出國報告（出國類別：開會）

超超臨界鍋爐先進材料國際會議

服務機關：台灣電力公司

姓名職稱：高全盛；機械工程師

派赴國家：美國

出國期間：**106** 年 **6** 月 **17** 日至 **6** 月 **26** 日

報告日期：**106** 年 **8** 月 **22** 日

出國報告審核表

出國報告名稱：超超臨界鍋爐先進材料國際會議		
出國人姓名 （2 人以上，以 1 人為代表）	職稱	服務單位
高全盛	機械工程師	台灣電力公司綜合研究所
出國類別	□ 考察 □進修 □研究 □實習 ■其他 開會 （例如國際會議、國際比賽、業務接洽等）	
出國期間： 106 年 6 月 17 日 至 106 年 6 月 26 日	報告繳交日期： 106 年 8 月 22 日	

出國人員自我審核	計畫主辦機關審核	審 核 項 目
■	□	1.依限繳交出國報告
■	□	2.格式完整（本文必須具備「目地」、「過程」、「心得及建議事項」）
■	□	3.無抄襲相關資料
■	□	4.內容充實完備.
■	□	5..建議具參考價值
■	□	6.送本機關參考或研辦
□	□	7.送上級機關參考
□	□	8.退回補正，原因：
□	□	（1）不符原核定出國計畫
□	□	（2）以外文撰寫或僅以所蒐集外文資料為內容
□	□	（3）內容空洞簡略或未涵蓋規定要項
□	□	（4）抄襲相關資料之全部或部分內容
□	□	（5）引用相關資料未註明資料來源
□	□	（6）電子檔案未依格式辦理
□	□	9.本報告除上傳至出國報告資訊網外，將採行之公開發表：
□	□	（1）辦理本機關出國報告座談會（說明會），與同仁進行知識分享。
□	□	（2）於本機關業務會報提出報告
□	□	（3）其他 ______________
□	□	10.其他處理意見及方式：

報告人：高全盛 106. 8. 21

單位主管：吳憲政 106. 8. 21

主管處主管：鍾年勉 106. 8. 23

總經理
副總經理：洪紹平 106. 8. 23

說明：

一、各機關可依需要自行增列審核項目內容，出國報告審核完畢本表請自行保存。

二、審核作業應儘速完成，以不影響出國人員上傳出國報告至「公務出國報告資訊網」為原則。

三、

行政院及所屬各機關出國報告提要

出國報告名稱：超超臨界鍋爐先進材料國際會議

頁數 47 含附件：□是■否

出國計畫主辦機關/聯絡人/電話：台電 人資處/陳德隆/02-23667685

出國人員姓名/服務機關/單位/職稱/電話：

高全盛/台灣電力公司/綜合研究所/機械工程師/(02)8078-2208

出國類別：□1 考察□2 進修□3 研究□4 實習■5 其他：開會

出國期間：106 年 6 月 17 日至 6 月 26 日　出國地區：葡萄牙

報告日期：106 年 8 月 22 日

分類號/目

關鍵詞：CSEF 鋼材、銲後熱處理、Super304H、Grade 91、異質銲接

內容摘要：（二百至三百字）

本次出國至美國參加美國電力研究院(EPRI)舉辦之 P87 技術轉移會議以及第 12 屆銲接與修復研討會，內容涵蓋先進超臨界機組材料之最新銲接發展及各項修復研究成果，可加速本公司新電廠先進材料銲接分析、損傷診斷、修復等自主技術，以提升作業效能，確保機組運轉可靠度。

在此次兩個會議中，對於先進超超臨界鍋爐材料之最新發展有下列重點，一、厚管件不能僅依循 AWS D10.10 進行銲後熱處理，須考量幾何形狀、熱電偶位置與數量等要點，才能避免過熱或 PWHT 不足；二、服役過之 Gr.91 之異質銲接，易在 PMZ 區觀察到裂紋、Carbide-free Ferrite 區域、潛變空孔及 Type I Carbides 等缺陷；三、不鏽鋼 Super304H 潛變試驗後結果顯示，富 Nb 的 Nb(C,N) 與潛變空孔的破壞有相關聯性，與 Sigma 相無關。

目　　錄

表目錄

圖目錄

一、 出國緣由、行程及主要任務

出國緣由：

本公司之林口與大林超臨界機組已點火試運轉，正式開啟公司超臨界機組時代，由於超臨界機組之運轉參數(溫度 602℃/壓力 24.5MPa)遠高於目前亞臨界機組(溫度 540℃/壓力 17.8MPa)，故材料添加更多合金元素，提升其高溫強度，使得超臨界鍋爐的材料銲接設計與顯微組織演變更為重要，致使新機組的銲件性能、異質材料銲接、修復技術、材料微組織演變、腐蝕、殘留應力等特性更為複雜，故為確保與提升未來機組運轉之可靠度與安全性，本公司在短、中、長期研發重點項目與內容之第二項「建立發電廠關鍵設備之壽命評估、再生自製與材料安全鑑定技術」的研發重點中，即訂定超臨界發電機組鍋爐的銲接及銲補維護為其核心工作，

因本公司為美國電力研究院(EPRI) P87 會員，P87 研究重點為燃煤電廠材料與銲接修復，適逢六月 EPRI 舉辦 2017 年 P87 技術轉移會議(Program 87 2017 Technology Transfer Meeting)以及第 12 屆銲接與修復研討會(Welding and Repair Technology for Power Plants 12th International Conference)，會議內容涵蓋前述先進超臨界機組材料之最新銲接發展及各項修復研究成果，此次參與會議，可加速本公司新電廠先進材料銲接分析、損傷診斷、修復等自主技術，以提升作業效能，確保機組運轉可靠度。

本次出國開會「超超臨界鍋爐先進材料國際會議」之重點如下：

a.先進超超臨界鍋爐材料之最新銲件性能評估。

b.腐蝕特性。

c.異質材料銲接。

d.修復技術。

此次職榮幸有機會出國參加國際會議，了解國外超臨界鍋爐材料最新發展與銲接修復，相信藉由瞭解國外經驗，對未來超臨界鍋

爐系統運轉之可靠度提升做出更大貢獻

本次出國案件係應用 106 年度出國計畫第 123 號，出國核定書為 EE106069 號，電人字第 1068053122 號函。

出國行程及主要任務：

本次出國期間自 106 年 6 月 17 日至 6 月 26 日，主要的任務為參加 EPRI 在美國奧蘭多(Orlando)城市舉辦 2017 年 P87 技術轉移會議(Program 87 2017 Technology Transfer Meeting)以及第 12 屆銲接與修復研討會(Welding and Repair Technology for Power Plants 12th International Conference)，收集先進超臨界鍋爐材料最新研究成果與銲接修復技術等相關資訊，作為公司未來超臨界機組維護、檢測與銲接之技術建立基礎。行程及工作內容概要說明於下表 1：

表 1 行程及工作內容

項次	起始日	迄止日	地點	工作內容概況
1	1060617	1060618	桃園-舊金山-奧蘭多	路程
2	1060619	1060620	奧蘭多	參與 2017 年 P87 技術轉移會議
3	1060621	1060623	奧蘭多	參加第 12 屆銲接與修復研討會
3	1060624	1060626	奧蘭多-舊金山-桃園	路程

二、 心得報告

2.1 研討會議程介紹

此次美國電力研究院在奧蘭多舉辦，由P87 Fossil Materials and Repair Program與Welding and Repair Technology Center(WRTC)主辦兩項會議，各國多位專家學者均有出席或簡報最新研究成果，會議中討論熱烈，職參加會議過程如圖1所示。

(a)迎賓大廳

(b)職參加會議

圖 1 研討會過程

(c)全體與會 P87 會議之專家學者合照

圖 1 研討會過程(續)

此次2017年P87技術轉移會議為兩天議程，第12屆銲接與修復研討會為三天議程，P87技術轉移會議與第12屆銲接與修復研討會共分以下多個議題進行發表，議程如圖2所示：

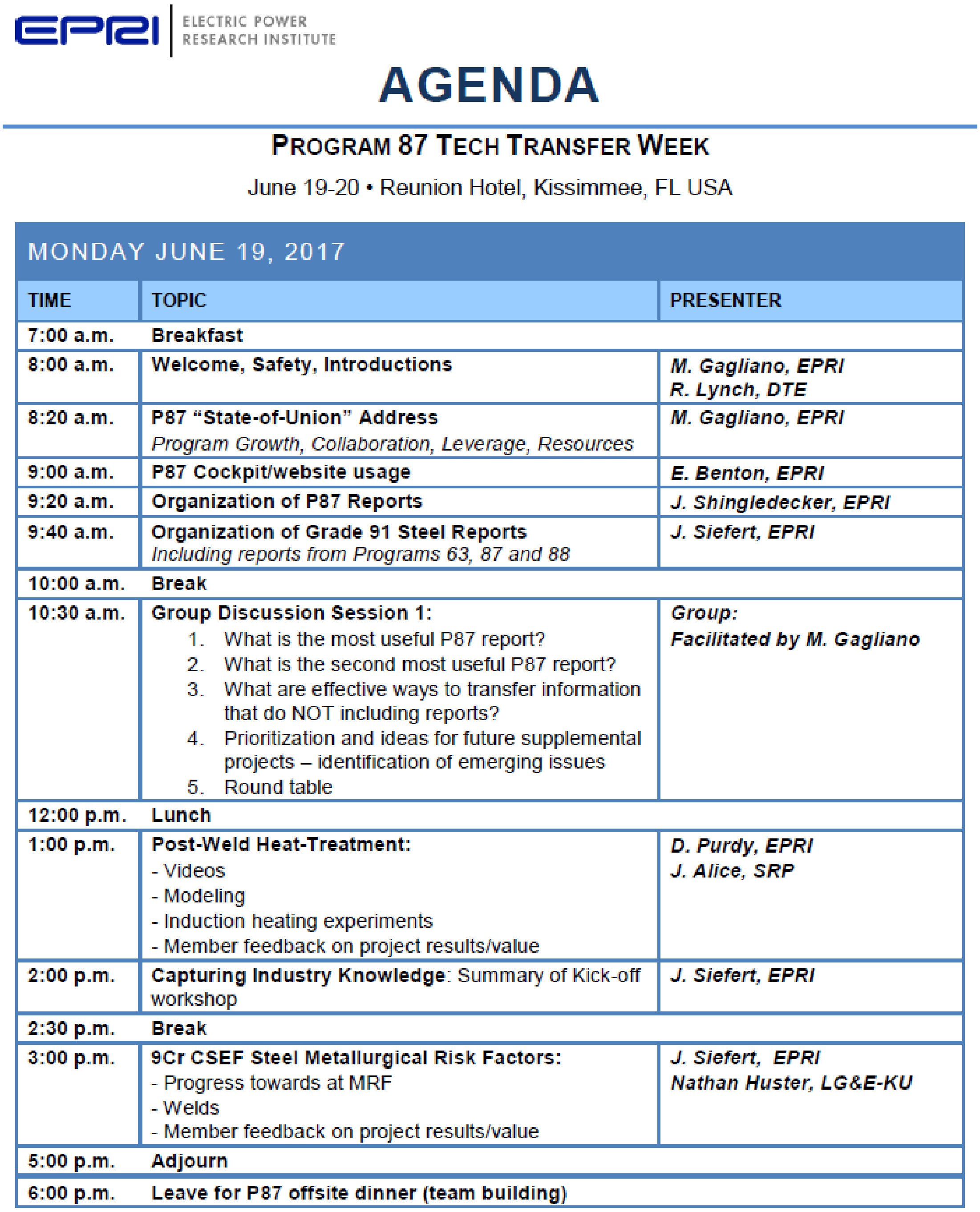
- P87 技術轉移會議
  - Introduction and Organization of P87 Reports
  - Post-Weld Heat-Treatment
  - 9Cr CSEF Steel Metallurgical Risk Factors
  - Small Sample Testing
  - Low-Temperature Corrosion
  - Stainless Steels
  - Rapid Fire Project Update Session
- 第 12 屆銲接與修復研討會

  Nuclear Session：
  - Operating Experience
  - Residual Stress
  - Code and Standards
  - Weldability
  - Advanced Manufacturing and Fabrication
  - Advanced Welding Techniques

Fossil Session

- Repair and PWHT
- Introduction to Alternative Weld Repairs
- Supporting Research for Grade 91
- Grade 91 Steel Repair Case Studies
- Dissimilar Metal Welds
- Advanced Materials and Inservice Monitoring

議題涵蓋 9%Cr 合金鋼、不銹鋼等領域，討論其銲接、腐蝕與修復之研究結果，並說明 P87 目前研究進度。



ELECTRIC POWER RESEARCH INSTITUTE

AGENDA

PROGRAM 87 TECH TRANSFER WEEK

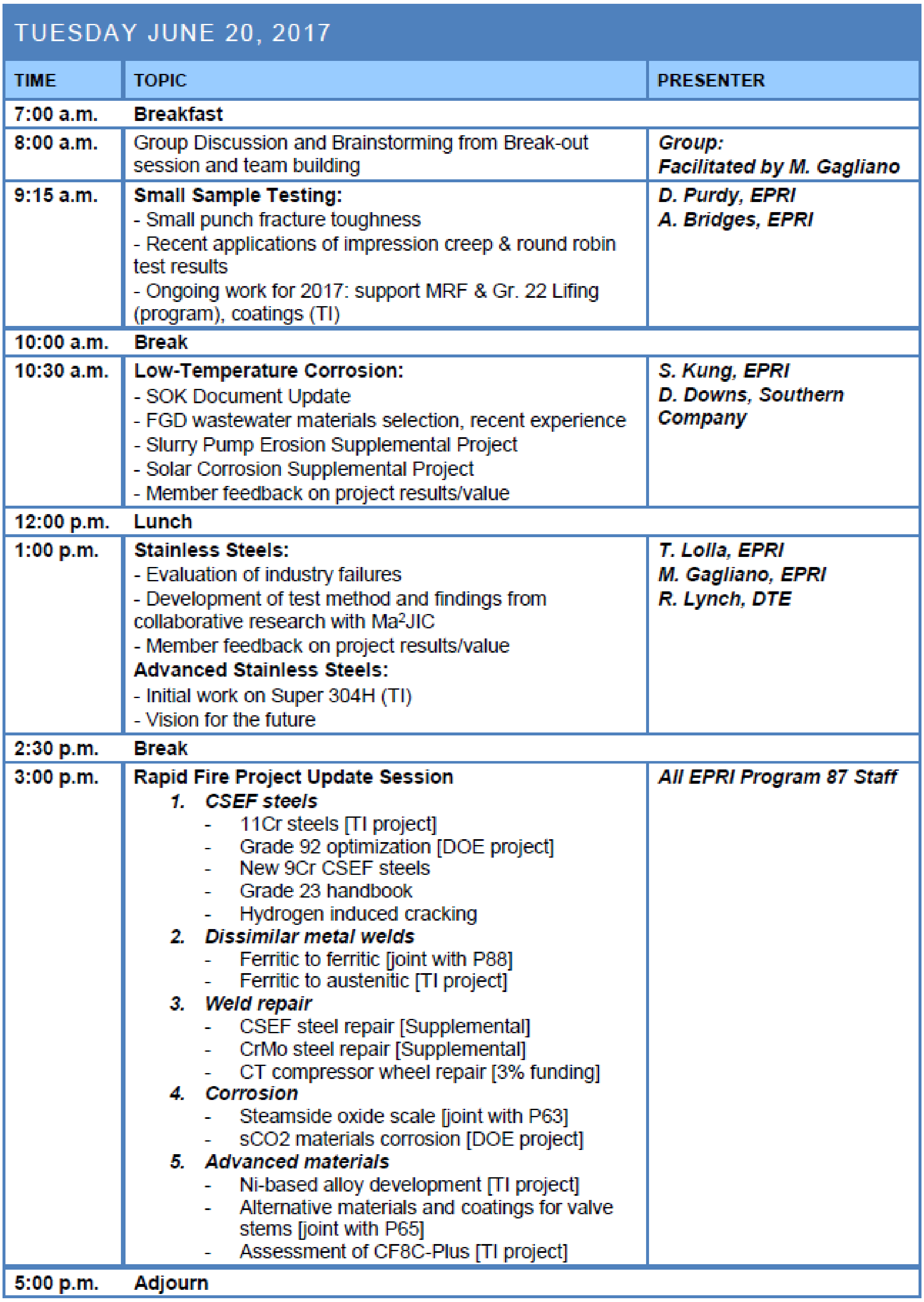
June 19-20 • Reunion Hotel, Kissimmee, FL USA

MONDAY JUNE 19, 2017

TIME	TOPIC	PRESENTER
7:00 a.m.	**Breakfast**	
8:00 a.m.	**Welcome, Safety, Introductions**	***M. Gagliano, EPRI*** ***R. Lynch, DTE***
8:20 a.m.	**P87 "State-of-Union" Address** *Program Growth, Collaboration, Leverage, Resources*	***M. Gagliano, EPRI***
9:00 a.m.	**P87 Cockpit/website usage**	***E. Benton, EPRI***
9:20 a.m.	**Organization of P87 Reports**	***J. Shingledecker, EPRI***
9:40 a.m.	**Organization of Grade 91 Steel Reports** *Including reports from Programs 63, 87 and 88*	***J. Siefert, EPRI***
10:00 a.m.	**Break**	
10:30 a.m.	**Group Discussion Session 1:** 1. What is the most useful P87 report? 2. What is the second most useful P87 report? 3. What are effective ways to transfer information that do NOT including reports? 4. Prioritization and ideas for future supplemental projects – identification of emerging issues 5. Round table	***Group:*** ***Facilitated by M. Gagliano***
12:00 p.m.	**Lunch**	
1:00 p.m.	**Post-Weld Heat-Treatment:** - Videos - Modeling - Induction heating experiments - Member feedback on project results/value	***D. Purdy, EPRI*** ***J. Alice, SRP***
2:00 p.m.	**Capturing Industry Knowledge**: Summary of Kick-off workshop	***J. Siefert, EPRI***
2:30 p.m.	**Break**	
3:00 p.m.	**9Cr CSEF Steel Metallurgical Risk Factors:** - Progress towards at MRF - Welds - Member feedback on project results/value	***J. Siefert, EPRI*** ***Nathan Huster, LG&E-KU***
5:00 p.m.	**Adjourn**	
6:00 p.m.	**Leave for P87 offsite dinner (team building)**	

(a) P87議程

圖 2 議程



TUESDAY JUNE 20, 2017

TIME	TOPIC	PRESENTER
7:00 a.m.	**Breakfast**	
8:00 a.m.	Group Discussion and Brainstorming from Break-out session and team building	***Group:*** ***Facilitated by M. Gagliano***
9:15 a.m.	**Small Sample Testing:** - Small punch fracture toughness - Recent applications of impression creep & round robin test results - Ongoing work for 2017: support MRF & Gr. 22 Lifing (program), coatings (TI)	***D. Purdy, EPRI*** ***A. Bridges, EPRI***
10:00 a.m.	**Break**	
10:30 a.m.	**Low-Temperature Corrosion:** - SOK Document Update - FGD wastewater materials selection, recent experience - Slurry Pump Erosion Supplemental Project - Solar Corrosion Supplemental Project - Member feedback on project results/value	***S. Kung, EPRI*** ***D. Downs, Southern Company***
12:00 p.m.	**Lunch**	
1:00 p.m.	**Stainless Steels:** - Evaluation of industry failures - Development of test method and findings from collaborative research with Ma^{2}JIC - Member feedback on project results/value **Advanced Stainless Steels:** - Initial work on Super 304H (TI) - Vision for the future	***T. Lolla, EPRI*** ***M. Gagliano, EPRI*** ***R. Lynch, DTE***
2:30 p.m.	**Break**	
3:00 p.m.	**Rapid Fire Project Update Session** ***1. CSEF steels*** - 11Cr steels [TI project] - Grade 92 optimization [DOE project] - New 9Cr CSEF steels - Grade 23 handbook - Hydrogen induced cracking ***2. Dissimilar metal welds*** - Ferritic to ferritic [joint with P88] - Ferritic to austenitic [TI project] ***3. Weld repair*** - CSEF steel repair [Supplemental] - CrMo steel repair [Supplemental] - CT compressor wheel repair [3% funding] ***4. Corrosion*** - Steamside oxide scale [joint with P63] - sCO2 materials corrosion [DOE project] ***5. Advanced materials*** - Ni-based alloy development [TI project] - Alternative materials and coatings for valve stems [joint with P65] - Assessment of CF8C-Plus [TI project]	***All EPRI Program 87 Staff***
5:00 p.m.	**Adjourn**	

(b) P87議程

圖 2 議程(續)

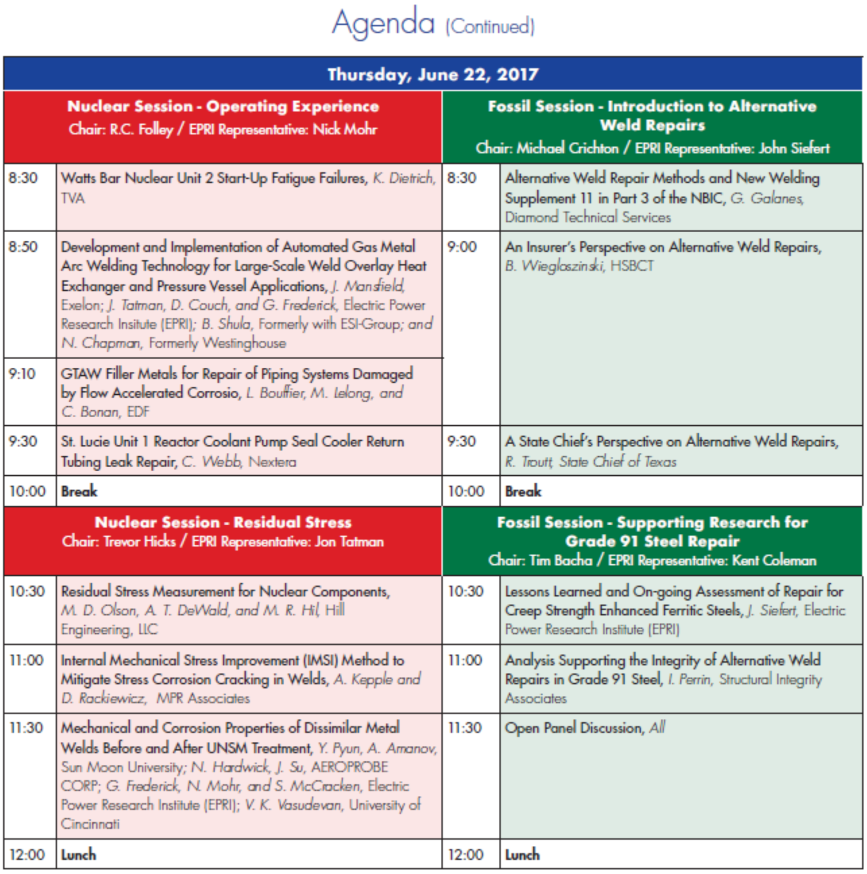
Agenda

Wednesday, June 21, 2017	
General Session Chairs: Greg Frederick and John Shingledecker / EPRI Representatives: Greg Frederick and John Shingledecker	
8:30	WRTC/Program 87 Introduction, *G. Frederick and J. Shingledecker*, Electric Power Research Institute (EPRI)
9:00	Keynote Address: The Use of Advanced In-Situ Testing Techniques to Address Real World Welding Challenges, *A. Ramirez*, The Ohio State University
9:30	Keynote Address: Outage Related Statistic and Ongoing Optimization Projects in IAEA, *H. Varjonen*, International Atomic Energy Agency
10:00	Keynote Address: Paradigm Shifts in Welding Technology in Response to Key Nuclear Industry Events, *R. Smith*, Structural Integrity Associates
10:30	**Break**
11:00	Challenges of Using Duplex Stainless Steels in Power Generation Applications, *S. Gingrich*, AECOM Corporation
11:30	Use of Numerical Simulation for Welding and Repair Qualification, *V. Robin, D. Borel, J. Delmas, K. Dorogan, and S. Hendili* Electricité de France
12:00	**Lunch**

Wednesday, June 21, 2017 (continued)			
Nuclear Session - Operating Experience Chair: R.C. Folley / EPRI Representative: Nick Mohr		**Fossil Session - Repair and PWHT** Chair: Darrell Wisner / EPRI Representative: Dan Purdy	
1:00	Susquehanna Unit 1 LPRM 24-09 ICMH Indication, *M. Comstock*, Talen Energy *and S. McCracken*, Electric Power Research Institute (EPRI)	1:00	Improving Through Wall Temperature Gradients during Post Weld Heat Treatment of Pipe to Valve Body Closure Welds, *J. Hainsworth*, WR Metallurgical
1:20	Reactor Vessel Bottom Mounted Instrumentation Nozzle Repair at EDF's Gravelines 1 Nuclear Power Plant, *D. Barton*, Westinghouse *and B. Delaunay*, EDF	1:30	Repairs of Fossil Boilers Versus HRSG's: Field Experience, Insights and Recommendations, *P. Kasik and G. Lawrence*, Alliant Energy
1:40	The Status of Weld Overlay Service for Nuclear Power Plants by INER, *S. Jeng*, The Institute of Nuclear Energy Research		
2:00	Alloy 52MSS Structural Weld Overlays and Safety Relief Valve Piping Realignment Lessons Learned, *P. Lester, D. Barborak*, AZZ WSI *and S. Vancluysen*, Tracetebel Engie	2:00	Post-Weld Heat Treatment Modeling of Thickness Transitions, *D. Purdy*, Electric Power Research Insitute (EPRI)
2:30	**Break**	2:30	**Break**
Nuclear - Student Session Chair: Adam Hope / EPRI Representative: Ben Sutton		**Fossil - Student Session** Chair: Rich Lynch / EPRI Representative: John Shingledecker	
3:00	Development of an Integrated Sensor Suite for Adaptive Wide Groove Welding, *S. Robertson and W. Hamel*, University of Tennessee	3:00	Microstructural Evolution of Grade 91 Dissimilar Metal Welds, *S. Orzolek, J. DuPont*, Lehigh University *and J. Siefert*, Electric Power Research Institute (EPRI)
3:30	Quantification of the Susceptibility to Ductility Dip Cracking in Weld Overlays of Ni-Based Alloy, *S. Luther and B. Alexandrov*, The Ohio State University	3:30	Stress Relaxation Cracking Susceptibility of High Temperature Alloys, *R. Kant and J. DuPont*, Lehigh University
4:00	System Architecture for Adaptive Feedback Welding in V-Groove Welding, *J. Penney and W. Hamel*, University of Tennessee	4:00	Temper Bead Welding for Weld Overlays, *J. Stewart and B. Alexandrov*, The Ohio State University
4:30	Microstructural Evolution of Graded Transition Joints, *J. Galler, J. DuPont*, Lehigh University, *M. Subramanian and S. Babu*, University of Tennessee	4:30	Microstructural Evolution of Grade 91 Dissimilar Metal Welds, *M. Kuper, B. Alexandrov*, The Ohio State University, *and J. Burgess*, Alstom
5:00– 8:00	**Vendor Expo**	5:00– 8:00	**Vendor Expo**

(c) 第12屆銲接與修復研討會議

圖 2 議程(續)



Agenda (Continued)

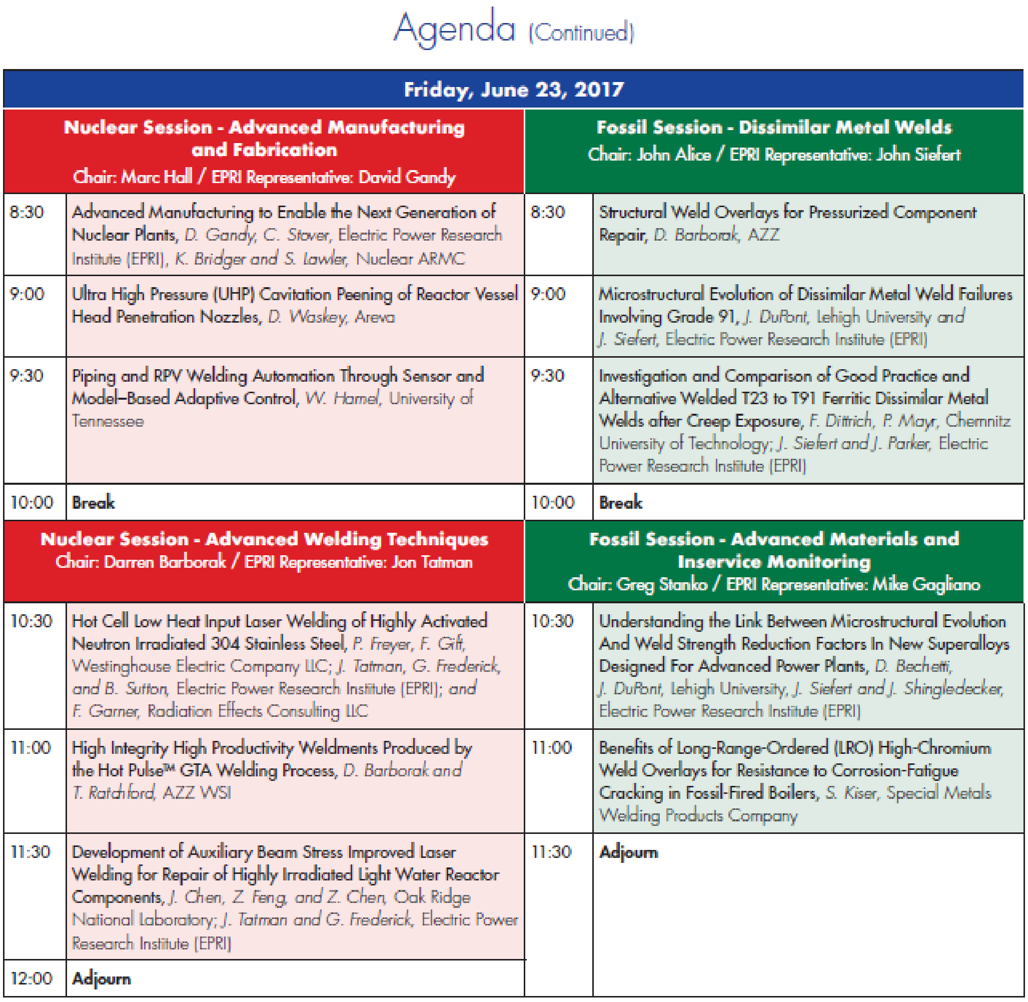
Thursday, June 22, 2017			
Nuclear Session - Operating Experience Chair: R.C. Folley / EPRI Representative: Nick Mohr		**Fossil Session - Introduction to Alternative Weld Repairs** Chair: Michael Crichton / EPRI Representative: John Siefert	
8:30	Watts Bar Nuclear Unit 2 Start-Up Fatigue Failures, *K. Dietrich*, TVA	8:30	Alternative Weld Repair Methods and New Welding Supplement 11 in Part 3 of the NBIC, *G. Galanes*, Diamond Technical Services
8:50	Development and Implementation of Automated Gas Metal Arc Welding Technology for Large-Scale Weld Overlay Heat Exchanger and Pressure Vessel Applications, *J. Mansfield*, Exelon; *J. Tatman, D. Couch, and G. Frederick*, Electric Power Research Insitute (EPRI); *B. Shula*, Formerly with ESI-Group; *and N. Chapman*, Formerly Westinghouse	9:00	An Insurer's Perspective on Alternative Weld Repairs, *B. Wieglaszinski*, HSBCT
9:10	GTAW Filler Metals for Repair of Piping Systems Damaged by Flow Accelerated Corrosio, *L. Bouffier, M. lelong, and C. Bonan*, EDF		
9:30	St. Lucie Unit 1 Reactor Coolant Pump Seal Cooler Return Tubing Leak Repair, *C. Webb*, Nextera	9:30	A State Chief's Perspective on Alternative Weld Repairs, *R. Troutt, State Chief of Texas*
10:00	**Break**	10:00	**Break**
Nuclear Session - Residual Stress Chair: Trevor Hicks / EPRI Representative: Jon Tatman		**Fossil Session - Supporting Research for Grade 91 Steel Repair** Chair: Tim Bacha / EPRI Representative: Kent Coleman	
10:30	Residual Stress Measurement for Nuclear Components, *M. D. Olson, A. T. DeWald, and M. R. Hil*, Hill Engineering, LLC	10:30	Lessons Learned and On-going Assessment of Repair for Creep Strength Enhanced Ferritic Steels, *J. Siefert*, Electric Power Research Institute (EPRI)
11:00	Internal Mechanical Stress Improvement (IMSI) Method to Mitigate Stress Corrosion Cracking in Welds, *A. Kepple and D. Rackiewicz*, MPR Associates	11:00	Analysis Supporting the Integrity of Alternative Weld Repairs in Grade 91 Steel, *I. Perrin*, Structural Integrity Associates
11:30	Mechanical and Corrosion Properties of Dissimilar Metal Welds Before and After UNSM Treatment, *Y. Pyun, A. Amanov*, Sun Moon University; *N. Hardwick, J. Su*, AEROPROBE CORP; *G. Frederick, N. Mohr, and S. McCracken*, Electric Power Research Institute (EPRI); *V. K. Vasudevan*, University of Cincinnati	11:30	Open Panel Discussion, *All*
12:00	**Lunch**	12:00	**Lunch**

Agenda (Continued)

Thursday, June 22, 2017 (continued)			
Nuclear Session - Codes and Standards Chair: Joe Weicks / EPRI Representative: Steve McCracken		**Fossil Session - Grade 91 Steel Repair Case Studies** Chair: Nathan Huster / EPRI Representative: John Siefert	
1:00	Proposed ASME B31P Standard ON Preheat and PWHT, *J. Swezy*, Boiler Tech Code, LLC and *P. Flenner*, Flenner Engineering	1:00	Welding Method 6 and Beyond – Perspective from a U.S.-Based Utility, *M. Crichton*, American Electric Power
1:30	Repair of Nuclear Class Piping Using Carbon Fiber Reinforced Composites, *J. O'Sullivan*, Procon	1:30	Replacement of Dissimilar Metal Weld Tube Sections in Finishing Superheater at Dominion's Virginia City Hybrid Energy Center, *F. Timmons and B. Shelton*, Dominion Energy
2:00	Structural Weld Overlay of Dissimilar Metal Weld on "A" Residual Heat Removal Low Pressure Coolant Injection Loop at James A. Fitzpatrick Plant, *J. Weicks*, Entergy; *D. Barborak*, AZZ WSI; and *J. Mansfield*, Exelon	2:00	FPL Case Histories Using Alternate Grade 91 Repairs Outside the Boiler, *K. Rapkin and A. Mayorca*, Florida Power & Light
2:30	Code Case N-865 for Pad Reinforcement Repair of ASME Class 2 and 3 Atmospheric Storage Tanks, *E. Gerlach*, Gerlach Engineering	2:30	Alternative Weld Repair of Grade 91 Hot Reheat and Main Steam Stop Check Valves, *N. Goldsmith and E. DuPont*, Xcel Energy
3:00	**Break**	3:00	**Break**
Nuclear Session - Weldability Chair: Carolin Fink / EPRI Representative: Ben Sutton		**Fossil Session - Grade 91 Steel Repair Case Studies** Chair: Scott Bowes / EPRI Representative: Ian Perrin	
3:30	Addressing Weldability Challenges in the Nuclear Power Industry with Computational Materials Engineering Tools, *A. Hope*, ThermoCalc, Inc. *and B. Sutton*, Electric Power Research Institute (EPRI)	3:30	Development, Control, and Application of T91 Cold Weld Repair Techniques, *K. Mitchell*, RWE
4:00	Welding Duplex Stainless Steel for Nuclear Applications, *B. Auvil, D. Segletes and R. Smith*, Structural Integrity Associates, Inc.	4:00	Future Activities in the Development of Alternative Weld Repairs for Creep Strength Enhanced Ferritic Steels, *J. Siefert*, Electric Power Research Institute (EPRI)
4:30	Effect of Nitrogen on the Solidification Cracking Susceptibility of ERNiCr-3 (FM82) Weld Metal, *C. Fink, M. R. Orr, J. C. Lippold*, The Ohio State University, *and F. Argentine*, BWX Technologies, Inc.	4:30	Open Panel Discussion, *All*
5:00	Development of "Screening Test" for High Nickel Based Alloy, *D. Abe*, IHI	5:00	**Adjourn**
5:30	**Adjourn**		

(d) 第12屆銲接與修復研討會議

圖 2 議程(續)



Agenda (Continued)

Friday, June 23, 2017			
Nuclear Session - Advanced Manufacturing and Fabrication Chair: Marc Hall / EPRI Representative: David Gandy		**Fossil Session - Dissimilar Metal Welds** Chair: John Alice / EPRI Representative: John Siefert	
8:30	Advanced Manufacturing to Enable the Next Generation of Nuclear Plants, *D. Gandy, C. Stover,* Electric Power Research Institute (EPRI), *K. Bridger and S. Lawler,* Nuclear ARMC	8:30	Structural Weld Overlays for Pressurized Component Repair, *D. Barborak,* AZZ
9:00	Ultra High Pressure (UHP) Cavitation Peening of Reactor Vessel Head Penetration Nozzles, *D. Waskey,* Areva	9:00	Microstructural Evolution of Dissimilar Metal Weld Failures Involving Grade 91, *J. DuPont,* Lehigh University *and J. Siefert,* Electric Power Research Institute (EPRI)
9:30	Piping and RPV Welding Automation Through Sensor and Model–Based Adaptive Control, *W. Hamel,* University of Tennessee	9:30	Investigation and Comparison of Good Practice and Alternative Welded T23 to T91 Ferritic Dissimilar Metal Welds after Creep Exposure, *F. Dittrich, P. Mayr,* Chemnitz University of Technology; *J. Siefert and J. Parker,* Electric Power Research Institute (EPRI)
10:00	**Break**	10:00	**Break**
Nuclear Session - Advanced Welding Techniques Chair: Darren Barborak / EPRI Representative: Jon Tatman		**Fossil Session - Advanced Materials and Inservice Monitoring** Chair: Greg Stanko / EPRI Representative: Mike Gagliano	
10:30	Hot Cell Low Heat Input Laser Welding of Highly Activated Neutron Irradiated 304 Stainless Steel, *P. Freyer, F. Gift,* Westinghouse Electric Company LLC; *J. Tatman, G. Frederick, and B. Sutton,* Electric Power Research Institute (EPRI); *and F. Garner,* Radiation Effects Consulting LLC	10:30	Understanding the Link Between Microstructural Evolution And Weld Strength Reduction Factors In New Superalloys Designed For Advanced Power Plants, *D. Bechetti, J. DuPont,* Lehigh University, *J. Siefert and J. Shingledecker,* Electric Power Research Institute (EPRI)
11:00	High Integrity High Productivity Weldments Produced by the Hot Pulse™ GTA Welding Process, *D. Barborak and T. Ratchford,* AZZ WSI	11:00	Benefits of Long-Range-Ordered (LRO) High-Chromium Weld Overlays for Resistance to Corrosion-Fatigue Cracking in Fossil-Fired Boilers, *S. Kiser,* Special Metals Welding Products Company
11:30	Development of Auxiliary Beam Stress Improved Laser Welding for Repair of Highly Irradiated Light Water Reactor Components, *J. Chen, Z. Feng, and Z. Chen,* Oak Ridge National Laboratory; *J. Tatman and G. Frederick,* Electric Power Research Institute (EPRI)	11:30	**Adjourn**
12:00	**Adjourn**		

(e) 第12屆銲接與修復研討會議

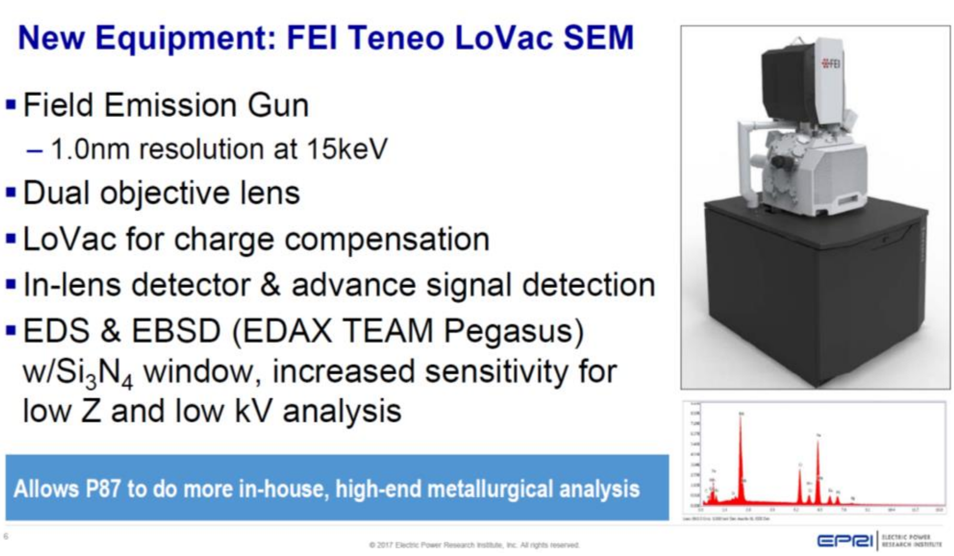
圖 2 議程(續)

2.2P87 研究近況

P87 在 2017 年有 45Funders，Base Funding 約 4 百萬美元，目前技術創新(Technology Innovation，TI)聚焦在 Gr. 91 weld repair、FGD wastewater field testing、Traditional CrMo weld repair、Initial Gr. 92 work、corrosion-fatigue of turbine blades、nanocoatings、Innovative transition joints for DMWs (step weld)、10-12%Cr steels，為提升本身研發能力，添購數項設備，如下所述：

- UTM-Universal Testing Machine (8000-50000 lbs.)，提升 Structural Feature Tests for Boiler Tubing and SIPH/Relaxation Cracking Failures。
- Struers Semi-automatic plane grinding/polishing system，提升製備金相品質與速率。
- 3D Laser Microscope/profiler(Keyence VR-3200 3D Laser Microscope/profiler)，提高影像分析水準與 3D 量測能力。
- SEM(Scanning Electron Microscope)(如圖 3 所示)，具備 Capable of low vacuum operation、Change pressure depending on the sample、Multiple electron detectors for high resolution secondary and back scatter imaging(如圖 4 中區分 Laves、$M_{23}C_6$、AlN，若低於 5kV 之影像，具備較佳晶粒對比與解析度，如圖 5)、EDS system-used for composition analysis(對低原子序元素可提高敏感度之偵測器)、EBSD detector-used for crystallographic analysis。

本所在去年底購置SEM，雖與EPRI購置不同型號，但也雷同數項特色，具備低真空操作、BSE影像偵測器、EBSD偵測器，顯示研究構想接近。



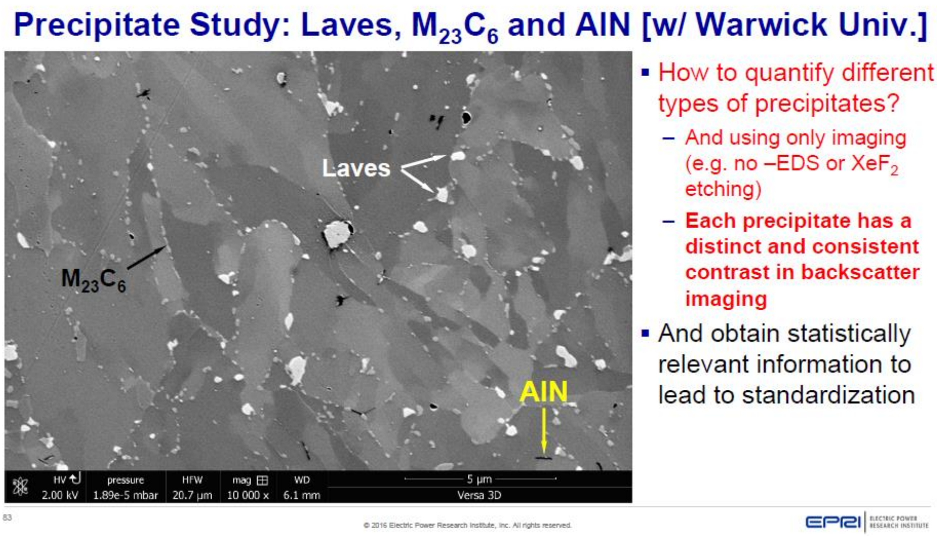
New Equipment: FEI Teneo LoVac SEM

- Field Emission Gun
  - 1.0nm resolution at 15keV
- Dual objective lens
- LoVac for charge compensation
- In-lens detector & advance signal detection
- EDS & EBSD (EDAX TEAM Pegasus) w/Si_3N_4 window, increased sensitivity for low Z and low kV analysis

Allows P87 to do more in-house, high-end metallurgical analysis

6

圖 3 SEM 特色



Precipitate Study: Laves, $M_{23}C_6$ and AlN [w/ Warwick Univ.]

- How to quantify different types of precipitates?
  - And using only imaging (e.g. no –EDS or XeF_2 etching)
  - **Each precipitate has a distinct and consistent contrast in backscatter imaging**
- And obtain statistically relevant information to lead to standardization

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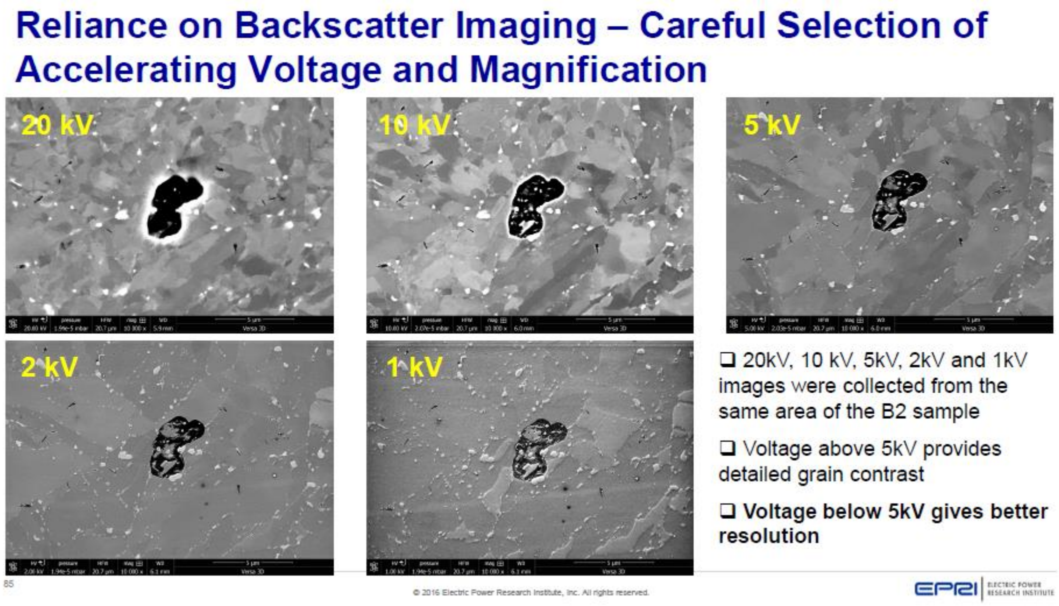
圖 4 BSE 影像



Reliance on Backscatter Imaging – Careful Selection of Accelerating Voltage and Magnification

❑ 20kV, 10 kV, 5kV, 2kV and 1kV images were collected from the same area of the B2 sample

❑ Voltage above 5kV provides detailed grain contrast

❑ **Voltage below 5kV gives better resolution**

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圖 5 不同電壓下影像

EPRI P87 規畫後續研發方向朝 CSEF Steels、Dissimilar Metal Welds、Weld Repair、Corrosion、Advanced Materials 發展，如圖 6 所示，其中 Grade 92、Grade 23 材料的發展、Ferritic to Ferrite or Austenitic 異質銲接與銲補特性、蒸氣側氧化都是本公司確切需要的課題，另對於不銹鋼材料，另有說明將進行珠擊、SIPH/ Relaxation Cracking、訂定不銹鋼 Guidelines、銲接特性等研究，符合公司新林口、大林與通霄機組的 SH 與 RH 不銹鋼管材研究與維護需求。

1. CSEF Steels
    - 11Cr steels
    - Grade 92 Optimization (US-DOE funded)
    - New 9Cr CSEF steels
    - Grade 23 Handbook
    - Hydrogen Induced Cracking
2. Dissimilar Metal Welds
    - Ferritic to Ferritic
    - Ferritic to Austenitic
3. Weld Repair
    - CSEF steel supplemental
    - CrMo steel supplemental
    - CT compressor wheel
4. Corrosion
    - Steamside oxide scale
    - sCO_2 materials corrosion
5. Advanced Materials
    - Ni-base alloy development
    - Alternative valve coatings
    - CF8C-Plus

圖 6　EPRI P87 研發方向

2.3Grade91 之銲後熱處理

CSEF(Creep-Strength Enhanced Ferritic)擁有許多細小的析出物、lath 結構與差排密度，使其具有優異的高溫強度，其中 ASME BPVC. IX 說明 Grade 91 屬於 Group No. 1、P-No.15E 材料，其銲後熱處理是相當重要的，在 ASME B31.1 131 Welding Preheat 與 132 Postweld Heat Treatment 分別列出其建議溫度與注意事項，如表 2 與表 3，若不正確的固定加熱墊、加熱墊或熱電偶的數量或管件的幾何形狀或方位都會造成銲後處理效果不佳，致使管件內壁溫度較低，導致顯微組織異常，如圖 7 所示，越厚(厚度>25mm)的管件僅依循 AWS D10.10 進行銲後熱處理，EPRI 指出是不足夠的。

表 2 預熱溫度

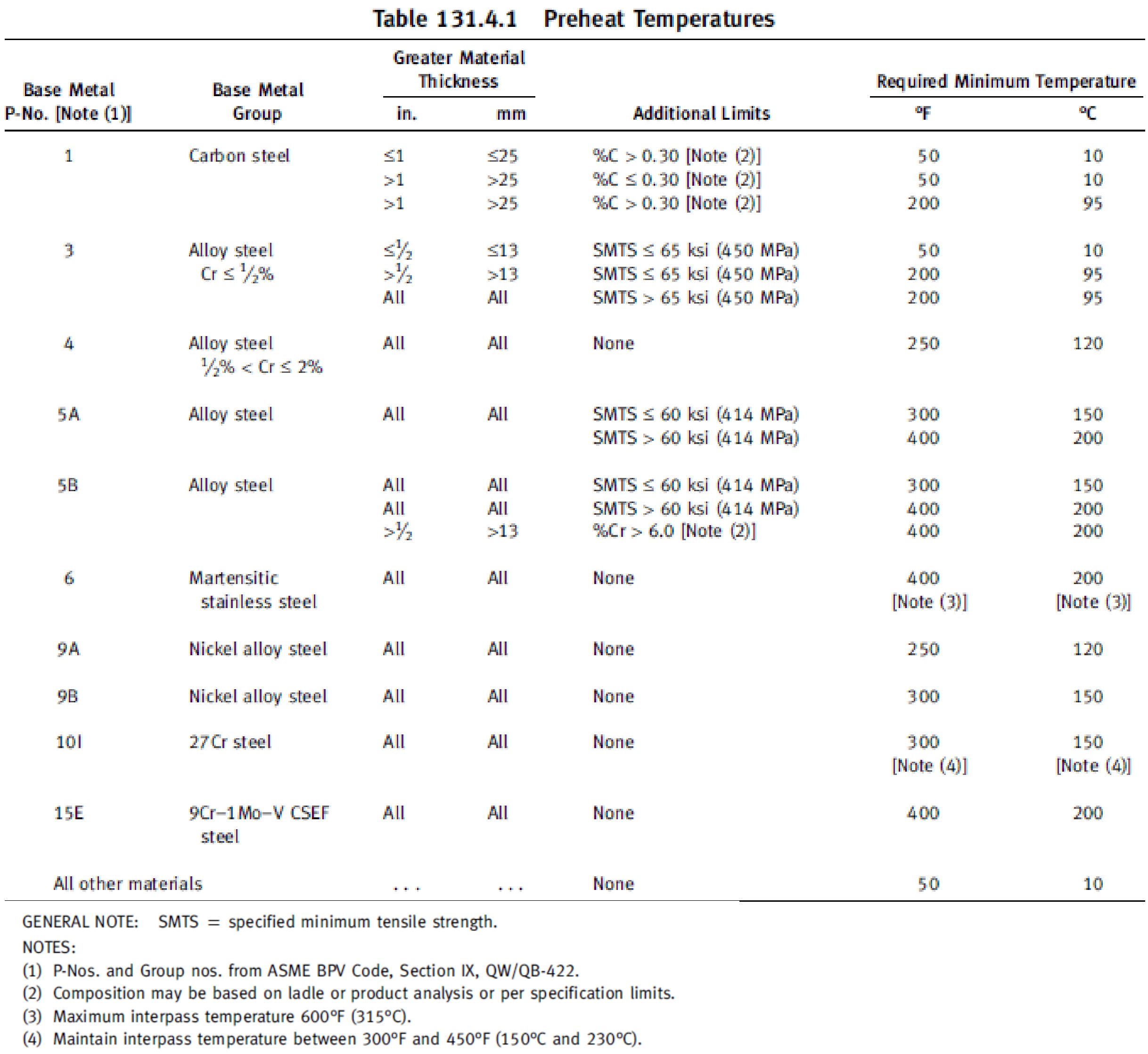


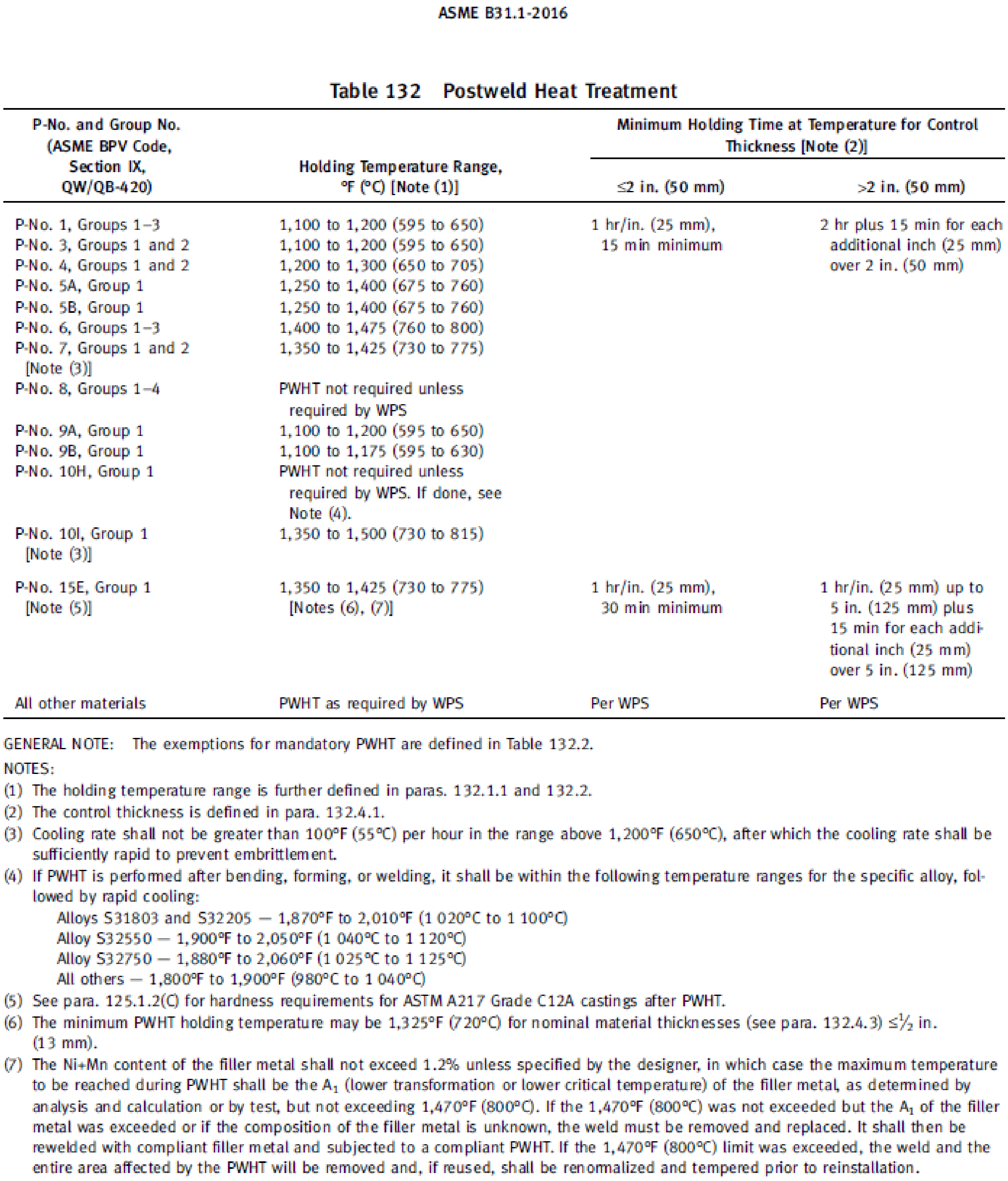
Table 131.4.1 Preheat Temperatures

Base Metal P-No. [Note (1)]	Base Metal Group	Greater Material Thickness		Additional Limits	Required Minimum Temperature	
		in.	mm		°F	°C
1	Carbon steel	≤1	≤25	%C > 0.30 [Note (2)]	50	10
		>1	>25	%C ≤ 0.30 [Note (2)]	50	10
		>1	>25	%C > 0.30 [Note (2)]	200	95
3	Alloy steel Cr ≤ ½%	≤½	≤13	SMTS ≤ 65 ksi (450 MPa)	50	10
		>½	>13	SMTS ≤ 65 ksi (450 MPa)	200	95
		All	All	SMTS > 65 ksi (450 MPa)	200	95
4	Alloy steel ½% < Cr ≤ 2%	All	All	None	250	120
5A	Alloy steel	All	All	SMTS ≤ 60 ksi (414 MPa)	300	150
				SMTS > 60 ksi (414 MPa)	400	200
5B	Alloy steel	All	All	SMTS ≤ 60 ksi (414 MPa)	300	150
		All	All	SMTS > 60 ksi (414 MPa)	400	200
		>½	>13	%Cr > 6.0 [Note (2)]	400	200
6	Martensitic stainless steel	All	All	None	400 [Note (3)]	200 [Note (3)]
9A	Nickel alloy steel	All	All	None	250	120
9B	Nickel alloy steel	All	All	None	300	150
10I	27Cr steel	All	All	None	300 [Note (4)]	150 [Note (4)]
15E	9Cr–1Mo–V CSEF steel	All	All	None	400	200
All other materials		. . .	. . .	None	50	10

GENERAL NOTE: SMTS = specified minimum tensile strength.

NOTES:
(1) P-Nos. and Group nos. from ASME BPV Code, Section IX, QW/QB-422.
(2) Composition may be based on ladle or product analysis or per specification limits.
(3) Maximum interpass temperature 600°F (315°C).
(4) Maintain interpass temperature between 300°F and 450°F (150°C and 230°C).

表 3 銲後熱處理溫度



ASME B31.1-2016

Table 132 Postweld Heat Treatment

P-No. and Group No. (ASME BPV Code, Section IX, QW/QB-420)	Holding Temperature Range, °F (°C) [Note (1)]	Minimum Holding Time at Temperature for Control Thickness [Note (2)]	
		≤2 in. (50 mm)	>2 in. (50 mm)
P-No. 1, Groups 1–3	1,100 to 1,200 (595 to 650)	1 hr/in. (25 mm), 15 min minimum	2 hr plus 15 min for each additional inch (25 mm) over 2 in. (50 mm)
P-No. 3, Groups 1 and 2	1,100 to 1,200 (595 to 650)		
P-No. 4, Groups 1 and 2	1,200 to 1,300 (650 to 705)		
P-No. 5A, Group 1	1,250 to 1,400 (675 to 760)		
P-No. 5B, Group 1	1,250 to 1,400 (675 to 760)		
P-No. 6, Groups 1–3	1,400 to 1,475 (760 to 800)		
P-No. 7, Groups 1 and 2 [Note (3)]	1,350 to 1,425 (730 to 775)		
P-No. 8, Groups 1–4	PWHT not required unless required by WPS		
P-No. 9A, Group 1	1,100 to 1,200 (595 to 650)		
P-No. 9B, Group 1	1,100 to 1,175 (595 to 630)		
P-No. 10H, Group 1	PWHT not required unless required by WPS. If done, see Note (4).		
P-No. 10I, Group 1 [Note (3)]	1,350 to 1,500 (730 to 815)		
P-No. 15E, Group 1 [Note (5)]	1,350 to 1,425 (730 to 775) [Notes (6), (7)]	1 hr/in. (25 mm), 30 min minimum	1 hr/in. (25 mm) up to 5 in. (125 mm) plus 15 min for each additional inch (25 mm) over 5 in. (125 mm)
All other materials	PWHT as required by WPS	Per WPS	Per WPS

GENERAL NOTE: The exemptions for mandatory PWHT are defined in Table 132.2.

NOTES:

(1) The holding temperature range is further defined in paras. 132.1.1 and 132.2.

(2) The control thickness is defined in para. 132.4.1.

(3) Cooling rate shall not be greater than 100°F (55°C) per hour in the range above 1,200°F (650°C), after which the cooling rate shall be sufficiently rapid to prevent embrittlement.

(4) If PWHT is performed after bending, forming, or welding, it shall be within the following temperature ranges for the specific alloy, followed by rapid cooling:
Alloys S31803 and S32205 — 1,870°F to 2,010°F (1 020°C to 1 100°C)
Alloy S32550 — 1,900°F to 2,050°F (1 040°C to 1 120°C)
Alloy S32750 — 1,880°F to 2,060°F (1 025°C to 1 125°C)
All others — 1,800°F to 1,900°F (980°C to 1 040°C)

(5) See para. 125.1.2(C) for hardness requirements for ASTM A217 Grade C12A castings after PWHT.

(6) The minimum PWHT holding temperature may be 1,325°F (720°C) for nominal material thicknesses (see para. 132.4.3) $\leq \frac{1}{2}$ in. (13 mm).

(7) The Ni+Mn content of the filler metal shall not exceed 1.2% unless specified by the designer, in which case the maximum temperature to be reached during PWHT shall be the A_1 (lower transformation or lower critical temperature) of the filler metal, as determined by analysis and calculation or by test, but not exceeding 1,470°F (800°C). If the 1,470°F (800°C) was not exceeded but the A_1 of the filler metal was exceeded or if the composition of the filler metal is unknown, the weld must be removed and replaced. It shall then be rewelded with compliant filler metal and subjected to a compliant PWHT. If the 1,470°F (800°C) limit was exceeded, the weld and the entire area affected by the PWHT will be removed and, if reused, shall be renormalized and tempered prior to reinstallation.

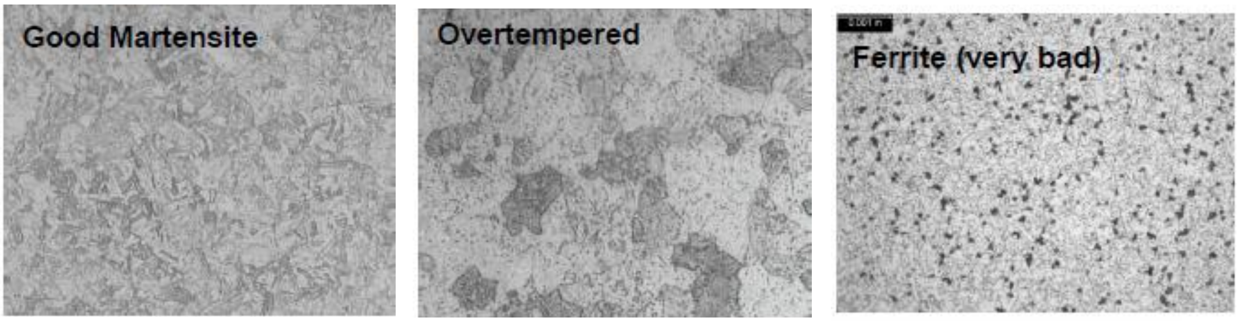
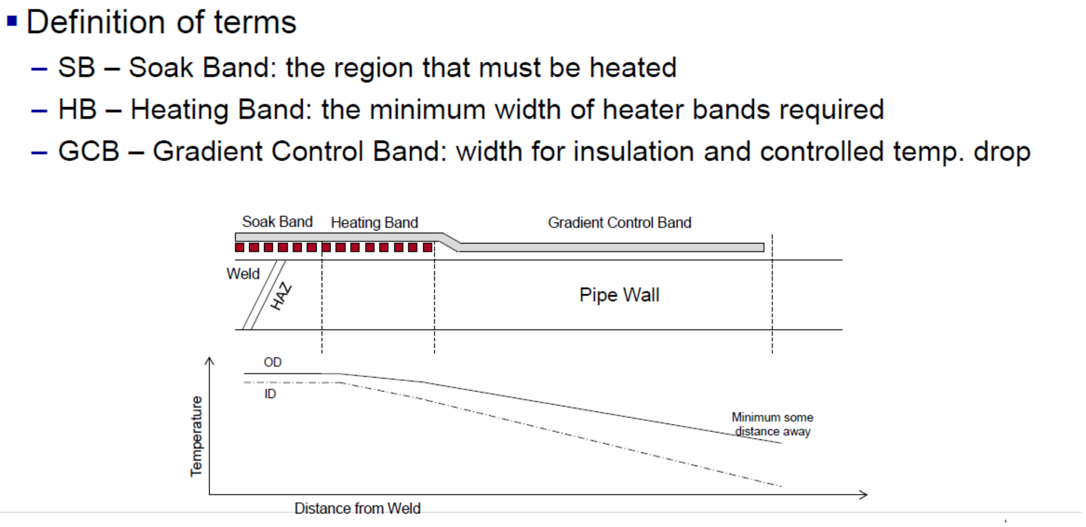


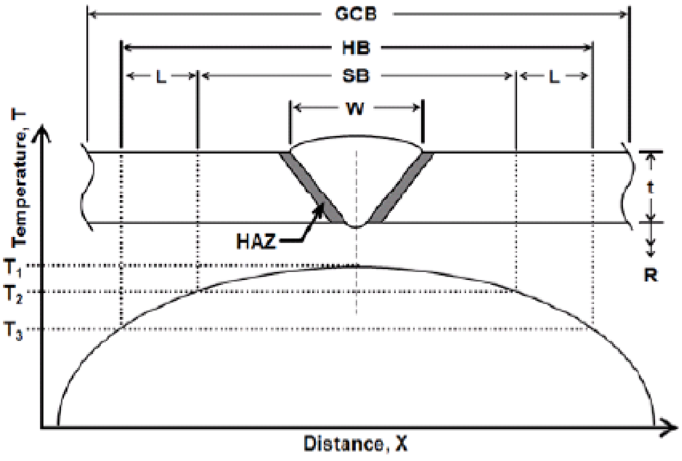
圖7 Grade 91銲後熱處理的顯微組織

AWS(American Welding Society) D10.10 提供現場進行銲後熱處理的準則，定義出儲熱區(Soak Band，SB)、加熱區(Heated Band)、溫度梯度控制區(Gradient Control Band，GCB)三區，如圖 8 所示



- Definition of terms
  - SB – Soak Band: the region that must be heated
  - HB – Heating Band: the minimum width of heater bands required
  - GCB – Gradient Control Band: width for insulation and controlled temp. drop

(a)SB、HB、GCB



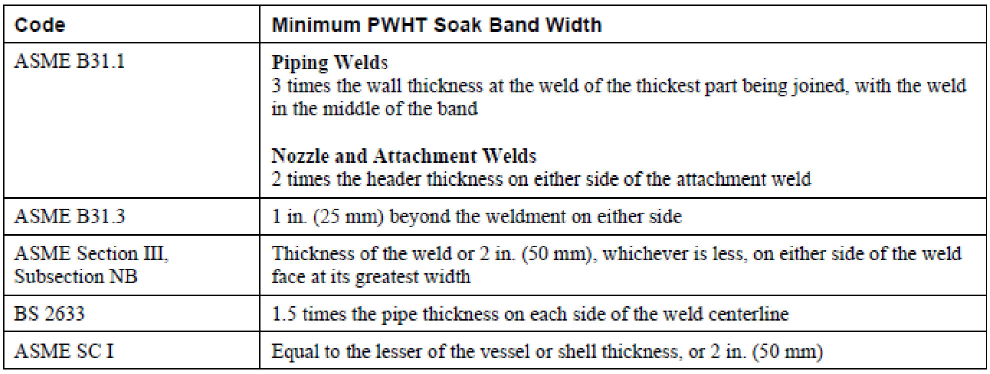
(b)AWS D10.10

圖 8 SB、HB、GCB 區域

儲熱區(Soak Band，SB)是指必須被充分加熱的區域，溫度位於 T_1、T_2 之間，T_1、T_2 為 ASME B31.1 規範或類似規範建議的最大與最小 PWHT 溫度。如 Grade 91 在 EPRI 報告 1023199 中建議最大與最小 PWHT 溫度為 770℃(T_1)與 730℃(T_2)，ASME 則規定 775(T_1)與 730(T_2)之間。AWS D10.10 建議儲熱區至少與壁厚一樣寬或 50mm。

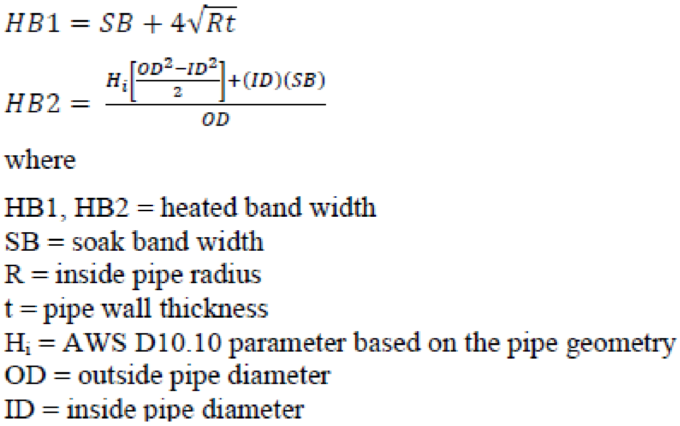
ASME B31.1 則建議儲熱區寬度是 3 倍的壁厚，表 4 列出不同規範的建議最小儲熱區寬度值。

表 4　不同規範之最小 PWHT 儲熱區寬度



Code	**Minimum PWHT Soak Band Width**
ASME B31.1	**Piping Welds** 3 times the wall thickness at the weld of the thickest part being joined, with the weld in the middle of the band **Nozzle and Attachment Welds** 2 times the header thickness on either side of the attachment weld
ASME B31.3	1 in. (25 mm) beyond the weldment on either side
ASME Section III, Subsection NB	Thickness of the weld or 2 in. (50 mm), whichever is less, on either side of the weld face at its greatest width
BS 2633	1.5 times the pipe thickness on each side of the weld centerline
ASME SC I	Equal to the lesser of the vessel or shell thickness, or 2 in. (50 mm)

加熱區(Heated Band)是指與加熱墊接觸的區域，即所需加熱墊的最小寬度，AWS D10.10 建議加熱區的邊緣溫度(T_3)不能少於儲熱區邊緣溫度的一半，AWS D10.10 進一步建議加熱區寬度應該是儲熱區的寬度再加上 50mm，或是可以下列公式計算：

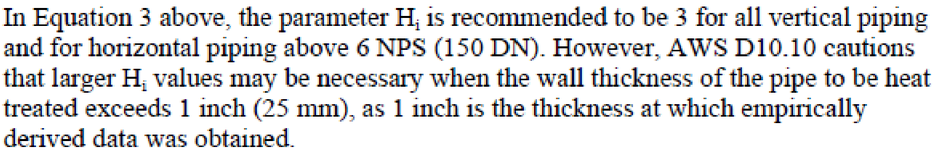


$$HB1 = SB + 4\sqrt{Rt}$$

$$HB2 = \frac{H_i\left[\frac{OD^2 - ID^2}{2}\right] + (ID)(SB)}{OD}$$

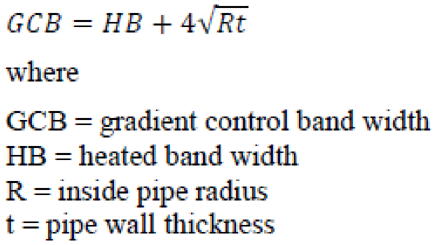
where

HB1, HB2 = heated band width
SB = soak band width
R = inside pipe radius
t = pipe wall thickness
H_i = AWS D10.10 parameter based on the pipe geometry
OD = outside pipe diameter
ID = inside pipe diameter



In Equation 3 above, the parameter H_i is recommended to be 3 for all vertical piping and for horizontal piping above 6 NPS (150 DN). However, AWS D10.10 cautions that larger H_i values may be necessary when the wall thickness of the pipe to be heat treated exceeds 1 inch (25 mm), as 1 inch is the thickness at which empirically derived data was obtained.

溫度梯度控制區(Gradient Control Band，GCB) 是指包覆絕緣層區域，AWS D10.10 建議 GCB 的寬度可以下列公式計算：



$$GCB = HB + 4\sqrt{Rt}$$

where

GCB = gradient control band width
HB = heated band width
R = inside pipe radius
t = pipe wall thickness

下圖 9 舉例說明在 508-762mm 外徑之管材建議放置監控與控溫熱電偶的位置。

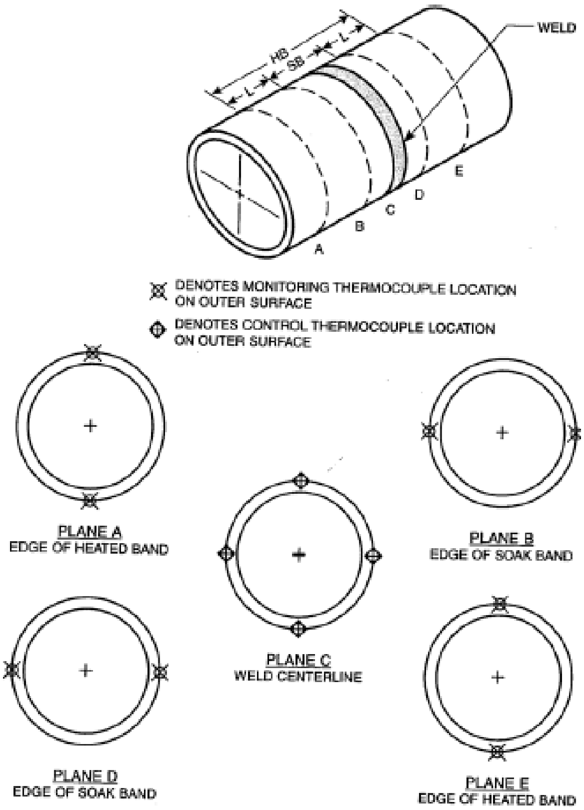


圖 9　建議放置監控與控溫熱電偶的位置

EPRI 研究指出越厚(厚度>25mm)的管件僅依循 AWS D10.10 進行銲後熱處理是不夠的，如僅 42%的儲熱區溫度是大於最小值設定溫度的，若管件越厚，其儲熱區溫度是越低的，如圖 10 所示。

如連接閥體的管件，因閥體較厚，常導致退火不足，管件較薄將導致此處過熱而軟化，如將控制熱電偶(TC)放置在銲道處，無保溫包覆閥體，模擬結果如圖 11 所示，顯示管件較薄而過熱軟化，所以材料厚度不同建議要分別控制熱輸入量。若熱電偶放置在遠離加熱墊的中央位置，整個閥體又無保溫包覆，閥體將成為 Heat Sink，將

使管件超過 Grade 91 銲後熱處理溫度。若改保溫包覆整個閥體，並兩個加熱墊與控制熱電偶(TC1 與 TC2)分開放置在兩個不同厚度的管件上，將使整體溫度較均勻，如圖 11 所示。

圖 12 為模擬溫度梯度控制區(GCB)分別包覆整個、包覆半個與不包覆閥體之情況，控制熱電偶放置在銲道上，結果如圖 12 所示，無包覆閥體顯示大區域面積的過熱(798℃)，包覆整個與包覆半個閥體，僅小部分區域過熱。

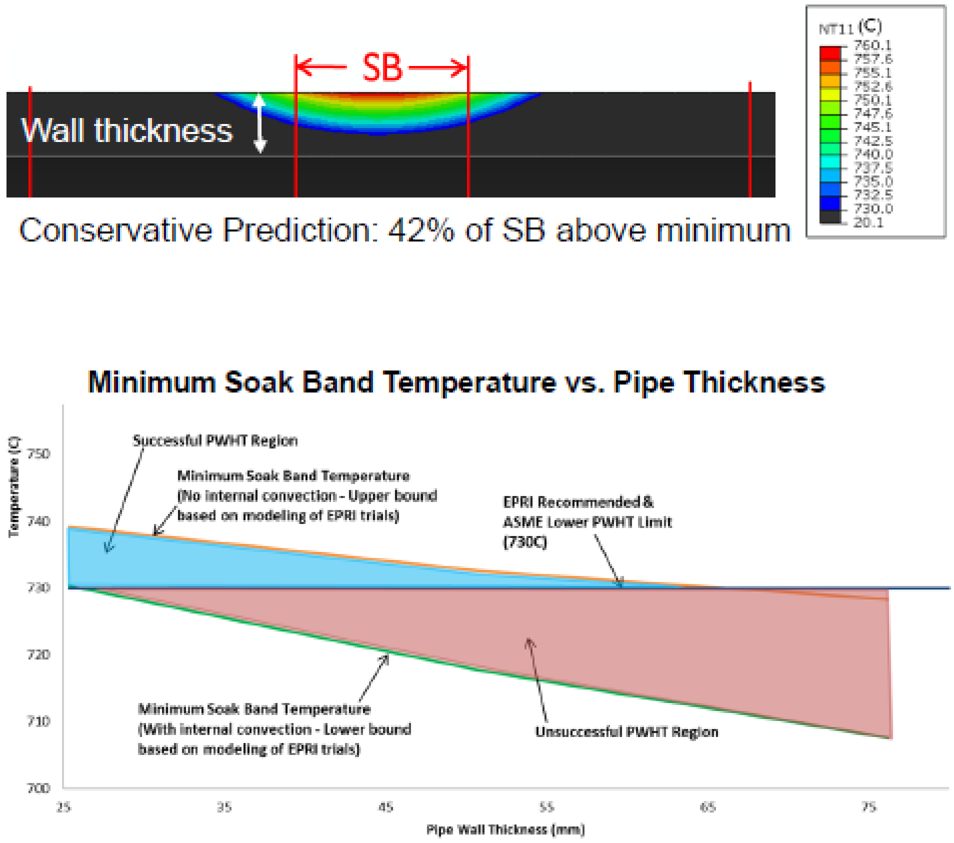
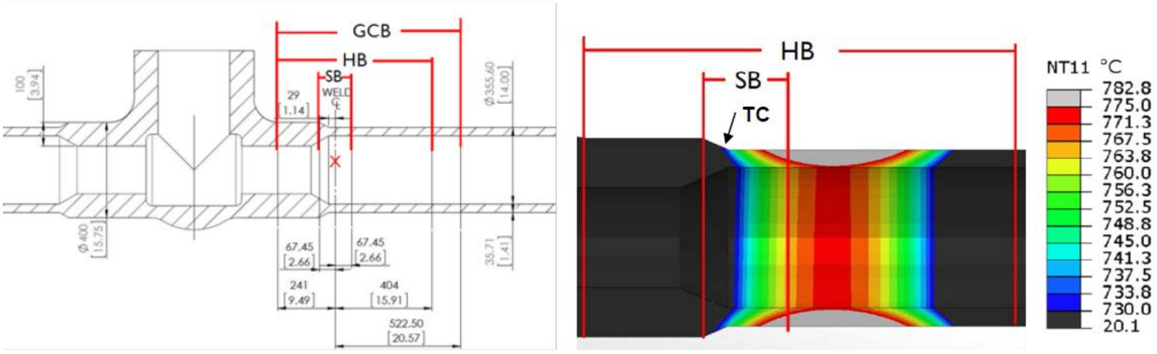
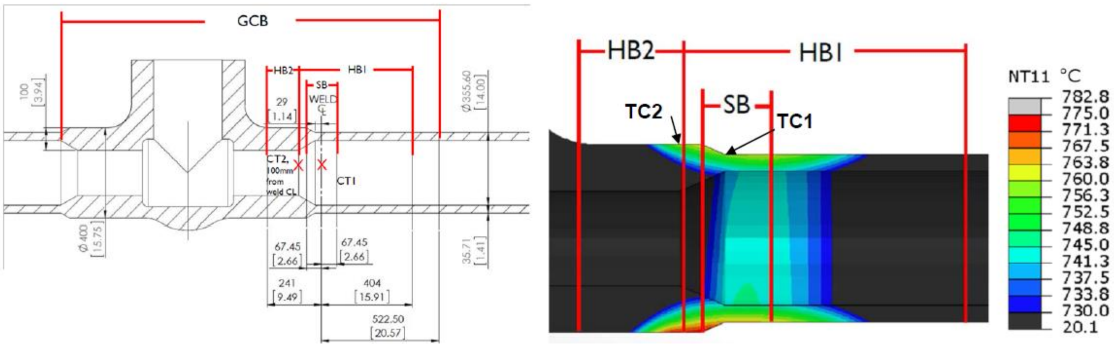


圖10　管件厚度與最小儲熱區溫度關係



(a)僅 1 個熱電偶



(b)2 個熱電偶

圖 11 熱電偶數量對 PWHT 之影響

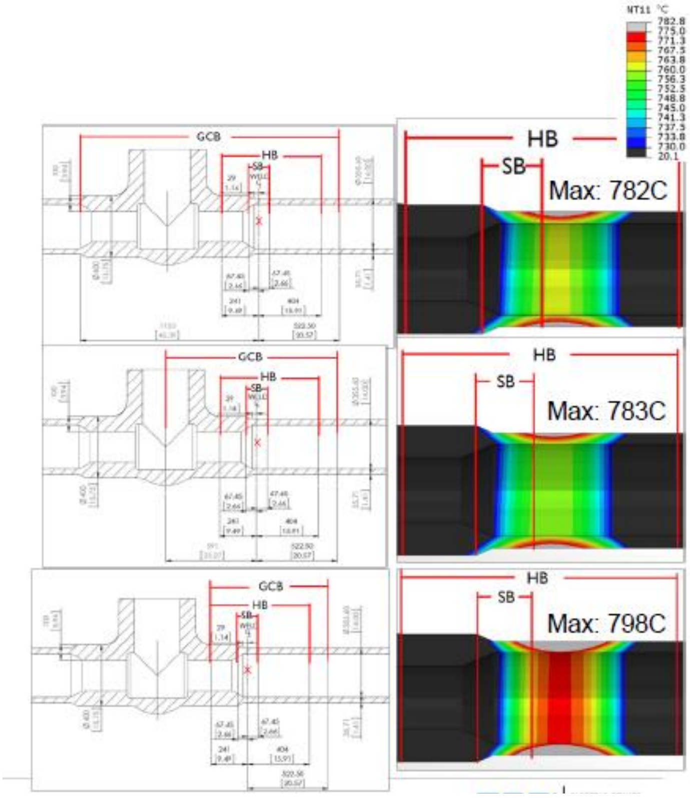
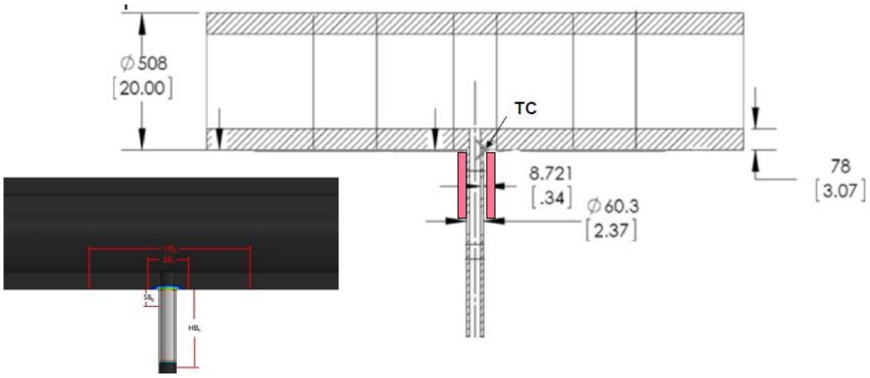
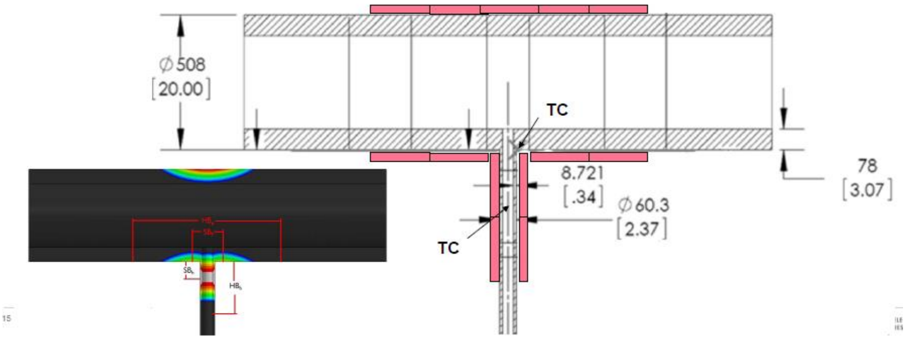


圖12 不同寬度的溫度梯度控制區影響

在 Extraction Tube、Drain Line、Header Tubes 情況下，因薄管連接到厚管件，兩者厚度差異到 10 倍以上，大型管件與長爐管會有 Heat Sink 現象，對銲道進行 PWHT 將產生過熱。若將單一熱電偶放置在銲道，保溫僅保護薄管壁之爐管，爐管將過熱到 950℃，如下圖 13(a)所示。若增設第二個熱電偶在薄管壁爐管上，薄管壁爐管最大溫度將降到 780℃，但厚管壁爐管之上側卻可能過熱，如圖 13(b)所示。



(a)保溫僅保護薄管壁之爐管



(b) 增設二個熱電偶

圖 13 洩水管之 PWHT 模擬

2.4 材料銲接性質

P91異質銲接是在電廠銲接作業中很重要的課題，如與低CrMo鋼銲接，常在融熔線因成分、微結構等性質差異大，導致碳遷移、熱膨脹係數(Coefficient of Thermal Expansion，CTE) 差異導致破壞，若與高Cr鋼或鎳基材料銲接，易在P91(Ferritic Steel)與部分混合區(Partially Mixed Zone，PMZ)之間形成裂紋，如圖14，或因CTE差異大導致氧化層剝落，進而局部腐蝕，或在母材與融熔線形成1-3μm寬度的Carbide-free Ferrite區域，在Carbide-free Ferrite區域和母材之間形成潛變空孔及Type I Carbides，如圖14。

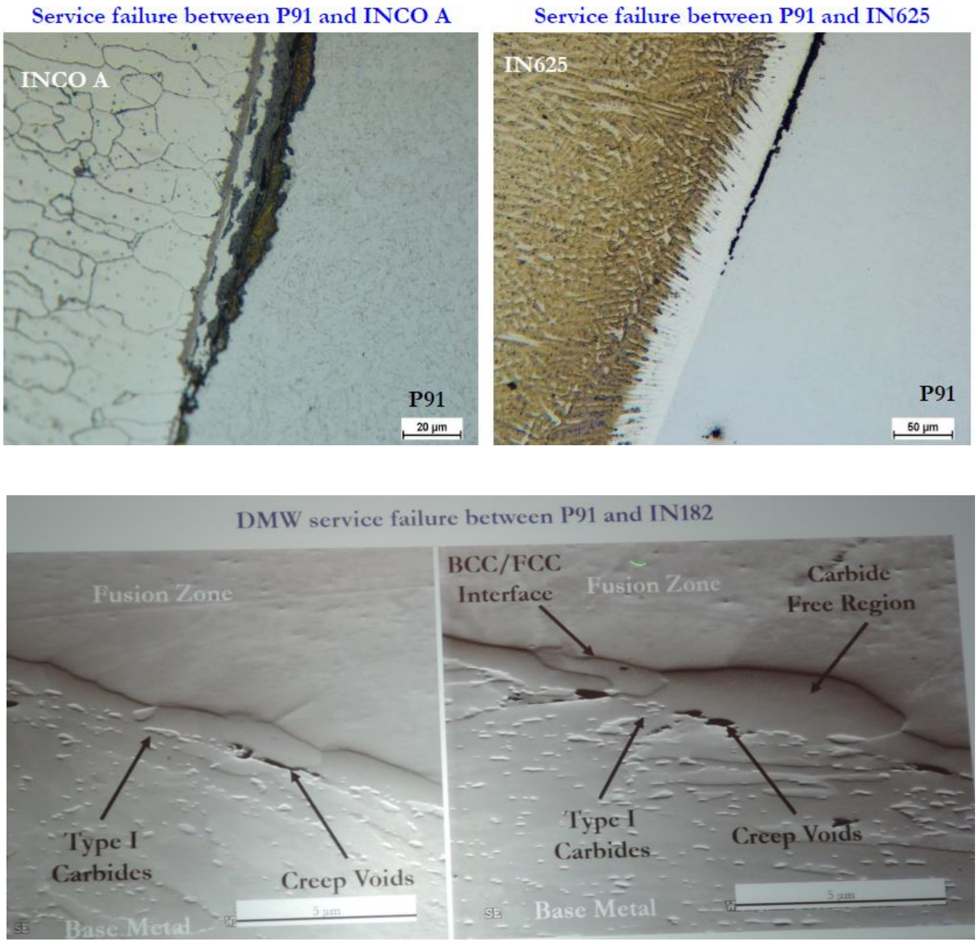


圖14　P91異質銲接破壞案例

Sean Orzolek學者在觀察617、P87、182銲後之微結構，在固化開始時，都是從熔融線平面(Planar)成長，再轉換成多孔(Cellular)成長，析出物均偏析在Cell邊界，如圖15所示，均無形成Ferrite區域

若計算(ThermoCalc)碳的Chemical Potential經760℃/1-4hrs的銲後熱處理，以Alloy 617和625對P91有最大的Chemical Potential差異，預期會有較高傾向的碳遷移，但實驗結果顯示仍無形成Ferrite區域。若計算(ThermoCalc)碳的Chemical Potential經625℃/2000hrs時效處理，仍是Alloy 617和625對P91有最大的Chemical Potential差異，但實驗結果顯示仍無形成Ferrite區域，但IN625與INCO A的PMZ區觀察到2μm寬的Type I carbides區域，故Sean Orzolek學者推論經更長時間時效處理，熔融線處碳將擴散到銲道，形成Ferrite區域，並在Ferrite區域側形成Type I carbides，如圖16與17，並將進行後續研究。

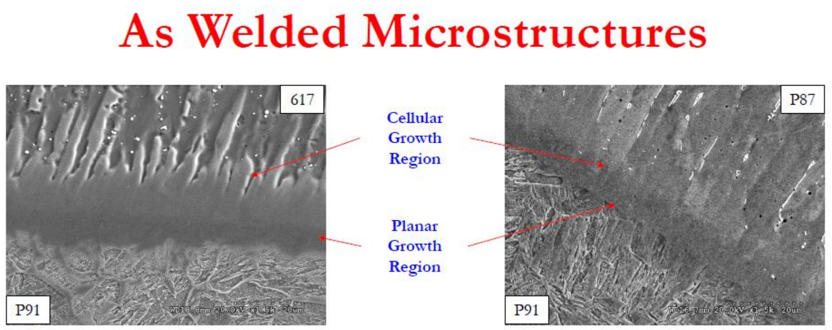


圖15 銲後顯微組織

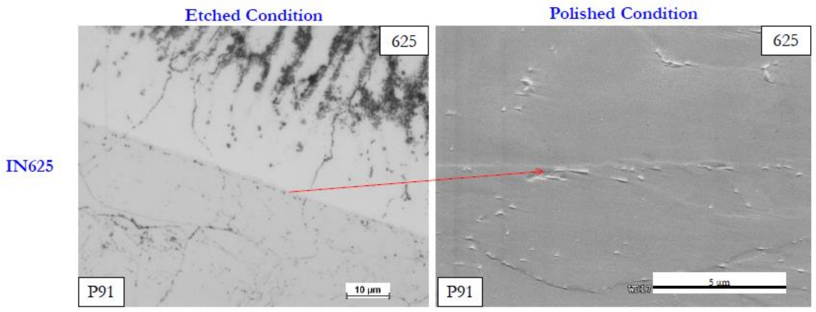


圖16 2μm寬的Type I carbides區域

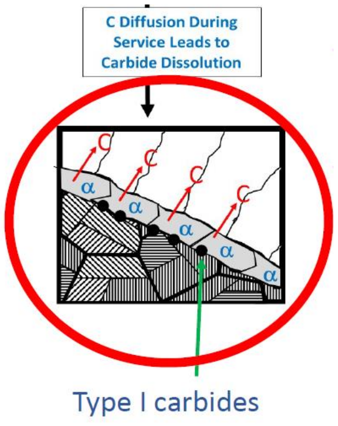
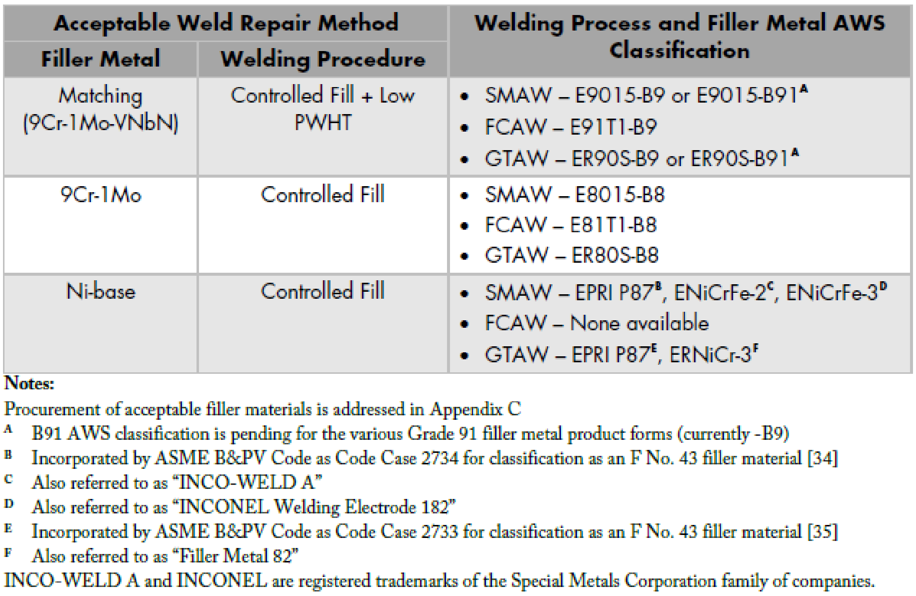


圖17 Type I carbides形成機制

2.5 Grade 91銲補方法

Grade 91 在傳統銲接修復上是採用 AWS-B9 銲條以及在 730-790℃進行 PWHT，但是會造成母材或熱影響區的性能衰退。EPRI 研發出表 5 中三種方法，並列在 NBIC (National Board Inspection Code) Part 3 2.5.3.6 Welding Method 6 [2015 ed.]與 NBIC Part 3 Welding Supplement 11，其中第 2 與 3 項不須銲後熱處理，表 6 列出其對應銲條成分。

表 5　Grade 91 銲補方法與其銲條種類



Acceptable Weld Repair Method		**Welding Process and Filler Metal AWS Classification**
Filler Metal	**Welding Procedure**	
Matching (9Cr-1Mo-VNbN)	Controlled Fill + Low PWHT	• SMAW – E9015-B9 or E9015-B91[A] • FCAW – E91T1-B9 • GTAW – ER90S-B9 or ER90S-B91[A]
9Cr-1Mo	Controlled Fill	• SMAW – E8015-B8 • FCAW – E81T1-B8 • GTAW – ER80S-B8
Ni-base	Controlled Fill	• SMAW – EPRI P87[B], ENiCrFe-2[C], ENiCrFe-3[D] • FCAW – None available • GTAW – EPRI P87[E], ERNiCr-3[F]

Notes:

Procurement of acceptable filler materials is addressed in Appendix C

[A] B91 AWS classification is pending for the various Grade 91 filler metal product forms (currently -B9)

[B] Incorporated by ASME B&PV Code as Code Case 2734 for classification as an F No. 43 filler material [34]

[C] Also referred to as "INCO-WELD A"

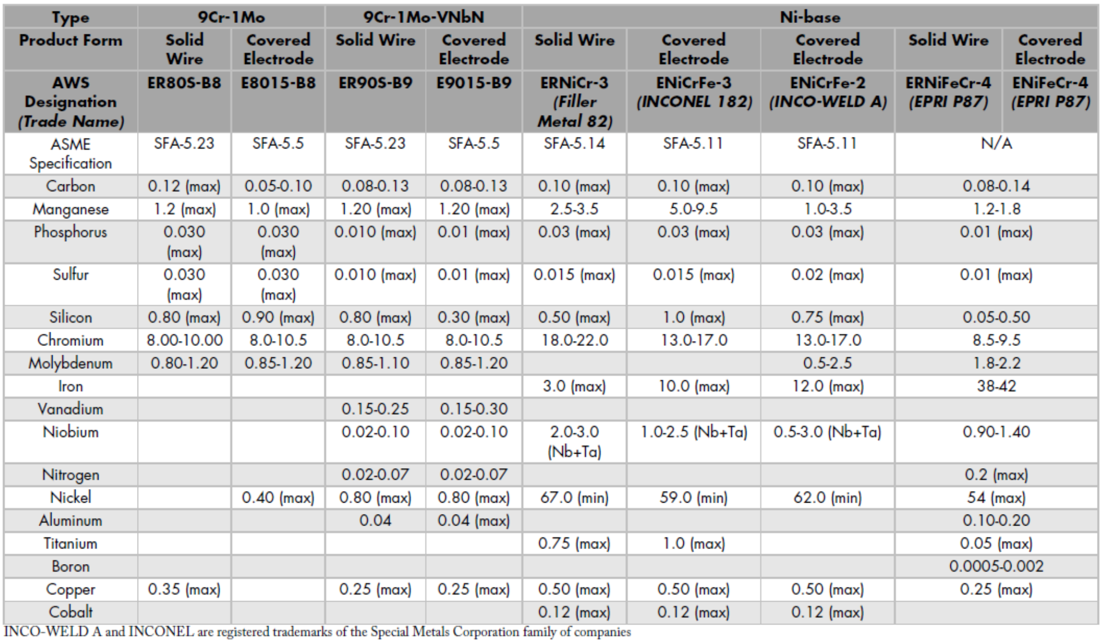
[D] Also referred to as "INCONEL Welding Electrode 182"

[E] Incorporated by ASME B&PV Code as Code Case 2733 for classification as an F No. 43 filler material [35]

[F] Also referred to as "Filler Metal 82"

INCO-WELD A and INCONEL are registered trademarks of the Special Metals Corporation family of companies.

表 6　銲條成分



Type	**9Cr-1Mo**		**9Cr-1Mo-VNbN**		**Ni-base**				
Product Form	**Solid Wire**	**Covered Electrode**	**Solid Wire**	**Covered Electrode**	**Solid Wire**	**Covered Electrode**	**Covered Electrode**	**Solid Wire**	**Covered Electrode**
AWS Designation *(Trade Name)*	**ER80S-B8**	**E8015-B8**	**ER90S-B9**	**E9015-B9**	**ERNiCr-3 *(Filler Metal 82)***	**ENiCrFe-3 *(INCONEL 182)***	**ENiCrFe-2 *(INCO-WELD A)***	**ERNiFeCr-4 *(EPRI P87)***	**ENiFeCr-4 *(EPRI P87)***
ASME Specification	SFA-5.23	SFA-5.5	SFA-5.23	SFA-5.5	SFA-5.14	SFA-5.11	SFA-5.11	N/A	
Carbon	0.12 (max)	0.05-0.10	0.08-0.13	0.08-0.13	0.10 (max)	0.10 (max)	0.10 (max)	0.08-0.14	
Manganese	1.2 (max)	1.0 (max)	1.20 (max)	1.20 (max)	2.5-3.5	5.0-9.5	1.0-3.5	1.2-1.8	
Phosphorus	0.030 (max)	0.030 (max)	0.010 (max)	0.01 (max)	0.03 (max)	0.03 (max)	0.03 (max)	0.01 (max)	
Sulfur	0.030 (max)	0.030 (max)	0.010 (max)	0.01 (max)	0.015 (max)	0.015 (max)	0.02 (max)	0.01 (max)	
Silicon	0.80 (max)	0.90 (max)	0.80 (max)	0.30 (max)	0.50 (max)	1.0 (max)	0.75 (max)	0.05-0.50	
Chromium	8.00-10.00	8.0-10.5	8.0-10.5	8.0-10.5	18.0-22.0	13.0-17.0	13.0-17.0	8.5-9.5	
Molybdenum	0.80-1.20	0.85-1.20	0.85-1.10	0.85-1.20			0.5-2.5	1.8-2.2	
Iron					3.0 (max)	10.0 (max)	12.0 (max)	38-42	
Vanadium			0.15-0.25	0.15-0.30					
Niobium			0.02-0.10	0.02-0.10	2.0-3.0 (Nb+Ta)	1.0-2.5 (Nb+Ta)	0.5-3.0 (Nb+Ta)	0.90-1.40	
Nitrogen			0.02-0.07	0.02-0.07				0.2 (max)	
Nickel		0.40 (max)	0.80 (max)	0.80 (max)	67.0 (min)	59.0 (min)	62.0 (min)	54 (max)	
Aluminum			0.04	0.04 (max)				0.10-0.20	
Titanium					0.75 (max)	1.0 (max)		0.05 (max)	
Boron								0.0005-0.002	
Copper	0.35 (max)		0.25 (max)	0.25 (max)	0.50 (max)	0.50 (max)	0.50 (max)	0.25 (max)	
Cobalt					0.12 (max)	0.12 (max)	0.12 (max)		

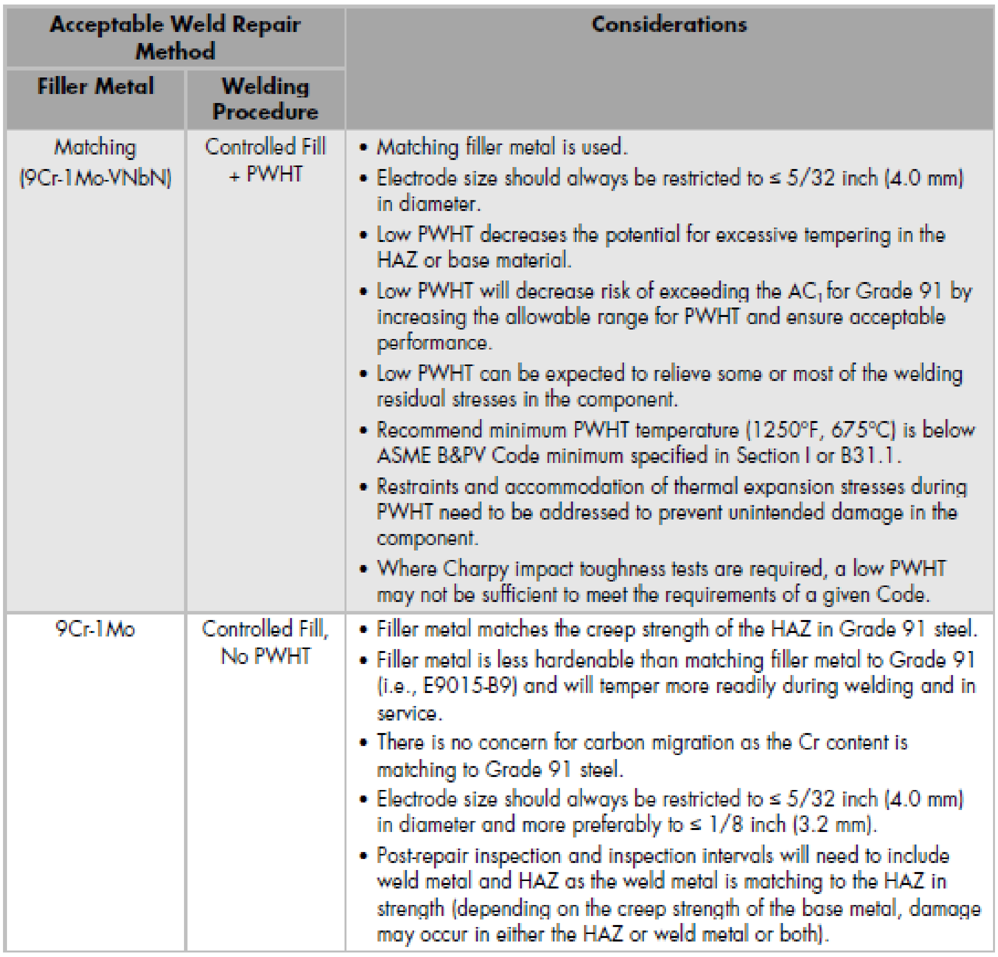
INCO-WELD A and INCONEL are registered trademarks of the Special Metals Corporation family of companies

在第一項方法中(填料為 9Cr-1Mo-VNbN)，若採用 675℃/2Hrs 的較低溫銲後熱處理，Gr91 熱影響區最大值將降到 350HV0.5，銲道硬度最大值將降到 335HV0.5。

在第二項方法中(填料為 9Cr-1Mo)，因 E8015-B8 填料的硬化能低於 E9015-B9，E8015-B8 填料在服役情形下(>538℃)會有回火效果，如在 CGHAZ 區域最大硬度值可能會減少約 100HV。

要進行 Controlled Fill 銲接時，須適當的控制熱輸入量，第一道次銲補缺陷時，要採用小直徑銲條，銲珠與銲珠需重疊 50%以上，每一道次之間要重疊 25-50%之間，因為這可促進填料的回火與控制不變形，詳細的 Controlled Fill 銲接注意事項與銲珠的走法控制如表 7 與圖 18 所示。

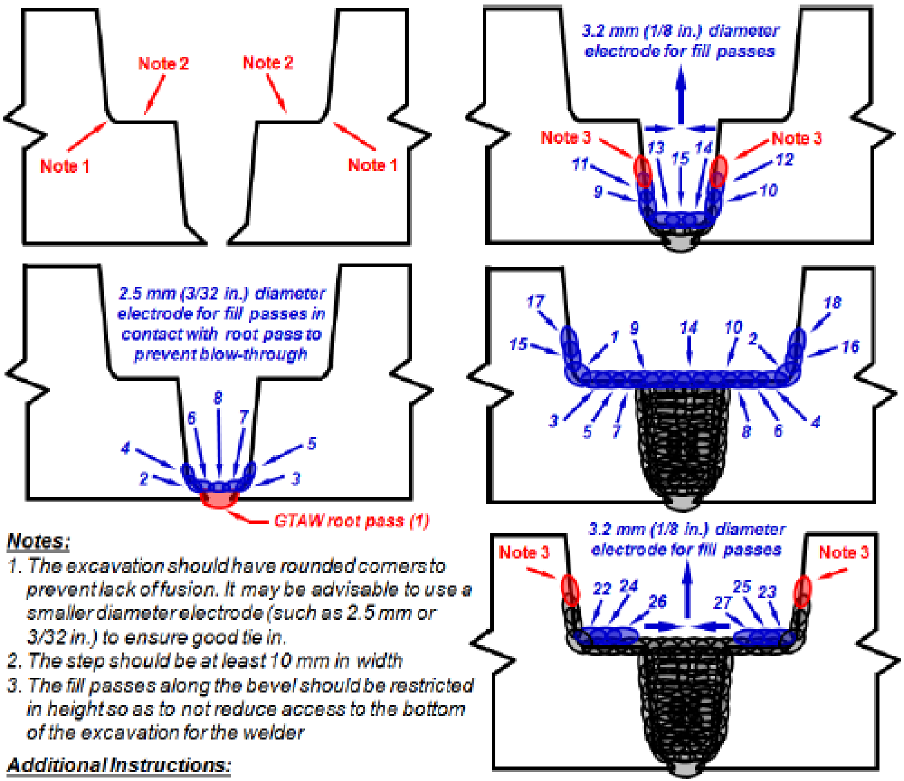
表 7 Grade 91 銲補方法



Acceptable Weld Repair Method		Considerations
Filler Metal	Welding Procedure	
Matching (9Cr-1Mo-VNbN)	Controlled Fill + PWHT	• Matching filler metal is used. • Electrode size should always be restricted to ≤ 5/32 inch (4.0 mm) in diameter. • Low PWHT decreases the potential for excessive tempering in the HAZ or base material. • Low PWHT will decrease risk of exceeding the AC_1 for Grade 91 by increasing the allowable range for PWHT and ensure acceptable performance. • Low PWHT can be expected to relieve some or most of the welding residual stresses in the component. • Recommend minimum PWHT temperature (1250°F, 675°C) is below ASME B&PV Code minimum specified in Section I or B31.1. • Restraints and accommodation of thermal expansion stresses during PWHT need to be addressed to prevent unintended damage in the component. • Where Charpy impact toughness tests are required, a low PWHT may not be sufficient to meet the requirements of a given Code.
9Cr-1Mo	Controlled Fill, No PWHT	• Filler metal matches the creep strength of the HAZ in Grade 91 steel. • Filler metal is less hardenable than matching filler metal to Grade 91 (i.e., E9015-B9) and will temper more readily during welding and in service. • There is no concern for carbon migration as the Cr content is matching to Grade 91 steel. • Electrode size should always be restricted to ≤ 5/32 inch (4.0 mm) in diameter and more preferably to ≤ 1/8 inch (3.2 mm). • Post-repair inspection and inspection intervals will need to include weld metal and HAZ as the weld metal is matching to the HAZ in strength (depending on the creep strength of the base metal, damage may occur in either the HAZ or weld metal or both).

表 7 Grade 91 銲補方法(續)

Acceptable Weld Repair Method		**Considerations**
Filler Metal	**Welding Procedure**	
Ni-base	Controlled Fill, No PWHT	• The electrode size for fill passes against the bevel should be 1/8 inch (3.2 mm) diameter as there have been reported difficulties in using smaller diameter electrodes. • The electrode size for all fill passes can be 5/32 inch (4.0 mm) diameter since there is no concern for tempering of the deposited weld metal. • There is increased defect tolerance in weld metal due to the high fracture toughness and creep strength inherent to filler metal. • NDE is more challenging during the repair (MT is not possible) and following repair (optimized procedures for UT are required to inspect the entirety of the weld repair region). • There is a tendency to form microfissures and/or lack of fusion defects (although detected by potential NDE techniques, such defects have not been shown to contribute to a reduction in performance). • The skill of the welder can be an important variable, as Ni-base fillers can exhibit poor weld pool fluidity and in general are more difficult to deposit. • The operating temperature of the component as welding residual stresses may not relax rapidly at temperatures <550°C (1022°F). • Post-repair inspection and inspection intervals will need to include filler metal and HAZ as there may be a risk for damage in both locations and consistent with reported DMW failures.



Notes:

1. *The excavation should have rounded corners to prevent lack of fusion. It may be advisable to use a smaller diameter electrode (such as 2.5 mm or 3/32 in.) to ensure good tie in.*
2. *The step should be at least 10 mm in width*
3. *The fill passes along the bevel should be restricted in height so as to not reduce access to the bottom of the excavation for the welder*

Additional Instructions:

- *The fill passes should be conducted working "outside-in", whereby the fill passes are first deposited on either side of the excavation and additional fill passes are deposited welding towards the center of excavation*
- *50% overlap is recommended for all welding passes either in contact with the bevel or fill*
- *Stringer beads only are recommended for all welding passes either in contact with the bevel or fill*
- *A 2.5 mm (3/32 in.) diameter electrode may be utilized for the weld passes in contact with the bevel but is not mandated nor required for acceptable performance*

圖 18 銲珠順序

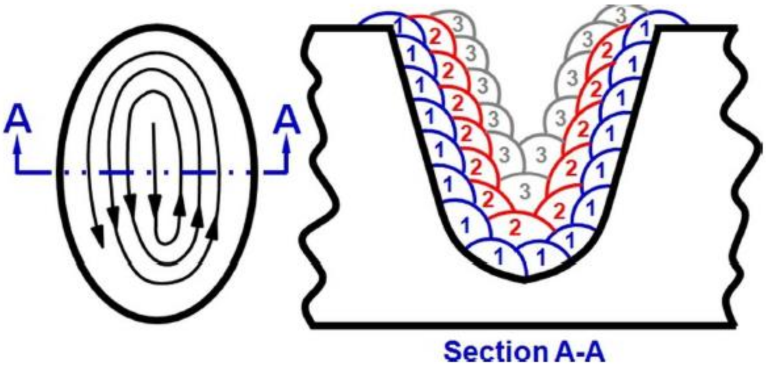
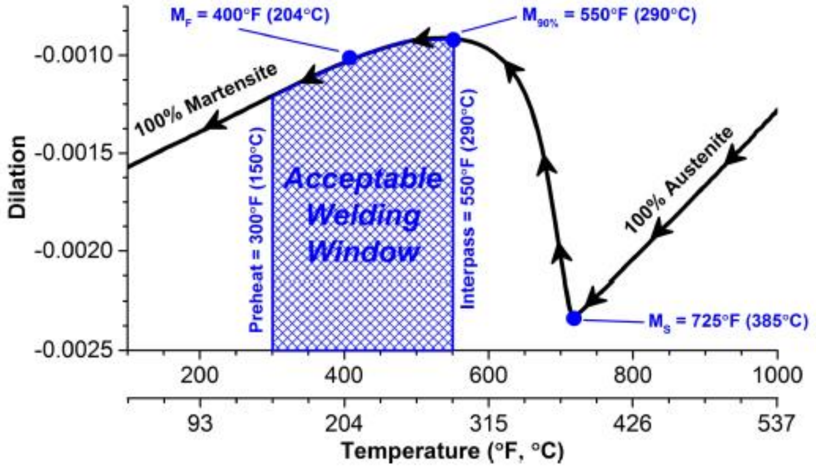


圖 18 銲珠順序(續)

典型 Grade 91 最小預熱溫度為 200℃與最大層間溫度為 315℃，但 EPRI 經過多次的銲接修復實驗，採用最小預熱溫度為 149℃與最大層間溫度 290℃，並無發生 Hydrogen-Induced Cracking。使用較低的最大層間溫度，可使銲道、熱影響區充分的相變態成麻田散鐵組織，如圖 19 中標示出的藍色區域。



Note: M_S = Initial of austenite to martensite transformation
$M_{90\%}$ = 90% transformed austenite to martensite
M_F = 100% transformed austenite to martensite

圖 19 最小預熱溫度與最大層間溫度與 Martensite 相轉換比率關係

若以第一項方法中(填料為 9Cr-1Mo-VNbN)銲補，需進行銲後熱處理，除須遵守 AWS D10.10 外，仍須注意下列數點，才能避免過熱：

- The pads must be properly sized and wrapped onto the parts without gaps or slackness.
- The pads should never overlap.
- The gaps between heating pads should be minimized.
- In addition to the thermocouple layout detailed in AWS D10.10, it is recommended to have at least one thermocouple installed under each stress relief heating pad to verify that the material under the pad has not exceed the lower critical temperature.
- Thermocouples under pads must also be insulated so they measure the metal temperature and not the pad temperature.
- A single control thermocouple should not control multiple heaters, as uniform heating will be difficult over the desired PWHT area.
- Monitoring or control thermocouples should be located underneath the pads in the location of the expected highest temperature.
- Use of multiple control zones for joints with dissimilar thickness transitions.
- Many companies specify redundancy in these control thermocouples in the event one becomes unattached during PWHT.
- Where access to the ID is possible, monitoring should be mandated. Single point monitoring is unacceptable.
- Excessively high ramp rates during PWHT (that is, where there is large thickness transition as in a pipe to a valve or fitting) can lead to a dwell above the lower critical temperature and result in soft regions.

2.6Grade91 氧化與剝落行為

在 ASME BPVC SEC I(2015 年)中 PG-19 與 PG-20 說明 CSEF 鋼與不銹鋼冷作成型、熱處理與金屬溫度上限的規定，如表 8 所示，其中 Grade91 為 600℃，在低於 600℃以下溫度，蒸氣側氧化與氧化層剝落所導致的破管事故，仍層出不窮。是因 Grade 91 多用在熱傳表面之爐管，故會造成氧化層剝落與堵塞會導致短期過熱、爐管金屬溫度的逐漸提高也將導致長期過熱、氧化層的剝落導致下游蒸汽渦輪機與閥的沖蝕、過濾器(Strainer/Screen)的堵塞等問題。

表 8 ASME BPVC SEC I 材料溫度限制

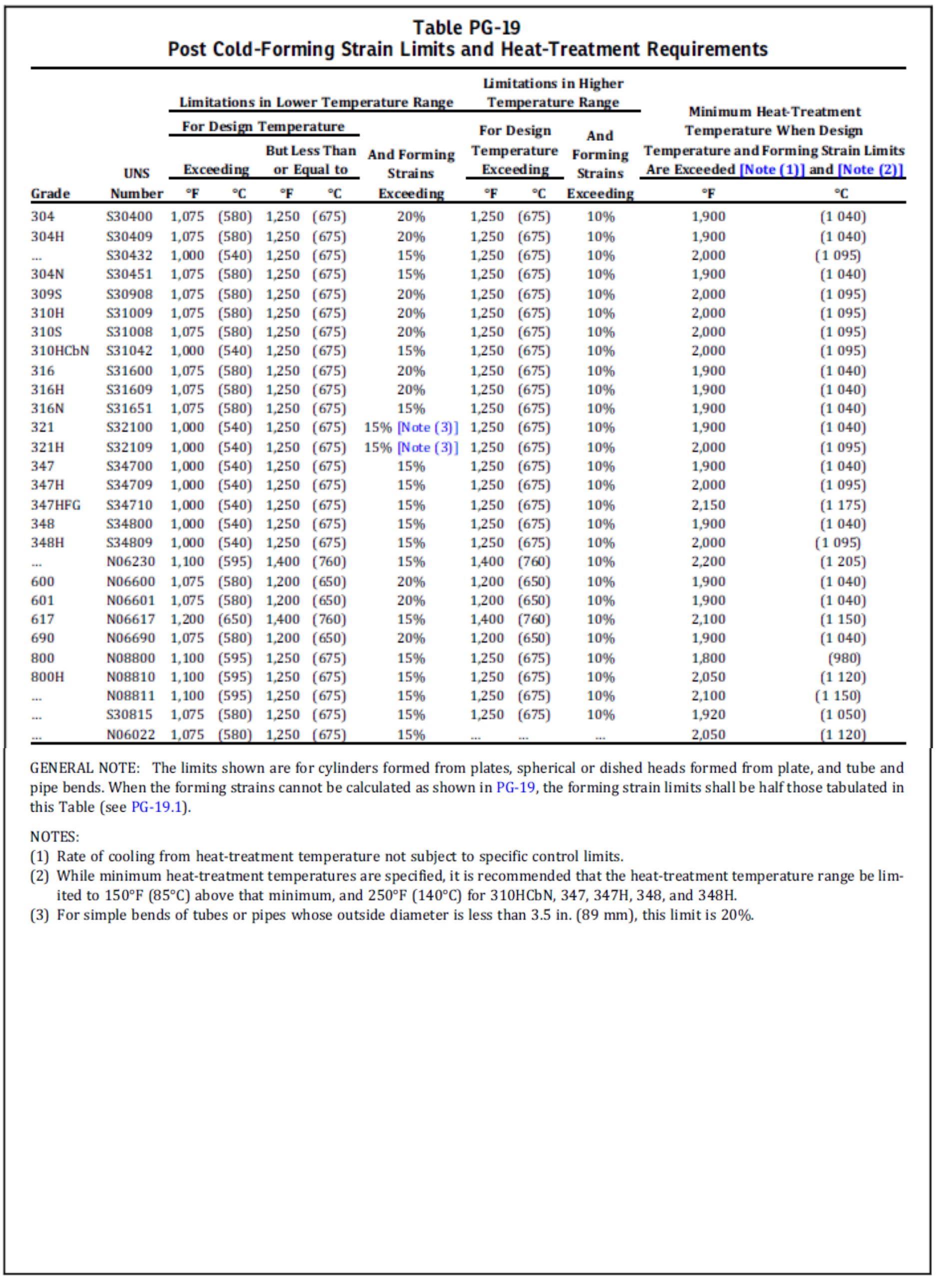


Table PG-19
Post Cold-Forming Strain Limits and Heat-Treatment Requirements

		Limitations in Lower Temperature Range					Limitations in Higher Temperature Range			Minimum Heat-Treatment Temperature When Design Temperature and Forming Strain Limits Are Exceeded [Note (1)] and [Note (2)]	
		For Design Temperature									
		Exceeding		But Less Than or Equal to		And Forming Strains	For Design Temperature Exceeding		And Forming Strains		
Grade	UNS Number	°F	°C	°F	°C	Exceeding	°F	°C	Exceeding	°F	°C
304	S30400	1,075	(580)	1,250	(675)	20%	1,250	(675)	10%	1,900	(1 040)
304H	S30409	1,075	(580)	1,250	(675)	20%	1,250	(675)	10%	1,900	(1 040)
...	S30432	1,000	(540)	1,250	(675)	15%	1,250	(675)	10%	2,000	(1 095)
304N	S30451	1,075	(580)	1,250	(675)	15%	1,250	(675)	10%	1,900	(1 040)
309S	S30908	1,075	(580)	1,250	(675)	20%	1,250	(675)	10%	2,000	(1 095)
310H	S31009	1,075	(580)	1,250	(675)	20%	1,250	(675)	10%	2,000	(1 095)
310S	S31008	1,075	(580)	1,250	(675)	20%	1,250	(675)	10%	2,000	(1 095)
310HCbN	S31042	1,000	(540)	1,250	(675)	15%	1,250	(675)	10%	2,000	(1 095)
316	S31600	1,075	(580)	1,250	(675)	20%	1,250	(675)	10%	1,900	(1 040)
316H	S31609	1,075	(580)	1,250	(675)	20%	1,250	(675)	10%	1,900	(1 040)
316N	S31651	1,075	(580)	1,250	(675)	15%	1,250	(675)	10%	1,900	(1 040)
321	S32100	1,000	(540)	1,250	(675)	15% [Note (3)]	1,250	(675)	10%	1,900	(1 040)
321H	S32109	1,000	(540)	1,250	(675)	15% [Note (3)]	1,250	(675)	10%	2,000	(1 095)
347	S34700	1,000	(540)	1,250	(675)	15%	1,250	(675)	10%	1,900	(1 040)
347H	S34709	1,000	(540)	1,250	(675)	15%	1,250	(675)	10%	2,000	(1 095)
347HFG	S34710	1,000	(540)	1,250	(675)	15%	1,250	(675)	10%	2,150	(1 175)
348	S34800	1,000	(540)	1,250	(675)	15%	1,250	(675)	10%	1,900	(1 040)
348H	S34809	1,000	(540)	1,250	(675)	15%	1,250	(675)	10%	2,000	(1 095)
...	N06230	1,100	(595)	1,400	(760)	15%	1,400	(760)	10%	2,200	(1 205)
600	N06600	1,075	(580)	1,200	(650)	20%	1,200	(650)	10%	1,900	(1 040)
601	N06601	1,075	(580)	1,200	(650)	20%	1,200	(650)	10%	1,900	(1 040)
617	N06617	1,200	(650)	1,400	(760)	15%	1,400	(760)	10%	2,100	(1 150)
690	N06690	1,075	(580)	1,200	(650)	20%	1,200	(650)	10%	1,900	(1 040)
800	N08800	1,100	(595)	1,250	(675)	15%	1,250	(675)	10%	1,800	(980)
800H	N08810	1,100	(595)	1,250	(675)	15%	1,250	(675)	10%	2,050	(1 120)
...	N08811	1,100	(595)	1,250	(675)	15%	1,250	(675)	10%	2,100	(1 150)
...	S30815	1,075	(580)	1,250	(675)	15%	1,250	(675)	10%	1,920	(1 050)
...	N06022	1,075	(580)	1,250	(675)	15%	...	...	...	2,050	(1 120)

GENERAL NOTE: The limits shown are for cylinders formed from plates, spherical or dished heads formed from plate, and tube and pipe bends. When the forming strains cannot be calculated as shown in PG-19, the forming strain limits shall be half those tabulated in this Table (see PG-19.1).

NOTES:
(1) Rate of cooling from heat-treatment temperature not subject to specific control limits.
(2) While minimum heat-treatment temperatures are specified, it is recommended that the heat-treatment temperature range be limited to 150°F (85°C) above that minimum, and 250°F (140°C) for 310HCbN, 347, 347H, 348, and 348H.
(3) For simple bends of tubes or pipes whose outside diameter is less than 3.5 in. (89 mm), this limit is 20%.

表 8 ASME BPVC SEC I 材料溫度限制(續)

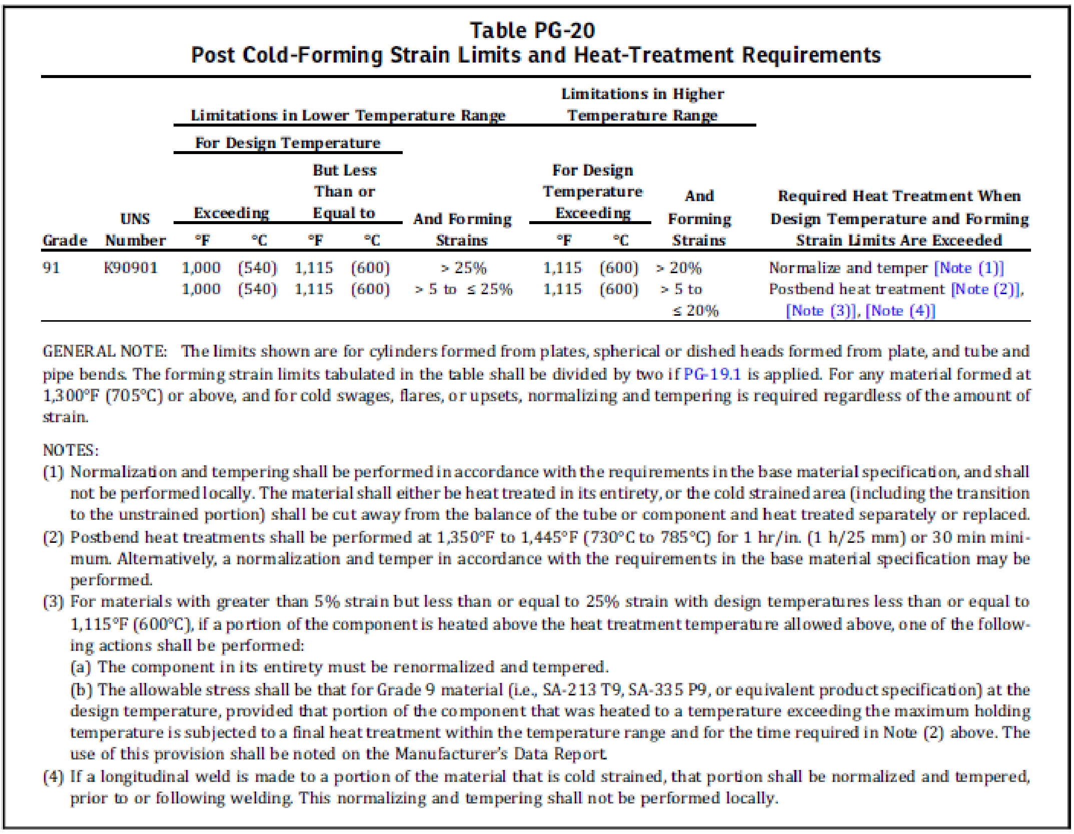


Table PG-20
Post Cold-Forming Strain Limits and Heat-Treatment Requirements

		Limitations in Lower Temperature Range					Limitations in Higher Temperature Range			
		For Design Temperature								
		Exceeding		But Less Than or Equal to			For Design Temperature Exceeding			
Grade	UNS Number	°F	°C	°F	°C	And Forming Strains	°F	°C	And Forming Strains	Required Heat Treatment When Design Temperature and Forming Strain Limits Are Exceeded
91	K90901	1,000	(540)	1,115	(600)	> 25%	1,115	(600)	> 20%	Normalize and temper [Note (1)]
		1,000	(540)	1,115	(600)	> 5 to ≤ 25%	1,115	(600)	> 5 to ≤ 20%	Postbend heat treatment [Note (2)], [Note (3)], [Note (4)]

GENERAL NOTE: The limits shown are for cylinders formed from plates, spherical or dished heads formed from plate, and tube and pipe bends. The forming strain limits tabulated in the table shall be divided by two if PG-19.1 is applied. For any material formed at 1,300°F (705°C) or above, and for cold swages, flares, or upsets, normalizing and tempering is required regardless of the amount of strain.

NOTES:

(1) Normalization and tempering shall be performed in accordance with the requirements in the base material specification, and shall not be performed locally. The material shall either be heat treated in its entirety, or the cold strained area (including the transition to the unstrained portion) shall be cut away from the balance of the tube or component and heat treated separately or replaced.

(2) Postbend heat treatments shall be performed at 1,350°F to 1,445°F (730°C to 785°C) for 1 hr/in. (1 h/25 mm) or 30 min minimum. Alternatively, a normalization and temper in accordance with the requirements in the base material specification may be performed.

(3) For materials with greater than 5% strain but less than or equal to 25% strain with design temperatures less than or equal to 1,115°F (600°C), if a portion of the component is heated above the heat treatment temperature allowed above, one of the following actions shall be performed:

(a) The component in its entirety must be renormalized and tempered.

(b) The allowable stress shall be that for Grade 9 material (i.e., SA-213 T9, SA-335 P9, or equivalent product specification) at the design temperature, provided that portion of the component that was heated to a temperature exceeding the maximum holding temperature is subjected to a final heat treatment within the temperature range and for the time required in Note (2) above. The use of this provision shall be noted on the Manufacturer's Data Report.

(4) If a longitudinal weld is made to a portion of the material that is cold strained, that portion shall be normalized and tempered, prior to or following welding. This normalizing and tempering shall not be performed locally.

這是由於 Gr91 的熱膨脹係數不像傳統的 CrMo 鋼與 Fe_2O_3 赤鐵礦（Hematite）、Fe_30_4 磁鐵礦（Magnetite）、$(Fe,Cr)_3O_4$ 的熱膨脹係數接近，如圖 20 所示，常會使 Fe_30_4、$(Fe,Cr)_3O_4$ 剝落。EPRI 認為服役管材之臨界氧化層厚度約 250-400 μm，如圖 21 中剝落情形有外層氧化層剝落、外層氧化層鼓起(Lifting/Buckling)、雙層氧化層剝落、穿過氧化層的裂紋等四類型，若檢驗剝落後氧化層，會觀察到雙層構造，如 Fe_2O_3 在 Fe_3O_4 外層(如圖 22)，但也有可能 Fe_2O_3 在內層。

Scale failures by coefficients of thermal expansion (CTE) mismatch

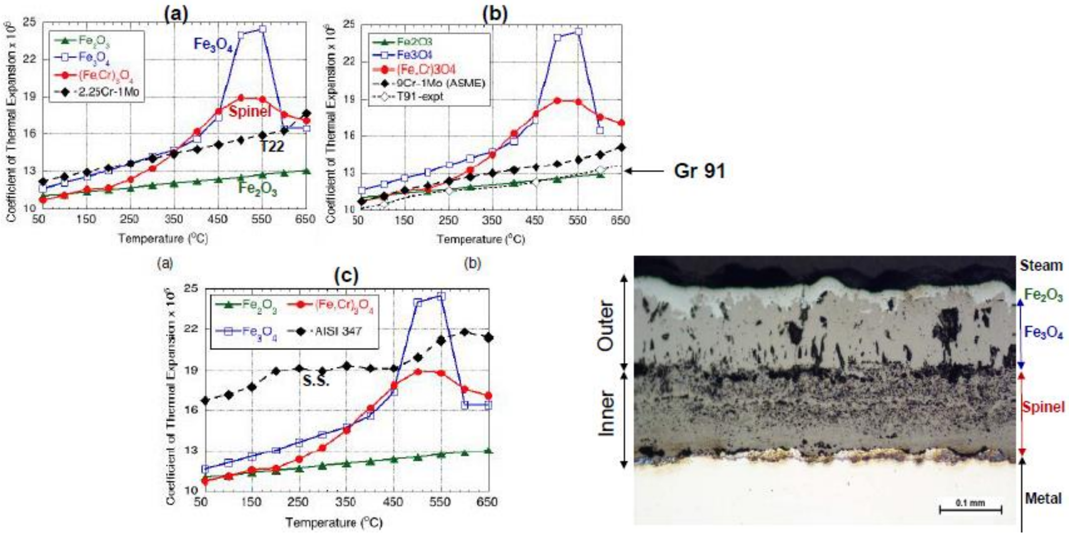
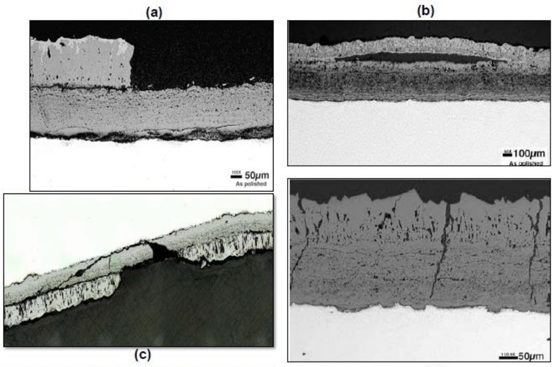


圖 20 氧化層與鍋爐鋼之 CTE

Scale failure modes for Gr 91

Different types of scale failure modes observed on Gr 91

a) Outer layer exfoliation
b) Outer layer lifting/buckling
c) Dual layer exfoliation
d) Through-scale cracking



Critical scale thickness on service exposed tubes = 250-400 μm

圖 21 Gr91 氧化層剝落類型

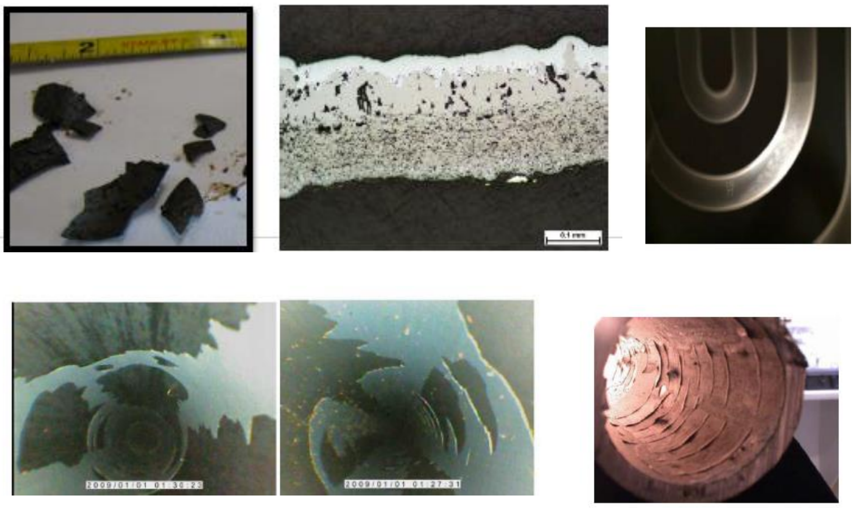
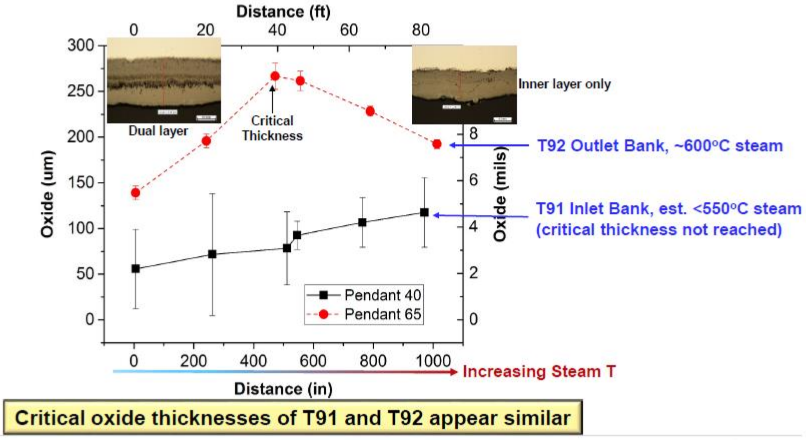


圖 22 氧化層剝落情形

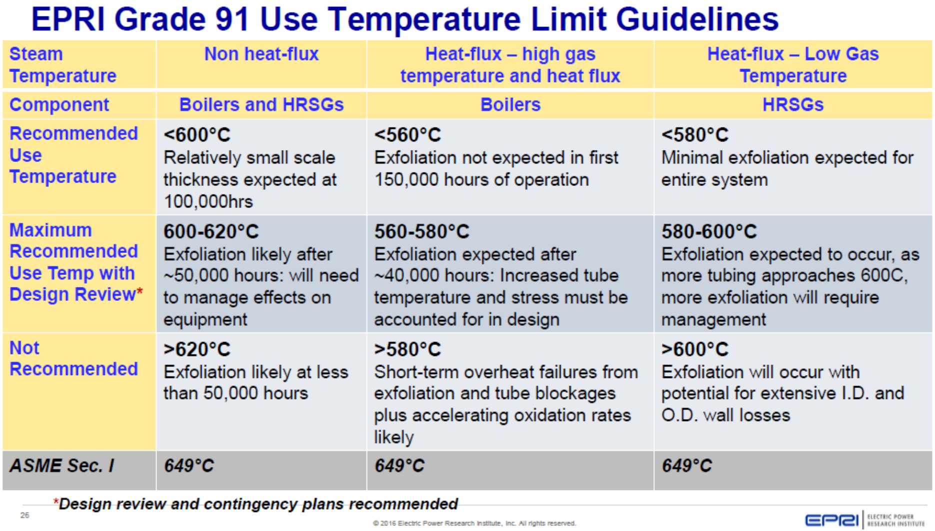
T91 與 T92 氧化行為類似，故其臨界氧化層厚度也類似，在圖 23 中顯示 T92 氧化層厚度達 250μm 時，就可能剝落，使原本是 Dual layer，改變成只有 Inner layer ，反觀 T91 氧化層未達到臨界厚度，故沒有剝落。建議對策為監控溫度、RT 檢查、更新成不銹鋼管。



Critical oxide thicknesses of T91 and T92 appear similar

圖 23　T91 與 T92 氧化行為

EPRI 採用蒸汽溫度模擬氧化與剝落之模型，探討氧化物成長動力學在 Isothermal 與 Heat-flux 情況下，推斷何時達到臨界氧化層厚度，以及計算金屬溫度的改變，並與實際電廠運轉案例驗證，故整理出圖 24 中 Grade 91 使用溫度限制的結論，若鍋爐蒸氣溫度在 560-580℃之間，可能在 40,000 小時後產生氧化層剝落，若 HRSG 蒸氣溫度在 580-600℃之間，即可能產生氧化層剝落情形。



EPRI Grade 91 Use Temperature Limit Guidelines

Steam Temperature	Non heat-flux	Heat-flux – high gas temperature and heat flux	Heat-flux – Low Gas Temperature
Component	Boilers and HRSGs	Boilers	HRSGs
Recommended Use Temperature	**<600°C** Relatively small scale thickness expected at 100,000hrs	**<560°C** Exfoliation not expected in first 150,000 hours of operation	**<580°C** Minimal exfoliation expected for entire system
Maximum Recommended Use Temp with Design Review*	**600-620°C** Exfoliation likely after ~50,000 hours: will need to manage effects on equipment	**560-580°C** Exfoliation expected after ~40,000 hours: Increased tube temperature and stress must be accounted for in design	**580-600°C** Exfoliation expected to occur, as more tubing approaches 600C, more exfoliation will require management
Not Recommended	**>620°C** Exfoliation likely at less than 50,000 hours	**>580°C** Short-term overheat failures from exfoliation and tube blockages plus accelerating oxidation rates likely	**>600°C** Exfoliation will occur with potential for extensive I.D. and O.D. wall losses
ASME Sec. I	***649°C***	***649°C***	***649°C***

****Design review and contingency plans recommended***

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圖 24 Grade91 使用溫度限制

2.7 不鏽鋼 Super304H 特性

為提高發電效率，世界各國陸續興建超臨界電廠，其過熱器與再熱器管材也不採用傳統的T91、T91、304H、347H等材料，分別採用可承受更高壓力與溫度的Super304H、HR3C與347HFG。EPRI評估傳統的300系列不銹鋼，原先是以Sigma相的尺寸數量(如圖25)估計金屬溫度與觀察空孔的形成，評估其老化程度，但對於Super304H則正進行研究，因Super304H是以304為基礎，進行改良與施以熱機處理，改良流程如圖26所示，從304H添加Ni與Nb，研製出347H，再施以熱機處理，研製出347HFG，再添加Cu與N，減少Ni，而研製出Super304H，N是Austenite Stabilizer，故減少具同樣Austenite Stabilizer的Ni，且N具備固融強化之效果，會形成TiN、NbN、CrNbN等細小析出物，2wt%的Cu亦形成細小的富Cu相，故添加Cu與N，大幅提高其高溫強度。

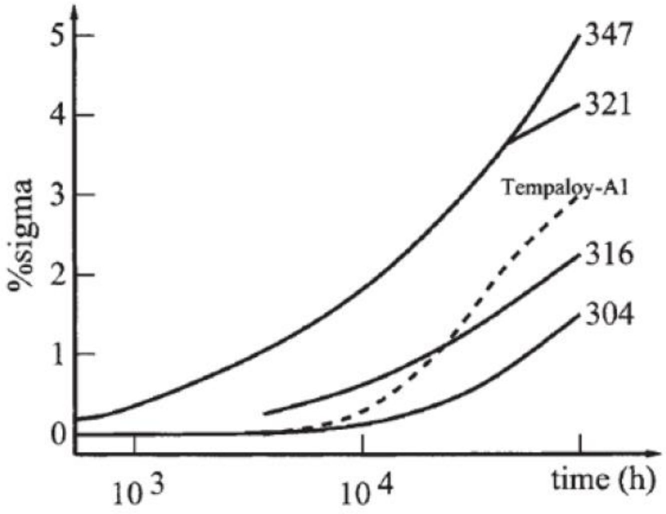


圖25 不銹鋼之Sigma相數量(700℃)

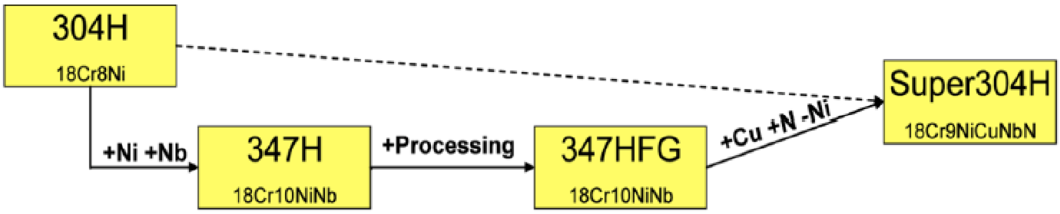


圖26 Super304H發展

熱機處理流程如圖27所示，在最後冷抽管材之前，先施以較高溫的固融處理，使得維持住NbC，NbC可抵抗粗化，最後管材經較低溫的固融處理，產生較細的再結晶組織以及細小且分散的的NbC，細小的晶粒組織(GS No.8.5)可促使Cr較快速的擴散到表面，而形成較佳保護性的氧化層。

在不同文獻中指出 Super304H 顯微組織初始狀態為基地內存在 micron 尺寸的富 Nb 析出物(NbN 與 Nb(C,N))，經 15,000 小時/600-700℃後，Cr-rich carbides 與 Sigma(Cr,Fe)相形成；晶粒尺寸經 75,000 小時/650℃後仍不會改變；經長時間使用後，因 10-20nm 的富 Cu 相析出，將導致強度提高；經 79,000 小時服役後，韌性會從 170 J/cm^2 降到 80J/cm^2，但韌性值不會再降到更低。在潛變過程中富 Nb 的 Nb(C,N)會析出與成長，而且 Nb(C,N)可能會破裂，在 Nb(C,N)析出物附近會形成潛變空孔，Nb(C,N)的體積分率約為 1-2%。

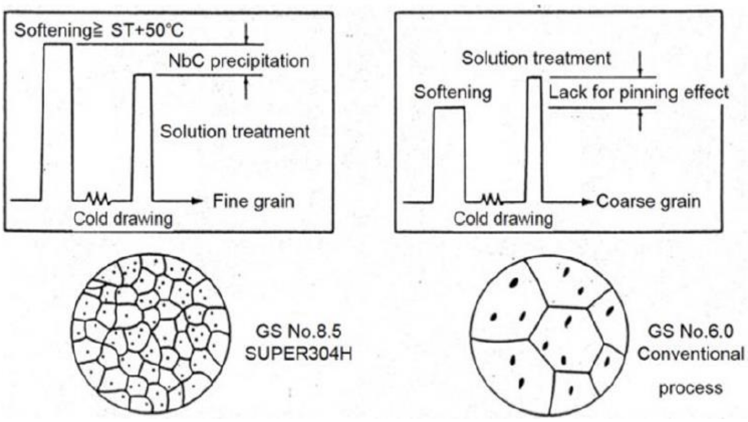
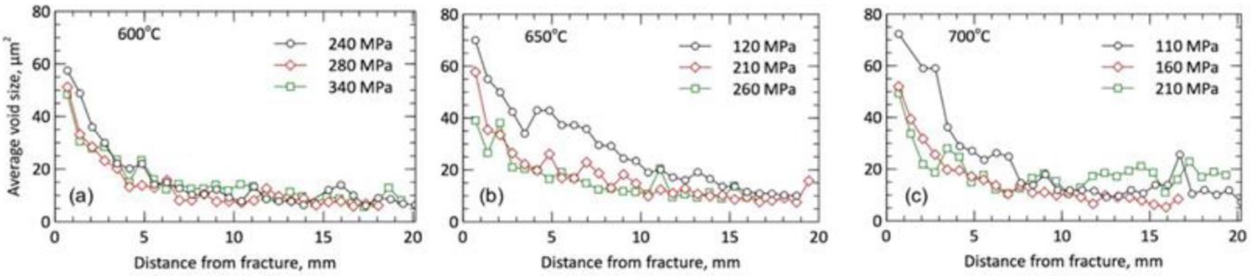


圖 27 熱機製程

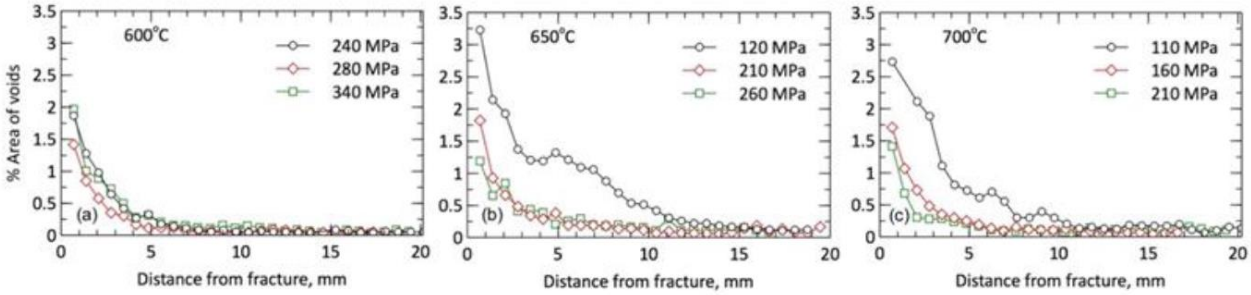
EPRI 以 600℃、650℃、700℃分別在 110-340MPa 進行潛變實驗，利用 Vilella’s 蝕刻液(1g Picric acid，5ml HCL，100ml Ethanol)觀察晶粒，另以電解法(5V，5%NaOH)觀察 Sigma 相。EPRI 統計平均空孔尺寸(Average Void Size)、空孔面積分率(Void Area Fraction)、空孔密度(Void Density)統計結果如下圖 28-30 所示，顯示在破斷面附近其空孔尺寸、空孔面積分率、空孔密度值大，但距離破斷面 13mm 後就維持固定值，在 650℃、700℃低應力下，空孔缺陷的量遠高於 600

℃。空孔形貌如圖 31 所示，空孔集中在體積分率約 1-2%的富 Nb 析出物旁邊。



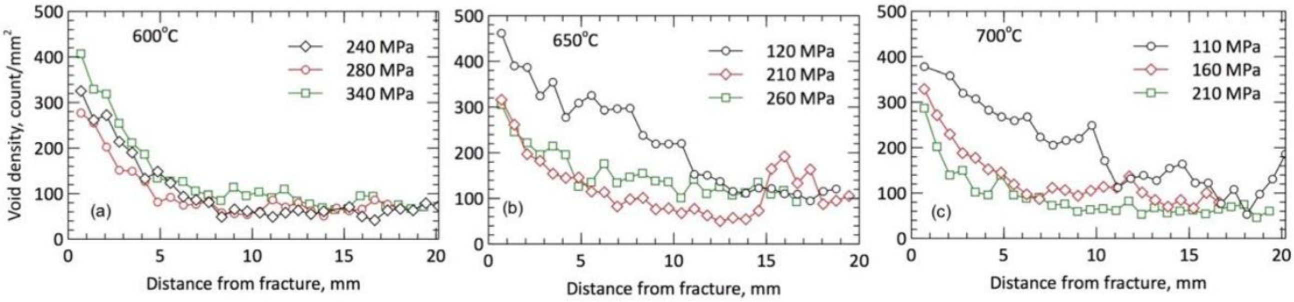
(a)600℃ (b)650℃ (c)700℃

圖 28 從破裂面起之平均空孔尺寸



(a)600℃ (b)650℃ (c)700℃

圖 29 從破裂面起之空孔面積分率



(a)600℃ (b)650℃ (c)700℃

圖 30 從破裂面起之空孔密度

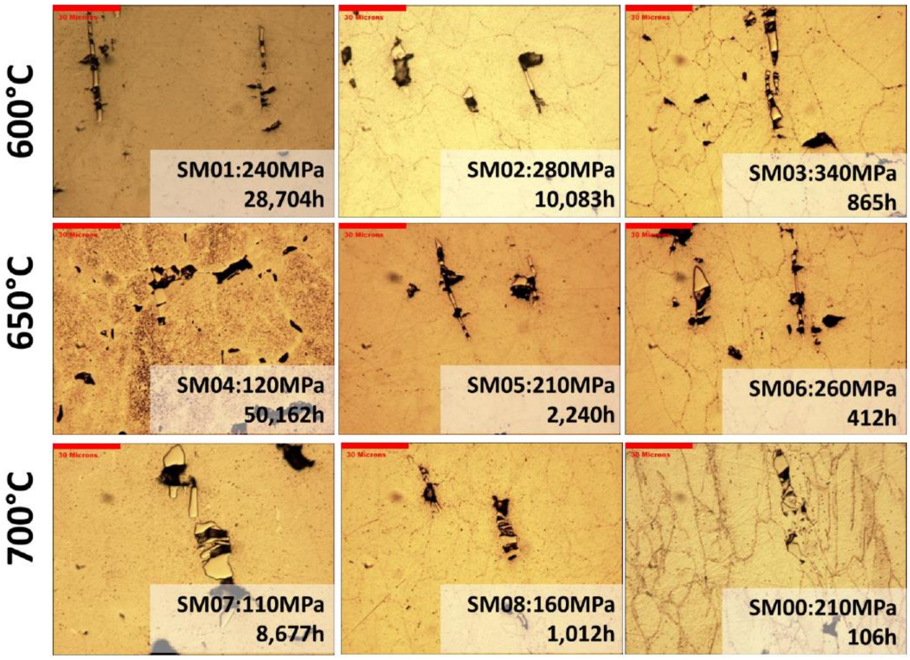


圖 31 破裂的 Nb-rich 相與潛變空孔

對富 Nb 的析出物進行 Line Scan，其結果如下圖 32 所示，顯示具有較高 Nb、C、N 元素，Fe、Cr、Ni、Cu 含量較低。另一圖 33 中看出富 Nb 相為 NbCN，周遭有富 Cr 相、富 Si 相、細小 Cu 相。

圖 34 為 EBSD 分析結果，可看到完整的 Sigma 相，以及 Sigma 相與 SiC 混合的析出相，少量的 BCC 結構的 Fe，以 FCC 為基地的組織。實驗結果顯示，富 Nb 相與潛變空孔的破壞似乎是有相關聯性，然而 Sigma 相為 Tetragonal intermetallic，成分以 FeCr 為主，在晶界與晶粒內都可能會形成，觀察到之 Sigma 相形成量遠低於傳統的不銹鋼(如 304H)，且尺寸小於 1 μm，有些 Sigma 相是含有 Hexagonal Si-rich 相，但目前無觀察到 Sigma 相與潛變空孔直接相關，而導致潛變破壞。

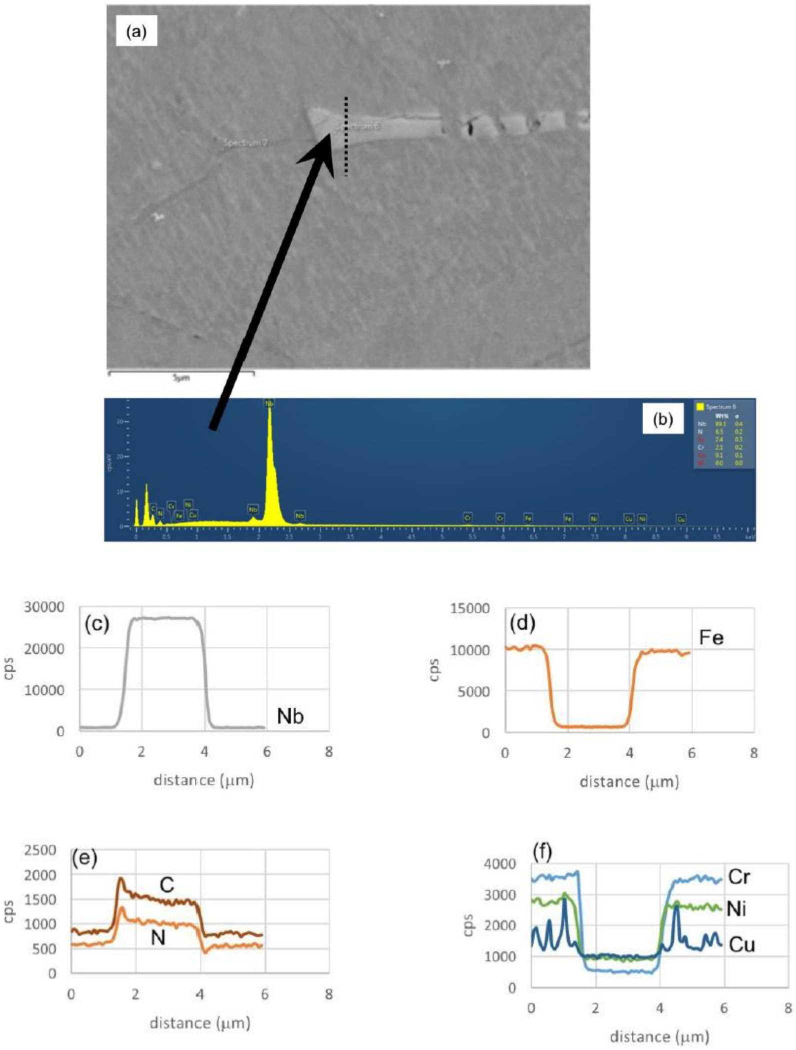
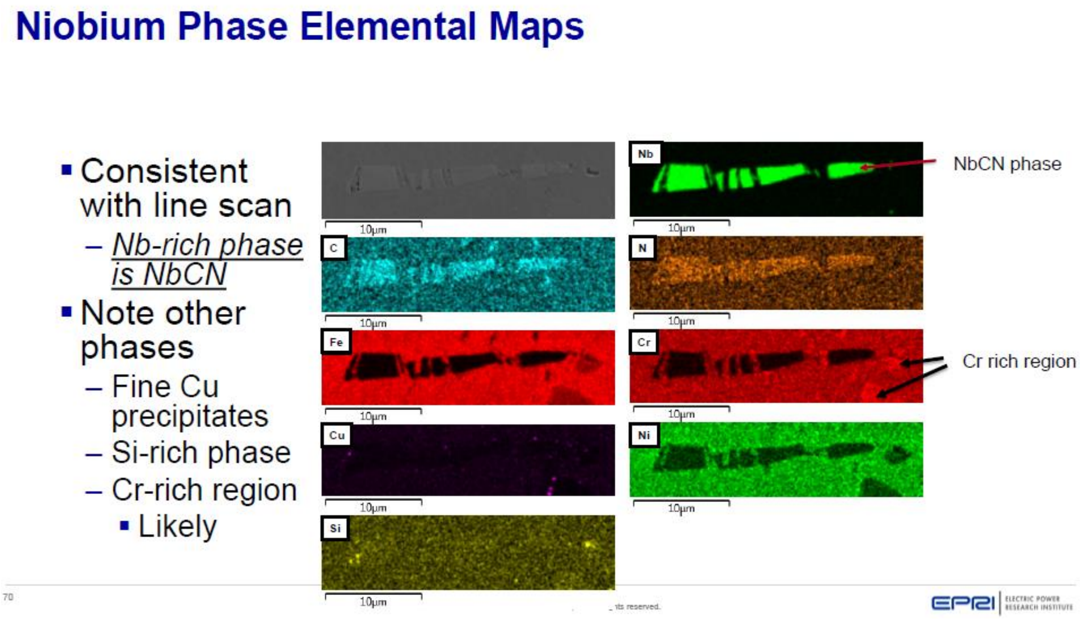


圖 32 Nb-rich 之 EDS 分析



Niobium Phase Elemental Maps

- Consistent with line scan
  - *Nb-rich phase is NbCN*
- Note other phases
  - Fine Cu precipitates
  - Si-rich phase
  - Cr-rich region
    - Likely

圖 33 Nb-rich 之 Maps 分析

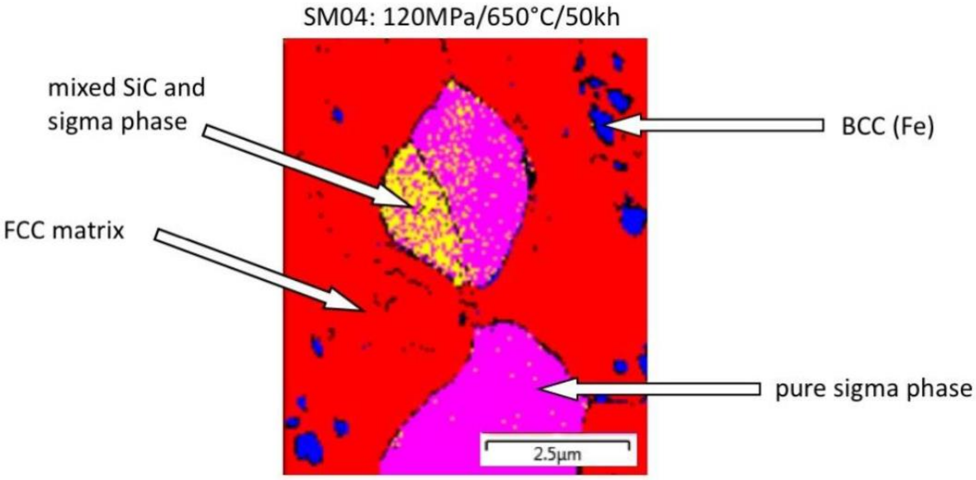

SM04: 120MPa/650°C/50kh
mixed SiC and sigma phase
BCC (Fe)
FCC matrix
pure sigma phase
2.5μm

圖 34　EBSD 分析

三、感想與建議

1. EPRI 指出越厚(厚度>25mm)的管件僅依循 AWS D10.10 進行銲後熱處理是不足夠的，建議考量管件幾何形狀(如閥件與集管連接，或集管與洩水管線連接，避免 Heat Sink 現象)，增加控制/監控熱電偶數量、加熱墊數量、固定加熱墊方法等注意要點。
2. P91 與鎳基材料銲接，易在部分混合區(Partially Mixed Zone，PMZ)之間形成裂紋、或 1-3μm 寬度的 Carbide-free Ferrite 區域、潛變空孔及 Type I Carbides，提供我們後續維護方向。
3. EPRI 發展 Controlled Fill 銲補方法，降低預熱溫度與銲後熱處理溫度，或免除銲後熱處理，降低銲補工時與減少母材性能衰退，值得我們參考。
4. Gr. 91 與 Gr. 92 服役管材之臨界氧化層厚度約 250-400 μm，即會產生剝落，並模擬計算出若鍋爐蒸氣溫度在 560-580℃之間，可能在 40,000 小時後產生氧化層剝落，建議對策為監控溫度、RT 檢查、更新成不銹鋼管。
5. 不鏽鋼 Super304H 潛變試驗後結果顯示，富 Nb 的 Nb(C,N) 與潛變空孔的破壞似乎是有相關聯性，Sigma 相與潛變空孔目前無太大關聯性，與傳統不銹鋼老化後特性相異。

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