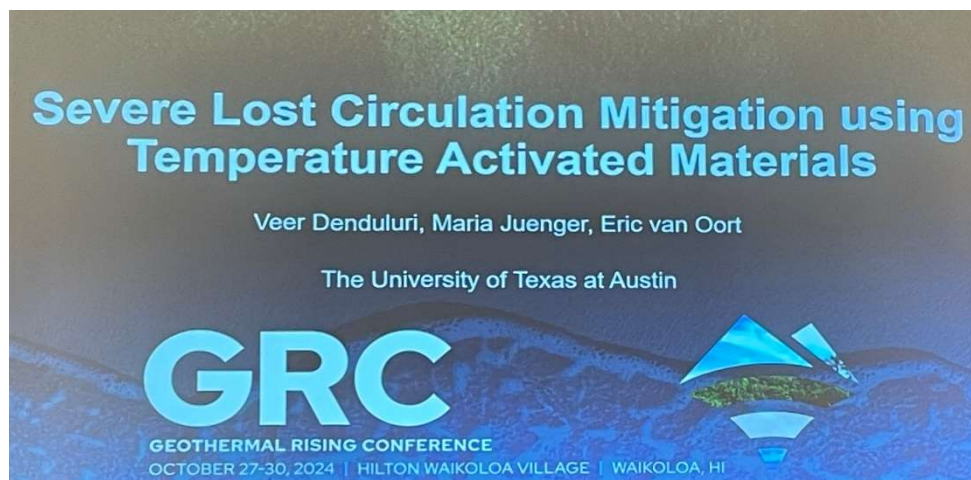


圖 22、GRE2024 技術報告投影片，題目：Managed Temperature Drilling: Real-Time Damage Monitoring of Insulated Drill Pipes and Automatic Controller to Mitigate Effects of Subsequent Temperature Increase

題目：使用熱活化堵漏材料緩解嚴重的泥漿循環流失

嚴重的漏泥經常發生在破裂和疏鬆的介質中。隨著鑽井深度增加，地層和鑽井液溫度也會升高，如果可以利用此時的高溫來幫助堵漏效果可能會很好。泥漿加入熱活化堵漏材料(TALCM)，它會因高溫造成黏度大幅增加，可用於減輕各種溫度條件中的損失。TALCM 的活化溫度可進行調整。堵漏時，溫度的預測則依賴建模，裂縫封堵試驗證實溫度活化材料可以有效緩解漏失。此材料有巨大的潛力可減少因地熱井漏泥相關的建井成本。報告部分投影片如下圖 23。



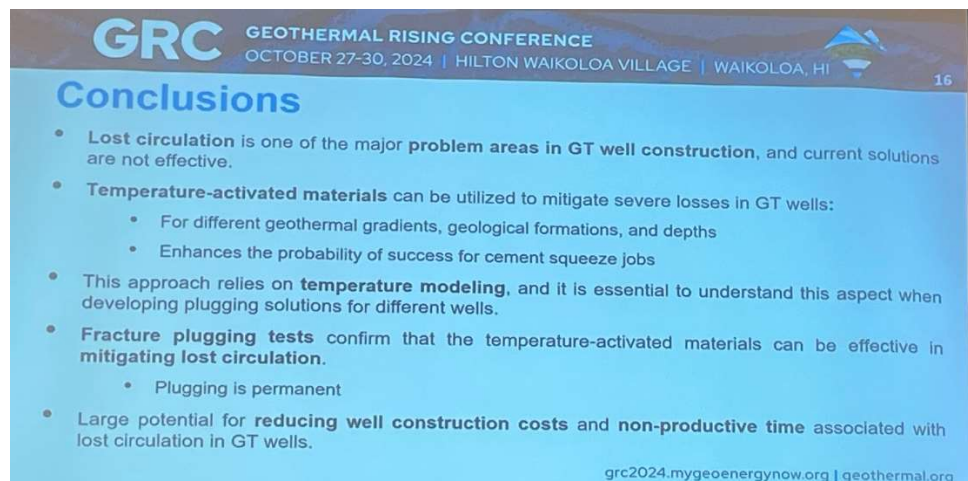
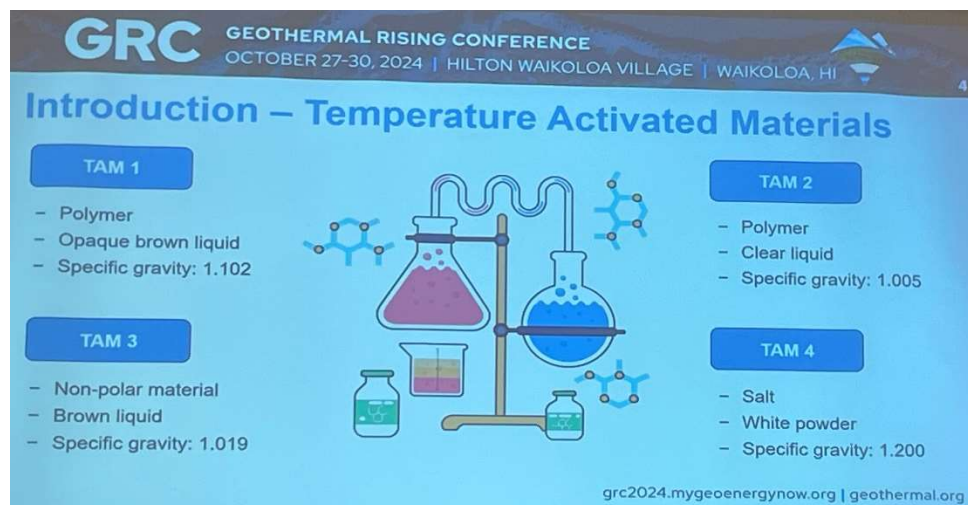
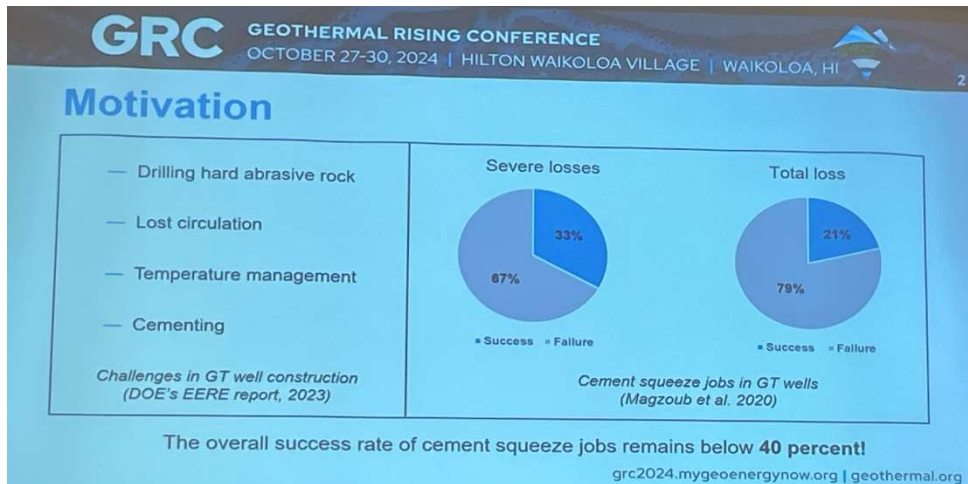
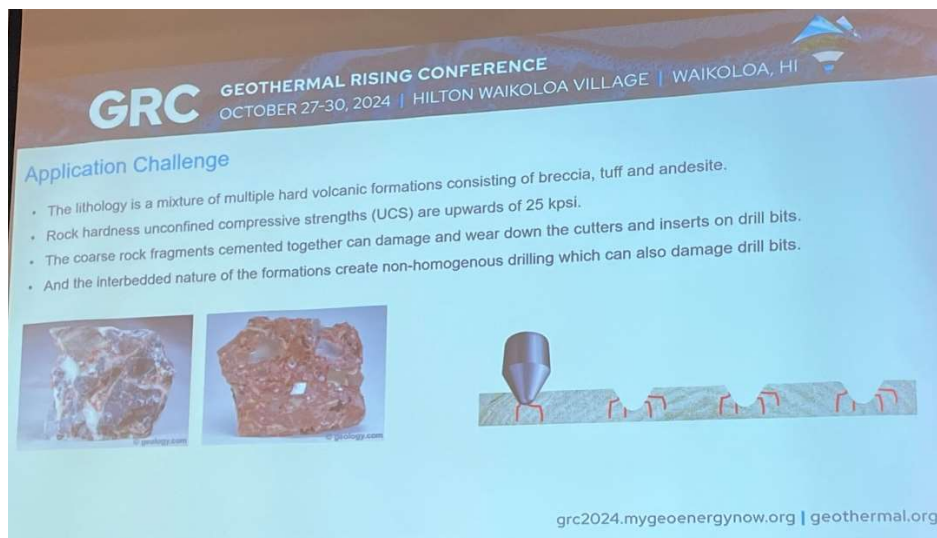


圖 23、GRE2024 技術報告投影片，題目：Severe Lost Circulation Mitigation using Temperature Activated Materials

題目：鑽探創新使印尼地熱井的交付速度更快

火山型地熱鑽井中，由於許多因素造成鑽探速率不高，其中包含 1. 岩性是

由角礫岩、凝灰岩和安山岩組成的多種硬火山地層的混合物。2. 岩石無圍抗壓強度 (Unconfined Compressive Strength, UCS) 高達 25 kpsi。3. 黏合在一起的粗岩石碎片會損壞鑽頭上的刀具。4. 地層間的差異造成不均勻鑽孔損壞鑽頭。過去幾十年來，一直使用傳統的牙輪鑽頭緩慢的鑽探地熱井。KS Orka 開闢一條利用混合鑽頭鑽井的新途徑，其在印尼的地熱井實現極佳的表現。17.5 吋混合鑽頭在 669 m 的深度，平均鑽進速率達 12.4 m/hr；12.25 吋混合鑽頭在 595 m 的深度平均鑽進速率達 9.71 m/hr。報告部分投影片如下圖 24。



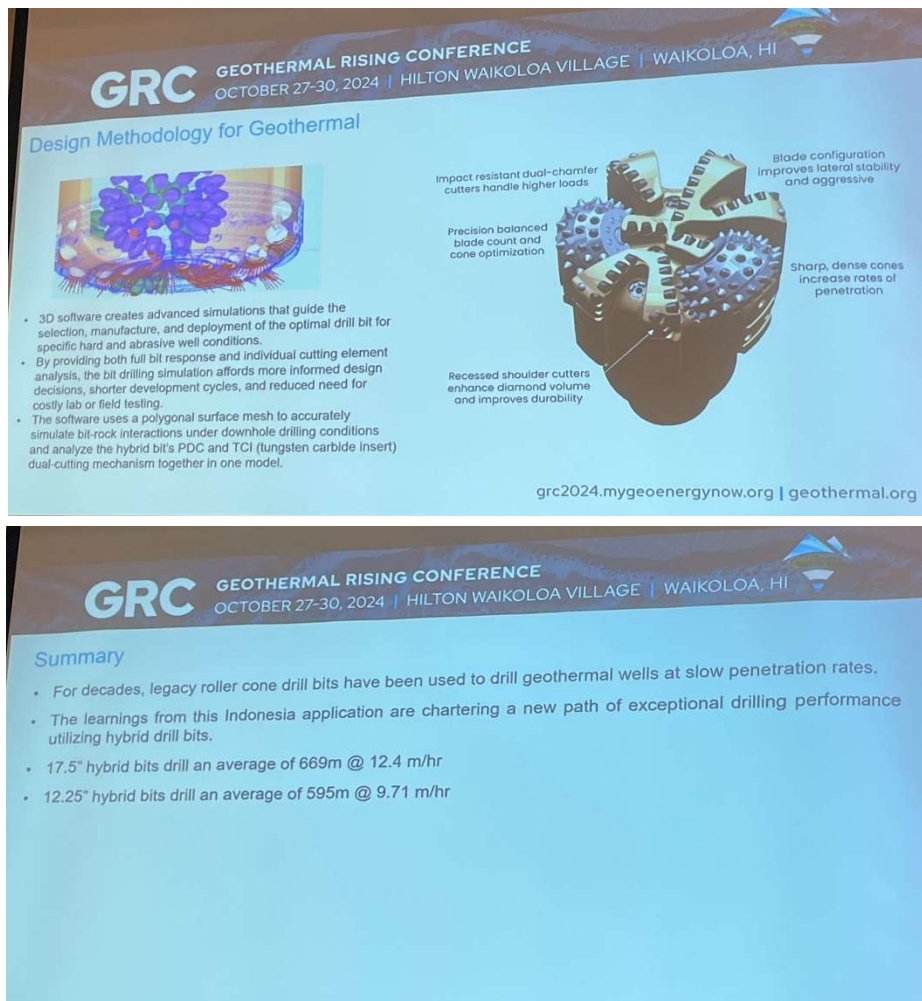


圖 24、GRE2024 技術報告投影片，題目: Drilling innovation enables faster delivery of geothermal wells in Indonesia

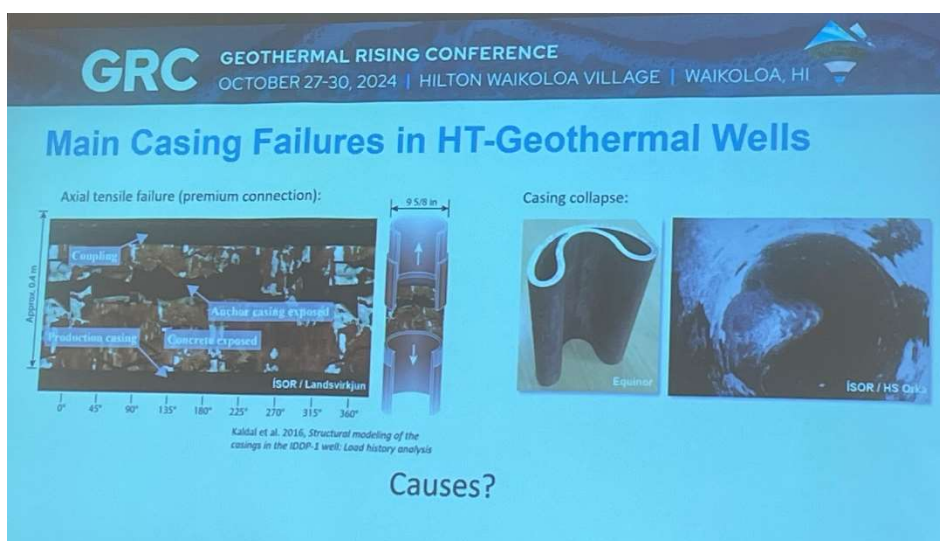
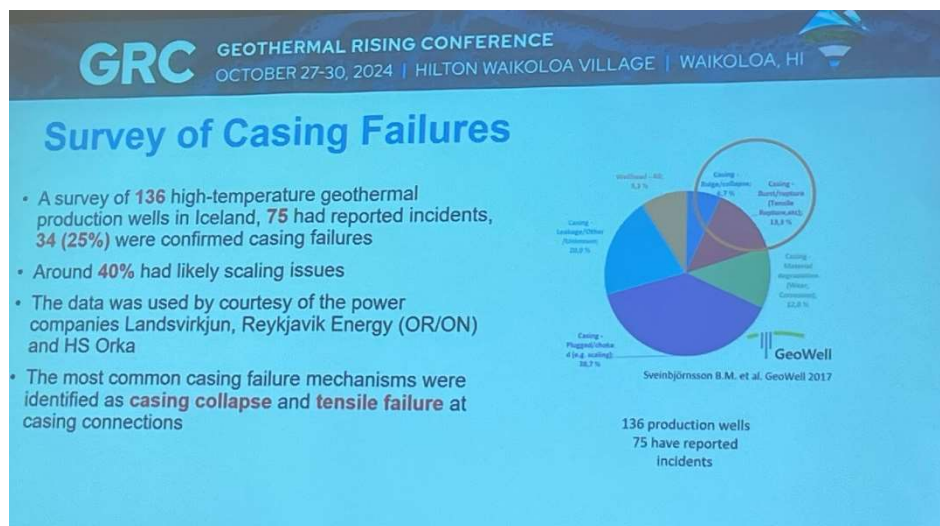
題目: 利用新技術提高高溫地熱井套管的結構完整性

目前的鑽井技術是根據過去幾十年的標準和經驗而設計的，石油和天然氣產業大部分採用 API 材料和方法；紐西蘭標準深層地熱井實務規範(NZS 2403:2015)定義深層地熱井最先進的流程設計和鑽井技術。一般來說，遵循這些指南的井可以得到可靠且安全的結構。

過去對冰島 136 口高溫地熱生產井的調查顯示，其中 75 口曾有故障，其中 34 口確認為套管故障。最常見的套管失效為套管塌陷(Casing collapse)和套管連接處的拉伸失效(Tensile failure)。套管塌陷通常和水的熱膨脹有關。水受熱膨脹時會產生壓力，如果膠結環孔空間存在過量的自由水，當水受熱膨脹時產生的高壓超過套管抗塌陷能力時，就可能導致塌陷。從 2015 年開始，ISOR 一直

在開發彈性接箍(Flexible Coupling)產品。這個想法來自冰島和世界各地套管故障的研究，這個設計已經在室溫、高溫及高壓條件下進行功能測試，預計於2024年11月在冰島內斯亞維利爾(Nesjavellir)高溫地熱井生產套管中使用(目前尚未商業化)。彈性接箍可透過位移補償套管的熱膨脹並讓套管的軸向壓應力控制在材料的彈性範圍內。

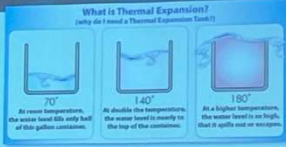
有鑑於 IDDP-1 和 IDDP-2 井都出現嚴重的套管斷裂，包括拉伸破裂和套管塌陷，高溫井的套管完整性有待提高。彈性接箍的設計及 COMPASS 專案正在開發的 APBR -防止套管坍塌技術將可大幅提高高溫地熱井套管的結構完整性，報告部分投影片如下圖 25。



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## Thermal Expansion of Water

- Water expands and builds pressure when heated
- If excess free water exists in the cemented annulus or water pocket is closed off in cement, high annular pressure can be generated as the water expands
- Water pressure behind the casing can lead to collapse when the casing collapse resistance is exceeded
- Can lead to severe loss in power output (MWe) of the well!

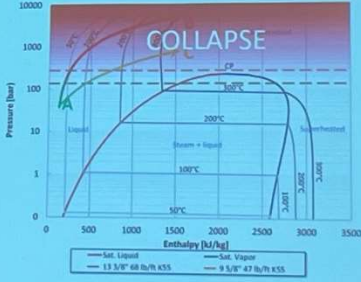


**What is Thermal Expansion?**  
(why do I need a Thermal Expansion Tank?)

At a lower temperature, the water level fills only half of the gallon container.

At double the temperature, the water level is nearly to the top of the container.

At a higher temperature, the water level is so high, that it spills out or overflows.



**COLLAPSE**

Pressure (bar)

Enthalpy (kJ/kg)

10000  
1000  
100  
10  
1  
0

0 500 1000 1500 2000 2500 3000 3500

100°C  
200°C  
300°C  
50°C

1.5" 68 02/76 K55  
2.0" 68 02/76 K55  
2.0" 68 02/76 K55

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## Conclusions

- Standards for well design, materials and the downhole structure serve a necessary purpose, but they have their limits.
- Casing integrity of HT-wells can be improved and is one of the bottle necks when drilling into superhot conditions, both wells IDDP-1 and IDDP-2 had severe casing failures of both tensile ruptures and casing collapses.
- Improved casing technology is needed for drilling into such conditions, e.g. for IDDP and KMT projects.
- **Flexible Couplings** are designed to mitigate casing failures caused by constrained thermal expansion by allowing displacement of each joint.
- **APBR – Casing Collapse Prevention** are designed to prevent casing collapse from occurring – in development within the COMPASS project.
- These ideas are based on experience, data and research from past decades, e.g. drilling data and downhole logging data.

圖 25、GRE2024 技術報告投影片，題目：Increased Structural Integrity of Casings of High-Temperature Geothermal Wells using Novel Technologies

題目：現地測試熱電模組(TEG)在不同溫度的電力輸出

目前的發電技術有設備大、自耗電高、運轉維護成本高等缺點。熱電材料發電技術無需機械動力轉換，應用廣泛，無運動部件，設備安裝簡單。它可以用來做餘熱回收與再生能源整合，有效利用各種來源的廢熱。TEG 致力於再生能源解決方案的開發，其體積小可適合多種應用，可自啟動發電，每當熱流體流過時就會產生電力，運作安靜可靠。當然 TEG 還是有些缺點，例如前只有少數測試、轉換效率較低及成本較高。此研究建立 TEG 功率輸出和溫差(TD)的耦合方程式。利用單一 TEG 晶片在不同 TD 下的實驗結果可用來預測大規模現場應用的功率輸



出。當溫差大於 90°C 時，TEG 成本可低於太陽能光電板，報告部分投影片如下圖 26。

**Power Outputs from the Field Tests of Thermoelectric Generators at Different Temperatures**

Yuan Tian, Yuhao Zhu, Kewen Li, Yu-kai Liang, Ji-ping Yang

China University of Geosciences (Beijing), Beijing 100083, China;  
Beijing Key Laboratory of Unconventional Natural Gas Geological Evaluation and Development Engineering, Beijing 100083, China;  
Cnooc (Guangdong) New Energy Engineering Design Co., LTD, China

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**Why Choose TEG**

- **Current power generation technology**  
There are problems and disadvantages such as large equipment, high self power consumption, high operation and maintenance costs.
- **TEG power generation technology**  
No need for mechanical power conversion, widely used, no moving parts, and simple equipment installation.

Typical duplex power generation equipment

(a) Schematic diagram of thermoelectric device structure;  
(b) Schematic diagram of each interface

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**Seebeck Effect & Thermoelectric Modules**

Seebeck effect

Thermoelectric module

ΔT  
 T<sub>c</sub>  
 T<sub>h</sub>  
 p-type  
 n-type  
 Copper  
 Aluminum substrate

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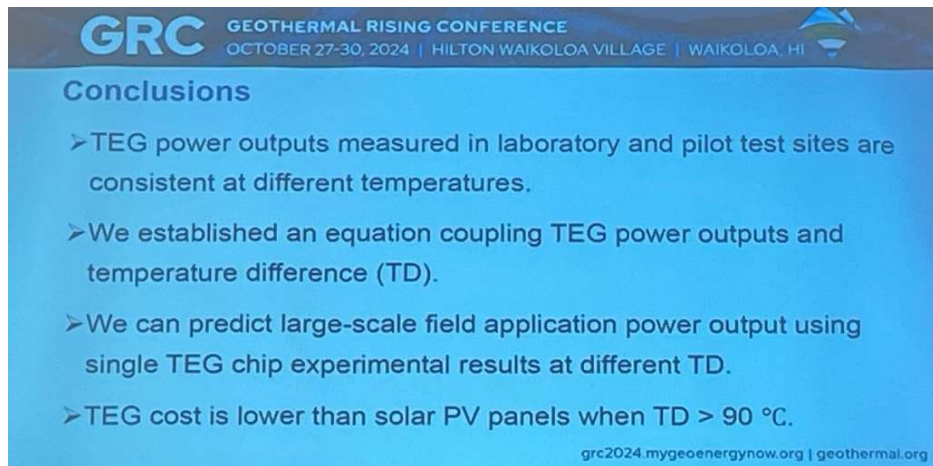


圖 26、GRE2024 技術報告投影片，題目：Increased Structural Integrity of Casings of High-Temperature Geothermal Wells using Novel Technologies

## 心得及建議

本次會議相當盛大，每天都有十來篇不同的海報發表、總計 179 篇論文報告、大型討論會議及數十家的參展廠商。時間重疊的部分盡量挑選和自身研究相關的主題或攤位去參觀或聆聽。其中最令人印象深刻的還是 cladtek 的攤位。這種金屬複合管完美結合碳鋼優異的機械性質及 CRA 的耐腐蝕性質，大幅降低純 CRA 管材的成本，是一個理想的複合材料。然而，複合材料的複合技術難度極高，兩種不同的金屬接合產生伽凡尼腐蝕、間隙腐蝕、接合強度及熱膨脹差異造成的熱應力等問題，大尺寸的管材也使其製造相當困難。國內多年前就有廠商想到相關的管材設計，不過目前仍難以生產。原本對這類的產品已不抱希望，沒想到 cladtek 已將其商業化，並已完成現地測試。建議後續應針對該公司的產品再深入瞭解，並評估其是否適用於國內大屯山酸性地熱井，如果可以成功應用此類產品，將可再進一步降低酸性地熱井的開發成本。

進中油公司前約莫有 10 年的時間都是從事鍍膜的研究工作，所以在會場看到鍍膜相關的海報時倍感親切。過去曾經看過鍍膜技術應用在鑽桿內部，用來增加鑽桿壽命防止過早被泥漿沖刷洗穿的資料。本次會議中發現，鍍膜技術也能夠應用在鑽桿隔熱，增加井下設備在高溫鑽井時的使用壽命。另外，DLC 鍍膜技術也可用在套管內降低結垢問題。根據這些研究報告，鍍膜技術在地熱鑽井及完井似乎仍有需多可用之處，以前學過的鍍膜技術仍有發揮的空間。未來若遇到相關的問題或許也能利用此技術協助探採事業單位解決問題。不過，目前國內尚未見過大型的管內鍍膜設備或技術。建議後續可以先在國內尋找可能的廠商進行評估或合作，後續再探討鑽桿或套管管內鍍膜的成效。

世界各地的地熱開發已愈來愈興盛，開發難度低的區域已經愈來愈少，大家逐漸往難度較高的高溫或乾熱岩等區域邁進。除了耳熟能詳的 AGS、EGS、GreenLoop 技術外，此次會議也見識到許多先進的設備或技術，例如混合鑽頭、彈性接箍、熱活化堵漏材料及熱電模組等。這些技術或設備在地熱領域提供更多的發展可能。國內目前在新技術這方面仍有不足，建議再多廣納人才加速新技術的引入或應用。