Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Federal Department of the Environment, Transport, Energy and Communications DETEC

Swiss Federal Office of Energy SFOE
Energy Research and Cleantech Division

Final Report 28.4.2023

Validation of advanced water-/steam systems for increased combined cycle power plant efficiency

(Validierung von fortschrittlichen Wasser-/Dampf Systemen zur Erhöhung des Wirkungsgrads von Kombikraftwerken)

Quelle: GE 2021

Date: 28 April 2023

Location: Baden

Publisher:
Swiss Federal Office of Energy SFOE
Energy Research and Cleantech
CH-3003 Bern
www.bfe.admin.ch

Subsidy recipients:
General Electric (Switzerland) GmbH
Brown Boveri Strasse 7
CH-5401 Baden
www.ge.com

Authors:
André Saxer, GE (Switzerland) GmbH, andre.saxer@ge.com
Roland Huber, GE (Switzerland) GmbH, roland.huber1@ge.com
François Droux, GE (Switzerland) GmbH, francois.droux@ge.com
Andreas Bauer, GE (Switzerland) GmbH, andreas.bauer@ge.com

SFOE project coordinators:
Men Wirz, men.wirz@bfe.admin.ch
Stephan Renz, Beratung Renz Consulting, info@renzconsulting.ch

SFOE contract number: SI/501569-01

Zusammenfassung

Ein vierjähriges Programm demonstriert die Durchführbarkeit und die technischen Möglichkeiten der GE "Once Through" Dampfkessel Technologie (GE OT HRSG), die für moderne Kombikraftwerke zur Stromerzeugung entwickelt und installiert wurde. In Kombination mit anderen Technologien führt diese Technologie zu höheren Wirkungsgraden im Kombikraftwerk und zu verbesserten Betriebsmöglichkeiten wie höchsten höher Lastgradienten und höheren Wirkungsgraden bei Teillast und außerhalb der Auslegungsbedingungen. Als Referenz hält GE den Weltrekord für den Wirkungsgrad von GuD-Anlagen (siehe EDF Bouchain Plant, Frankreich [1]) mit 62,22 %. Die Anlage, die für die Validierung der in diesem Bericht dargestellten Verbesserungen ausgewählt wurde, besteht aus zwei Wellensträngen, die jeweils mit einer 9HA.02-Gasturbine und einer STF-D650-Dampfturbine ausgestattet sind, welche einen W88-Generator antreiben. Zum ersten Mal gelangt in einer GuD Anlage der H-Klasse ein GE OT HRSG Technologie zum Einsatz, welcher einen hohen Wirkungsgrad der GuD Anlage ermöglicht. Mit dieser Konfiguration wird der Nettowirkungsgrad auf über 64 % gesteigert, wodurch niedrigere spezifischen CO2-Emissionen pro erzeugter kWh elektrischer Energie erreicht werden.

Die Anwendung der OT-Technologie ermöglicht einen weiteren Schritt in Richtung einer GuD Anlage mit überkritischem Wasser-Dampf-Prozess, welcher eine weitere Wirkungsgradsteigerung ermöglicht. Die derzeitig zum Einsatz gelangende unterkritische Anlage - mit modernsten Parametern von ca. 185 bar Frischdampfdruck und bis zu 600 °C Frischdampf- und Zwischenüberhitzungstemperaturen - bereitet den Weg für Zyklen mit noch höheren Dampfdrücken und -temperaturen: Durch die Erhöhung der Dampfparameter wird die Ausnutzung der von der Gasturbine erzeugten Abwärme weiter gesteigert. Dies führt zu einer Effizienzsteigerung der Stromerzeugung durch den nachgeschalteten Dampfprozess bei unverändertem Brennstoffverbrauch der Gasturbine und ermöglicht es dem Kraftzwerksbetreiber, den relativen Brennstoffverbrauch und CO2-Emissionen zu senken. Die OT Technologie vermeidet dickwandige, große Kesseltrommeln, welche durch ihre thermische Trägheit die Betriebsflexibilität aufgrund festigkeitsbedingter Zwänge einschränken. Diese spezifischen Eigenschaften der OT Technologie sind Schlüsselfaktoren für den Einsatz eines Kombikraftwerkes in einem elektrischen Verbundnetz mit hohem Anteil von erneuerbaren Energieen mit geringer Vorhersagbarkeit wie Windkraft oder Photovoltaik. Damit trägt diese Technologie zum wirtschaftlichen Betrieb und wettbewerbsfähigen Stromkosten bei.

Eine erfolgreiche Implementierung der GE OT HRSG Technologie erfordert die Entwicklung und Erprobung von Werkstoffen, Materialschweißnähten und der Materialoxidation (versursacht durch die Wasser-/Dampfchemie) so nah wie möglich an den realen Betriebsbedingungen im Feld. Die bei den Validierungstests im Labor und in einer kommerziellen Anlage gesammelten Betriebs- und Testdaten belegen, dass die Werkstoffspezifikation und -auswahl, die Schweißverfahren, das Management von Verunreinigungen im Wasser-/Dampfkreislauf sowie die speziell für die GE OT HRSG Technologie entwickelten Prozesssteuerungskonzepte erfolgreich waren. Es wurden verbesserte Werkstoffpaarungen und Schweißnahtgeometrieparameter entwickelt, welche die Temperaturwechselfestigkeit erheblich verbessern. Labortests zeigen, dass die Werkstoffkorrosion bei erhöhten Dampftemperaturen und unter überkritischen Bedingungen ähnlich sind wie bei aktuellen unterkritischen Dampfprozessparametern. Zusätzlich zeigen Feldtests, dass die Kontrolle der Chemie im Wasser-/Dampfkreislauf mit einem verbesserten Konzept zur Kontrolle von Verunreinigungen und ohne zusätzliche Behandlung erreicht werden kann, wenn die Ultra Pure Water Solution von GE (US2020200051A1) verwendet wird. Die entwickelte Lösung war erfolgreich bei der Entfernung von Verunreinigungen innerhalb akzeptabler Anfahrzeiten und Betriebsgrenzen, ohne dass zusätzliche Kondensataufbereitungsanlagen erforderlich waren. Die Ergebnisse der Labortests bestätigen die Eignung des gewählten Wasserchemie-Mangementkonzepts für überkritische Zyklen im Hinblick auf das Risiko einer beschleunigten Korrosion in solchen Umgebungen.

Die entwickelte Prozesssteuerung für den GE OT HRSG hat sich beim An- und Abfahren sowie im stationären Betrieb als robust und zuverlässig erwiesen. Die vorhergesagten Anfahrzeiten und Lastwechsel wurden erreicht.

Die Übertragung dieser Technologien auf großtechnische und kommerziell betriebene Anlagen ist daher ein Wegbereiter für künftige Wasser-Dompfprozesse in GuD Anlagen mit überkritischen Dampfparametern oberhalb der heutige üblichen Prozessparameter.

Dennoch litt das Programm unter den Auswirkungen der weltweiten COVID-19-Pandemie und kam schließlich nicht in vollem Umfang wie ursprünglich geplant voran: Mit der ersten Pandemiewelle wurde die ausgewählte Baustelle für die Validierungstests von der örtlichen Regierung geschlossen. Das Projektteam wurde gebeten, die Arbeiten nach der Wiedereröffnung der Baustelle zu beschleunigen, um die Auswirkungen auf den Termin für den kommerziellen Betrieb so gering wie möglich zu halten. Infolgedessen wurden einige der geplanten Validierungstests, die für das spezifische Projekt nicht elementar sind, einem anderen Projekt mit derselben Technologie zugewiesen. Die nach Abschluss dieses Programms durchzuführenden Arbeiten wurden ermittelt und der erforderliche Aufwand geschätzt.

Résumé

Un programme de 4 ans démontre la viabilité et les capacités de la technologie GE "Once Through" (OT) HRSG telle qu'elle a été développée et installée dans des centrales à cycle combiné modernes pour la production d'électricité. En conjonction avec la mise en œuvre d'autres technologies, ce type de chaudière de récupération permet d'augmenter l'efficacité des cycles combinés et d'améliorer leurs capacités d'exploitation, comme par exemple des gradients de charge plus élevés et des meilleurs rendements à charge partielle et pour les conditions de fonctionnement éloignée du point de conception. À titre de référence, GE détient le record mondial d'efficacité des centrales à cycle combiné (réf. centrale EDF de Bouchain, France [1]) avec 62,22 %. La centrale identifiée pour valider les améliorations décrites dans ce rapport comporte deux unités à ligne d'arbre unique, chacune équipée d'une turbine à gaz 9HA.02 et d'une turbine à vapeur STF-D650, entraînant un générateur W88. Pour la première fois dans une centrale de classe H, un chaudière à récupération de chaleur de type OT specifique de GE, permettant une efficacité élevée du cycle combiné. Cette configuration permet d'obtenir une efficacité nette au-delà de 64% d'efficacité du cycle combiné et permet ainsi de produire un taux spécifique plus faible de CO_2 par kWh d'électricité produite.

Le recours à de la technologie OT permet de franchir une nouvelle étape dans l'efficacité globale des cycles supercritiques appliqués à des turbines à vapeur intégrées à une turbine à gaz. Les centrales à cycle sous-critique actuelles - avec des paramètres de pointe d'environ 185 bars de pression de vapeur vive et jusqu'à 600 °C de température pour la vapeur haute pression et vapeur de resurchauffe - prépare le terrain pour des cycles avec des pressions et des températures de vapeur plus élevées: l'augmentation des conditions de vapeur (pression et température) accroît l'utilisation de la chaleur résiduelle générée par la turbine à gaz avec des gains d'efficacité supplémentaires dans la production d'électricité de la turbine à vapeur pour la même consommation de combustible. Ceci permet à un opérateur de réduire sa consommation relative de combustible et ses émissions de CO_2. La technologie Once-Through permet d'éviter les grands ballons de chaudière à parois épaisses qui pourraient limiter la flexibilité opérationnelle en raison de contraintes physiques liées à l'inertie thermique. Ces caractéristiques sont des facteurs clés de succès pour les producteurs d'électricité dans un réseau avec une part croissante d'énergie renouvelables à faible prévisibilité comme l'éolien ou le photovoltaïque. En outre, ces leviers permettent une exploitation économique et un coût compétitif de l'électricité.

Une mise en œuvre réussie de la technologie OT HRSG de GE - permettant d'améliorer l'économie (coût de l'électricité) - nécessite le développement et les essais en laboratoire des matériaux, des joints

de soudure des matériaux et de l'oxydation reproduisant une chimie de l'eau et de la vapeur, aussi proches que possible des conditions réelles. Les données recueillies lors des essais tant en laboratoire que sur l'unité en exploitation prouvent que la spécification et la sélection des matériaux, les méthodes de soudage et leurs paramètres, la gestion des impuretés du cycle eau/vapeur ainsi que les concepts de contrôle des processus spécifiquement développés pour la solution GE d'une chaudière de récupération (HRSG) de type OT specifique à GE ont été validés avec succès. Des perfectionnements dans la combinaison des matériaux et dans la géométrie des soudures pour la configuration GE ont été mis au point et ont permis d'améliorer de manière significative leur capacité à répondre aux variations thermiques. Les essais en laboratoire indiquent que l'impact de la corrosion à des températures élevées et dans des conditions supercritiques corroborent l'expérience récoltée sur les cycles actuels. Outre le comportement en corrosion, les essais sur le terrain démontrent que le contrôle de la chimie de l'eau peut être réalisé avec un concept amélioré de gestion des impuretés et sans traitement supplémentaire en utilisant la solution d'eau d'appoint «ultra-pure» de GE (US2020200051A1). La solution développée a permis d'éliminer les impuretés dans des temps de démarrage acceptables et dans les limites de fonctionnement , sans nécessiter l'installations supplémentaires d'une unité de traitement des condensats. Les résultats des essais en laboratoire confirment l'adéquation du concept de chimie de l'eau sélectionné pour les cycles supercritiques en ce qui concerne le risque de corrosion accélérée dans de tels environnements.

La dynamique et les contrôles des processus développés pour le GE OT HRSG se sont avérés robustes et fiables pendant le démarrage, l'arrêt et le fonctionnement en régime stationnaire. Les temps de démarrage et les variations de charges prévues ont été atteints.

Par conséquent, le transfert de ces technologies vers des unités à échelle réelle et exploitées commercialement permettent d'envisager pour le futurs des centrales à cycle combiné avec une pression de vapeur supercritique et des températures de fonctionnement supérieures à celles du cycle actuel.

Néanmoins, le programme a souffert de l'impact de la pandémie mondiale de COVID-19 et n'a finalement pas progressé dans les délais prévus à l'origine: Dès la première vague de pandémie, le site de construction choisi pour les essais de validation a été bloqué par le gouvernement local. Il a été demandé à l'équipe de projet d'accélérer les activités sur le site après sa réouverture afin de limiter au maximum l'impact sur le début de l'exploitation commerciale. En conséquence, certains des tests de validation prévus - qui n'étaient pas élémentaires pour le projet spécifique - ont été réaffectés à un autre projet de la même technologie. Les travaux à réaliser après la clôture de ce programme ont été identifiés et l'effort nécessaire a été estimé.

Summary

A 4-year program demonstrates the viability and technical capabilities of the GE “Once Through” (OT) HRSG technology as developed for and installed in modern Combined Cycle Power Plant (CCPP) for electricity production. Combined with other technologies this technology results in increased combined cycle efficiencies and improved operating capabilities like higher load gradients and elevated efficiencies at part load and off design conditions. As reference GE owns the world record for CCPP efficiency (ref. EDF Bouchain Plant, France [1]) with 62.22%. The plant identified for validating the improvements depicted in this report features two single-shaft generating blocks, each equipped with a 9HA.02 gas turbine and a STF-D650 steam turbine, driving a W88 generator and, for the first time installed in an H-Class Plant, a GE Once Through Heat Recovery Steam Generator enabling high combined cycle efficiency. This configuration pushes the net combined cycle efficiency beyond 64% and thus enables to produce a lower specific CO_2 per kWh electricity produced.

The installation of the OT technology enables a next step-change in overall efficiency with supercritical steam turbine cycles integrated with a gas turbine. The current subcritical installation – with state-of-the-art parameters of approx. 185 bar live steam pressure and up to 600 °C live steam and reheat temperatures - prepares the path for cycles with higher steam pressures and temperatures: raising steam conditions (pressure and temperature) increases the usage of the waste heat generated by the Gas Turbine with subsequent efficiency gains in power generation of Steam Turbine at the same fuel consumption, allowing an operator to reduce its relative fuel consumption and CO_2 emissions. The Once-Through technology avoids thick-walled large steam drums which might limit the operational flexibility due to physical constraints through its thermal inertia. Such features are key success factors for the electricity producers in a grid where the penetration with renewable generators of low predictability like Wind or PV is high. Moreover, these levers drive economic operation and competitive cost of electricity.

A successful implementation of the GE’s OT HRSG technology requires the development and lab testing of materials, material weld joints and oxidation based on water-/steam chemistry as close as possible to harsh in-field conditions. The operation and test data collected in lab environment and in a commercial unit provide evidence that the materials specification and selection, the welding methods and its parameters, the water-/steam cycle impurity management as well as the process controls concepts specifically developed for GE’s solution of an OT Heat Recovery Steam Generator (HRSG) have been successfully validated. Enhanced materials pairing and weld geometry parameters for the GE configuration have been developed and have shown to significantly improve the thermal cycling capability. Laboratory tests indicate that the corrosion impact in elevated temperatures and under supercritical conditions are similar to current cycles. In addition to the corrosion behavior, field tests demonstrate that the control of the chemistry in a water-/steam cycle can be achieved with an improved impurity control concept and without additional treatment when utilizing GE’s Ultra Pure Water Solution (US2020200051A1). The developed solution was successful in removing impurities within acceptable start-up times and operational limits without the need of additional condensate treatment installations. Results from the lab tests confirm the suitability of the selected water chemistry concept for supercritical cycles with regards to the risk of accelerated corrosion in such environments.

The developed process dynamics & controls for the GE OT HRSG has been proven robust and reliable during start-up, shut-down and steady-state operation. The predicted start-up times and load changes have been achieved.

Hence, the transfer of these technologies to full scale and commercially operated units are enablers for future cycles in CCPP applications with supercritical steam pressure and above todays cycle operating temperatures.

Nevertheless, the program suffered from the impact of the global COVID-19 pandemic and has finally not fully progressed as originally planned: With the first pandemic wave, the selected construction site

for the validation testing has been locked down by the local government. The project team was asked to accelerate the site activities after re-opening of the site to keep the impact on the commercial operation date to a minimum. In consequence, some of the planned validation tests – not elementary for the specific project – have been re-assigned to another project of the same technology. The work to be completed after this program closure has been identified and the required effort estimated.

Key Takeaways

- GE's Combined Cycle Power Plant (CCPP) bottoming cycle technology with OT Heat Recovery Steam Generator (HRSG) enables an improved combined cycle efficiency in future installations, thus making it a reliable contributor to the reduction of CO_2 emissions for electricity production.

- The DMW materials (WP1), controls systems (WP3) & water-/steam chemistry (WP2) concepts developed and demonstrated in this program can be transferred without major changes to supercritical applications, hence enabling elevated combined cycle efficiency.

- The water-/steam cycle chemistry with its dosing regime and cleaning cycles allows to operate GE's OT HRSG technology without the need of additional substantial investments as well as increased operation and maintenance cost for a condensate treatment. The concept and subsequent operation regime improve the economics and Cost of Electricity (CoE) for this technology.

- The CCPP commissioned during this program – equipped with the improved water-/steam chemistry regime and next generation of plant dynamics and controls technology - demonstrates the dynamic potential with the OT HRSG technology for cyclic & part load operations with fast ramp up to 100 MW/min. Thus, the technology is ready to support grids with demanding requirements and with large portions of unpredictable generators like wind and PV. High loading gradients are feasible and provide a mitigation to respond to potential shortages in electricity as required by several grid-codes, for example by the revised of the Swiss Federal Energy Law[1].

[1] Faktenblatt Bundesgesetz für eine sichere Stromversorgung mit erneuerbaren Energien. Revision Energiegesetz und Stromversorgungsgesetz, Nov. 20, 2020

Contents

Table of Figures

Abbreviations:

ASME	American Society of Mechanical Engineers.
CCPP	Combined Cycle Power Plant.
CTE	Coefficient of Thermal Expansion.
DFFWD	Dynamic Feed Forward Control System.
DPI	Dye Penetrant Investigation.
DMW	Dissimilar Metal Weld (= metal joints of different expansion coefficients).
EHS	Environment Health & Safety.
FE	Finite-Element calculation method.
GTAW	Gas Tungsten Arc Welding.
HRSG	Heat Recovery Steam Generator (Boiler).
ID	Inner Diameter.
MECL	Minimal Environnemental Compliant Load.
OD	Outer Diameter.
OT	Once Through (technology) = steam generation without drum = enabler for supercritical applications.
PV	Photovoltaic.
PWHT	Post weld heat treatment
SS	Stainless Steel.
WP	Work Package (Project).

1 Introduction

1.1 Starting point and background

The power generation industry is facing unprecedented challenges. High fuel costs and increased penetration of renewable power have resulted in greater demand for high efficiency and operational flexibility, imperatives to reduce carbon footprint and place an even higher premium on efficiency or higher electricity production for the same fuel consumption, thus driving the lowest CO_2 footprint per kWh electricity produced. Power producers are seeking highly efficient, reliable and operationally flexible solutions - like steep electricity production gradients and fast start up ramps - that provide long term profitability in a volatile environment. New generation power plants must also be cost-effective to help to ensure affordability for both domestic and industrial consumers. Gas Turbine driven Combined Cycle Power Plants (CCPP) meet these requirements by providing reliable, dispatchable generation with a low cost of electricity, reduced environmental impact and broad operational flexibility.

GE introduced the 7HA / 9HA heavy duty gas turbine product portfolio in 2014 in response to these demands. These air-cooled, H-class gas turbines are engineered to push the net combined cycle efficiency beyond the state of the art while helping to deliver operational flexibility through deep, emission-compliant turndown and high ramp rates. The largest of these gas turbines, the 9HA.02, is engineered to exceed 64% combined cycle efficiency (net, ISO) in a 1x1, single-shaft configuration. To unleash the full potential of the Gas Turbine, the downstream Water-/Steam Cycle with its HRSG must be designed accordingly. The technology to support high flexible and steep ramp rates as well as higher efficiency at part load and off design conditions requires the application of the OT (Once Through) HRSG technology. The OT HRSG technology is mandatory to generate Steam at and above critical conditions (220.6 bar) enabling higher combined cycle efficiency. The current “drum” type technology is thermodynamically limited to subcritical conditions. When increasing pressure towards critical conditions, the density of steam and liquid are increasingly similar and natural recirculation and separation of liquid water and steam in the drum stops working.

In addition, the OT cycle does not require a steam drum (connected to the evaporator section). At elevated pressures the required wall thickness of such a drum may affect the operation of the GT due to limitations in acceptable temperature gradients caused by thermal induced stress.

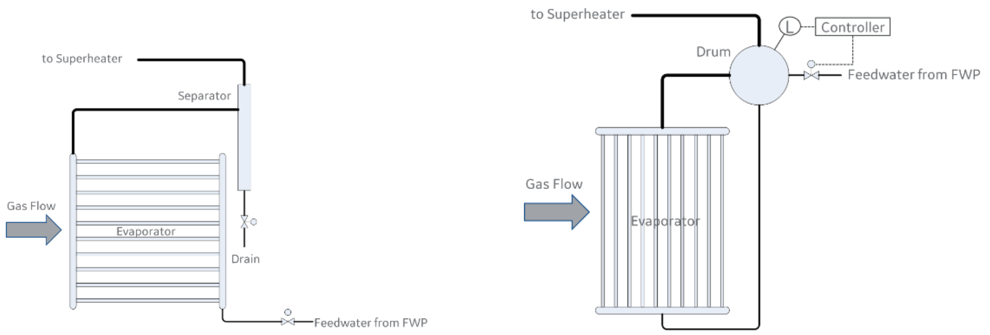


Figure 1: OT evaporator section principle vs drum type evaporator.

However, the application and operation of the OT HRSG technology is faced with the following main challenges:

- Horizontal tubes in OT section: In comparison to a drum type HRSG where the evaporation of the feedwater is dimensionally limited to the evaporator and its connected drum, the phase change of water to steam in a OT heat exchanger can be controlled to take place at any location within the (single) tube by variation of feedwater flow. With horizontal installation, the length of the individual stream or tube can be adapted as required and is less dependent of the overall height or geometry of the HRSG. In vertical installations, the collecting headers are to be located at top and bottom of the HRSGs, enforcing the tube length to be a multiple of the HRSG height.

- Pressure variation/discrepancy over the height of the HRSG heat exchangers: With the horizontal arrangement of the heat exchanger tubes, it is mandatory to compensate i) the pressure differences across the evaporator height (> 20 m) and ii) the gas Turbine exhaust Temperature spread or distribution pattern respectively to achieve an acceptable temperature variation of the steam leaving the OT section. This is achieved through a split of the OT exchanger into multiple sections stacked vertically: Each steam portion leaving a section needs to be individually temperature controlled to achieve a minimum spread. As a side effect, these geometrically smaller OT sections, in relation to conventional tube bundles or harps, have improved transportability.

- HRSG OT control: Generally, the OT HRSG control has an elevated complexity compared to the drum type HRSG: Whereas the pressure and corresponding evaporation temperature in a drum establishes basically itself in function of the flue gas temperature, the steam temperature leaving the OT exchanger can be actively controlled. By variation of the feedwater flow, the evaporating point is moved along the tube. Doing so, the available exchanger surface to evaporate is increased or lowered resulting in a lowered or increased available surface to superheat the steam. As a consequence, the control of an OT section is inherently less stable compared to drum technology. GE developed a DFFWD (dynamic feed-forward) control system to anticipate the steam outlet temperature by controlling the inlet flow of water. Due to the delayed response on control actions, the DFFWD compensates the sluggish behavior of the individual evaporator sections and allows for simultaneously control the individual parallel sections (WP3).

- Water-/Steam Cycle chemistry: In drum type evaporators, the water chemistry is controlled – next to other measures – by continuously operated blow-down from the drum, releasing concentrated impurities from the cycle. As the OT cycle has no dedicated area of evaporation, a blowdown is not possible. Consequently, the OT cycle requires a different WSC chemistry monitoring and operating concept. To avoid costly condensate cleaning units – so called polishers – a new operating scheme has been developed which is based on impurity monitoring and control (WP2)

State-of-the-art installations of CCPPs include steam parameters beyond 160 bar and 565 °C supporting the gas turbines capability for higher efficient cycles.

This project builds up on the results of tests done in the GE test power plant in Birr 2 in the years 2013 to 2015 (co-funded by the SFOE, SI/501004-01). In that program a small scale OT HRSG was engineered and tested behind a small gas turbine. No steam turbine was included, and the steam produced was discharged to the atmosphere. The main objective of the Birr 2 test campaign was to “proof-concept” the operation of an OT section without integration of a bottoming cycle: i) the feasibility of a small scale OT HRSG to produce steam at & above supercritical conditions was demonstrated. ii) “proof-of-concept” for the controls system to produce steam at the desired temperature & pressure by controlling the OT HRSG inlet water flow. No tests on materials for lifetime evaluation were included, and the control software was not developed and integrated with the GT controller. The load profiles were limited. The control of the quality of the water/steam is crucial for trouble free operation of a CCPP. The Birr 2 scope did not include impacts of long-term operation and so the impact of the WSC impurities were not foreseen and not tested. In the current program, new key elements of the water-steam system and integration of the OT HRSG technology in a combined cycle power plant are developed, tested and validated. Live steam parameters are at and above the present experience levels. The current project includes tests and validation of material-pairing, water chemistry, start-up and plant dynamics & controls of the water-/steam cycle as found in the latest CCPP.

Program key data:

Start date:	May 1, 2017.
Contract signing date:	September 21, 2017.
Planned end date:	October 2020.

1.2 Motivation for the project

The motivation for this project is twofold:

a) Develop, apply & demonstrate GE's OT HRSG technology validated in the Birr 2 test facility in a commercial heavy duty CCPP.

b) Validation of key bottoming cycle technologies: DMWs, process dynamics & controls with the OT HRSG and the water/steam cycle. In particular, the results of this program should enable the combined cycle supercritical applications for future efficiency increase of CCPP.

1.3 Project targets and structure

The program is composed of four Work Packages (WP) with the following objectives:

1) **Work Package 1 – Dissimilar Metal Weld (DMW)**: With the step to higher steam temperatures the ferritic materials reach their limits: the steam leaving the evaporator is superheated to the targeted value in the downstream heat exchangers (superheaters) where temperatures exceed the application limits of the ferritic materials. In order to avoid manufacturing the complete high pressure steam path with advanced steels, a change of material is required. Thus, dissimilar metal welded materials pairings are necessary. Industrially available & certified materials for Temperature above 600 °C need to be tested at 1:1 geometrical configuration & under real thermal cyclic conditions. In this program lab tests simulation & validation of thermal cyclic behavior of DMWs are conducted. This effectively replaces multiyear field validation. This is done for a matrix of current and future materials used in sub & supercritical applications such as martensitic and austenitic stainless steels and Ni-based materials. The success is measured in terms of number of completed thermal cycles until crack initiation.

2) **Work Package 2 – Water/Steam Chemistry Control**: As mentioned above, the increase in CCPP efficiency can be achieved by operating at higher live steam pressure and temperatures. Since generally chemical reactions run faster at higher temperatures and pressures, accelerated corrosion and oxidation of the HRSG materials is likely at those conditions, which may ask for stricter control of the water/steam chemistry. Therefore, Water/Steam chemistry lab testing is done to obtain baseline corrosion rates for different materials, impurity levels, and steam properties in autoclaves (pressure vessels). Based on these laboratory test data a specification of the allowable operating range for the Water/Steam Chemistry Parameters is derived to achieve the required performance and lifetime of the water steam cycle. At the validation site an improved Water/Steam Cycle water chemistry control concept was applied, and the site testing was done to ascertain, that the Water/Steam chemistry parameters can be maintained within the allowable range.

3) **Work Package 3 – OT HRSG Transient Process Control**: Development of the plant dynamics & control concepts and software simulation and validation for the start-up, transient & steady-

state operation of the OT HRSG. Steam temperature overshoot, time to stability, temperature spread control, time to dry operation under different operating modes are key performance indicators.

4) **Work Package 4 – Field Validation of OT HRSG & Steam/Water Control**: Field validation of WP2 & WP3 scope in the first units in South East Asia equipped with the evolved GE OT HRSG technology. The focus is on the validation of OT HRSG operational concepts developed in WP2 and WP3. This includes OT evaporator filling, steam temperature & water/steam chemistry control. The tests performed for the water-/steam cycle chemistry is also targeting to validate the achieved purity levels in the first application of OT HRSGs without condensate plant polishing equipment. It is important to mention here, that the OT HRSG selected for field validation in South East Asia is not equipped with DWM technology. When manufacturing and construction of the OT HRSG for field testing began, the DMW material testing under WP1 was still in progress and the technology must be considered unvalidated. From a customer risk exposure management perspective, it was therefore not possible (and never intended under this research project) to apply the new DMW technology at this customer site.

1.4 Project and Report Structure

The technologies developed within this program cover two very different technology areas leading to different validation strategies:

- WP1 is focused on long term material testing under laboratory conditions. As field implementation of this technology is not part of the project, this WP runs on its own schedule independent from WP2, WP3 & WP4.
- WP2 and WP3 on the other side are focused on the development of control strategies which are first developed using already validated simulation tools and then, in a 2nd step, after site implementation, are validated under real conditions in a shorter term (compared to material testing) field test.

The key milestones in this program are shown in [Table 1]

Table 1: Program main milestones. Delayed vs baseline schedule.

For the ease of reading, the structure of this report follows the WP sequencing:

- Chapter 2 covers the dedicated discussion on WP1 including the facility and validation process description followed by the results discussion.
- Chapter 3 gives a short overview of the field validation site and overall test program. The detailed discussion of testing and testing results is covered in the respective chapters designated for WP2 and WP3.

- Chapters 4 & 5 include the discussion of the development methodologies for the two different technologies in WP2 and WP3 **and** the detailed results discussion from field validation (WP4) in the individual chapters.
- Chapters 6 & 7 summarize the outcomes of all work packages in conclusions and outlook.

2 WP1: DMW Lab Testing

2.1 DMW Introduction

As mentioned in the WP 1 description in [Chapter 1.3], with the move to steam higher temperature and pressure, higher grade material will be required in certain areas of the HRSG to maintain the required lifetime of components. This in turn introduces the need to transition between different material resulting in the need of DMW.

[Figure 2] shows the front end section of a HRSG flow diagram with the Heat Exchangers (Harps) representing the effective area where the steam is generated and the manifolds where the steam from the multitude of smaller heat exchanger tubes is collected into the main steam piping going to the steam turbine. It is upstream of the manifold area where GE is placing the DMW to transition between the different material grades.

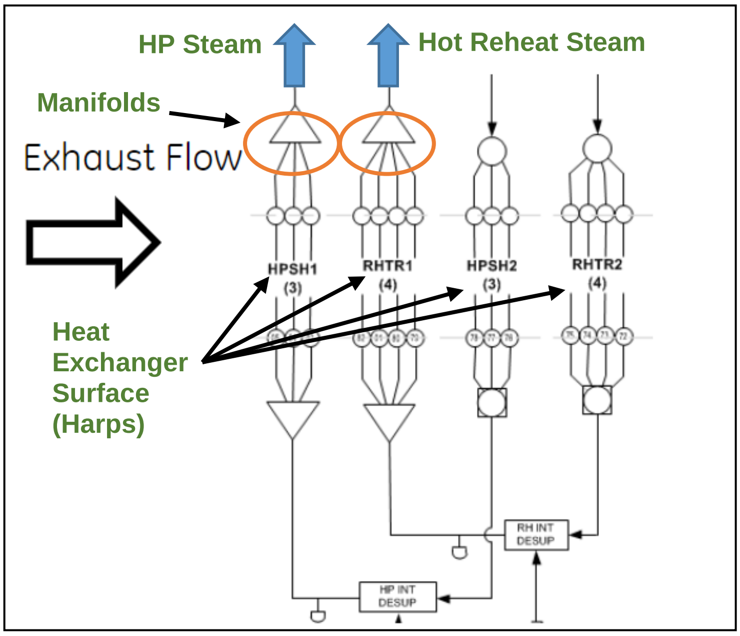


Figure 2: Front end section of a HRSG flow diagram.

The pre-manufactured HRSG modules are built in such a way, that all DMWs are welded in the factory in a controlled environment. All welding that is performed at the construction site is done for similar metals only.

[Figure 3] shows three manufacturing steps from initial DMW weld to finished pre-manufactured module: a) DMW welding of two short pipe sections of different metals, b) welded connecting pieces (spools) ready for heat treatment, c) details of connecting pieces (spools) welded to manifold.

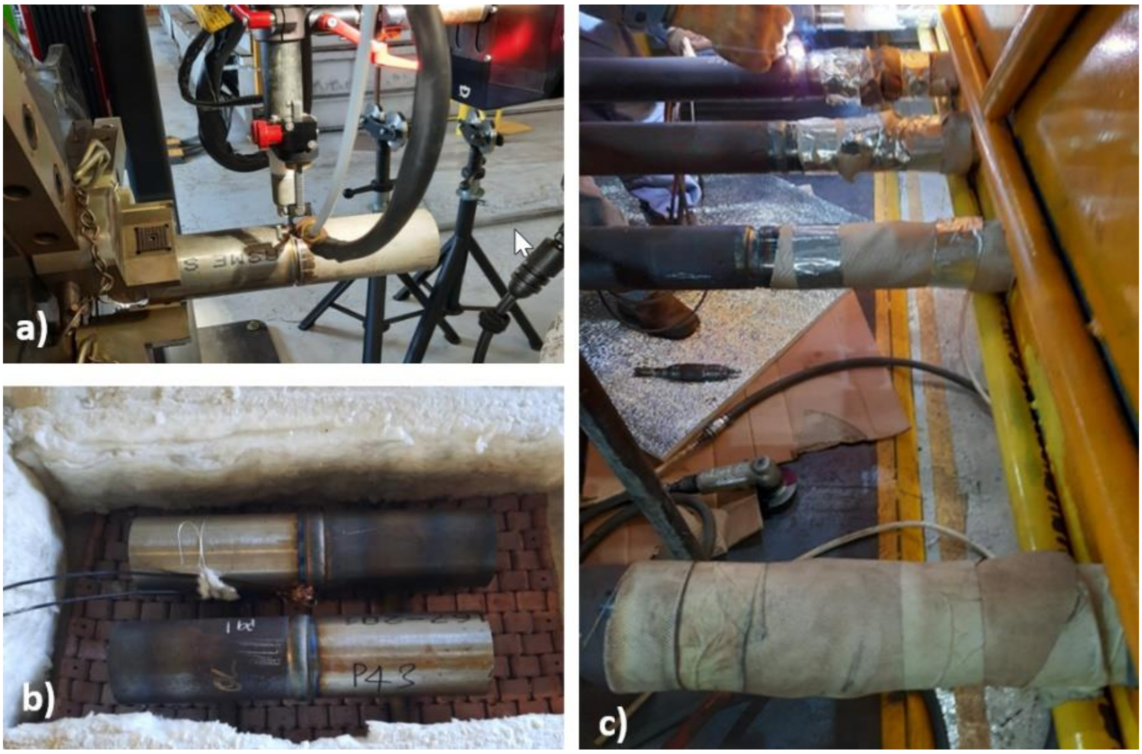


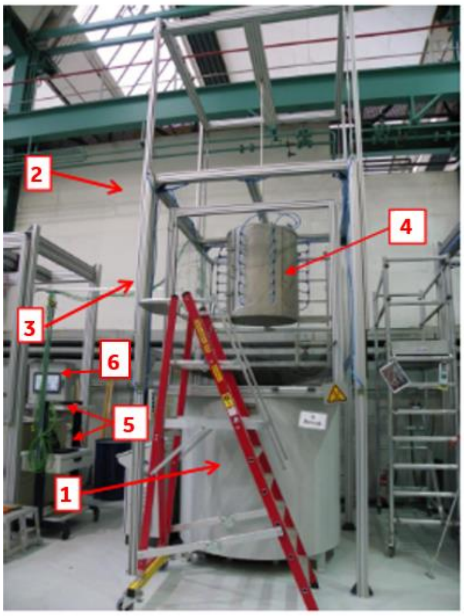
Figure 3: Manufacturing details of a typical Steam Manifold with DMW connecting pieces.

The pictures were taken after successful completion of WP1 material qualification during manufacturing of first DMW HRSG for customer application in 2022 (see also [Figure 38]).

2.2 DMW Test Rig Description

DMW test rig in form of fluidized bed thermocycle test facilities: The fluidized bed tests simulate cyclic thermal loading on the DMW samples by heating and forced cooling air in a timeframe from 30 mins to 90 mins.

In the frame of WP1 a small and a large test rig were established at GE's factory site in Birr/Switzerland with the capacity to accommodate testing of several full size DMWs simultaneously within the cycling rig and the ability to minimize the heating and cooling cycle times so that testing could be performed within acceptable timescales [Figure 4]. The testing concept chosen was to transfer the test welds between a heated fluidized bed and a cooling zone where cooling air was directed onto each test piece by means of a linear manipulator developed by GE Switzerland [Figure 5]. The linear movement allows a fast and reliable transfer of the test samples from hot to cold and a sample weight up to 300 kg. Heat treatment furnaces are perfectly suited for heating because the fluidized aluminum oxide powder provides an excellent heat input into the test samples leading to a quick temperature equilibration and short cycle times. The cooling chambers are equipped with 7 cooling nozzle rows with max 9 nozzles per row each, providing impingement cooling to the tests sample surface. With this setup cooling air flows of up to 3000 l/min and cool down rates up to 70 K/min could be reached.



1) New Fluidized Beds with 600 and 800 mm diameter cooling chambers
2) New Manipulator: Upper element pneumatically 1400mm extendable
3) Protection enclosure with acrylic glass windows on all sides
4) Cooling sleeve with 7 cooling nozzle rows (each row with max 9 nozzles)
5) Data logging system with laptop
6) Programmed logical control system

Figure 4: New (large) fluidized bed test station with 600 mm size in diameter and 1080 °C capability.

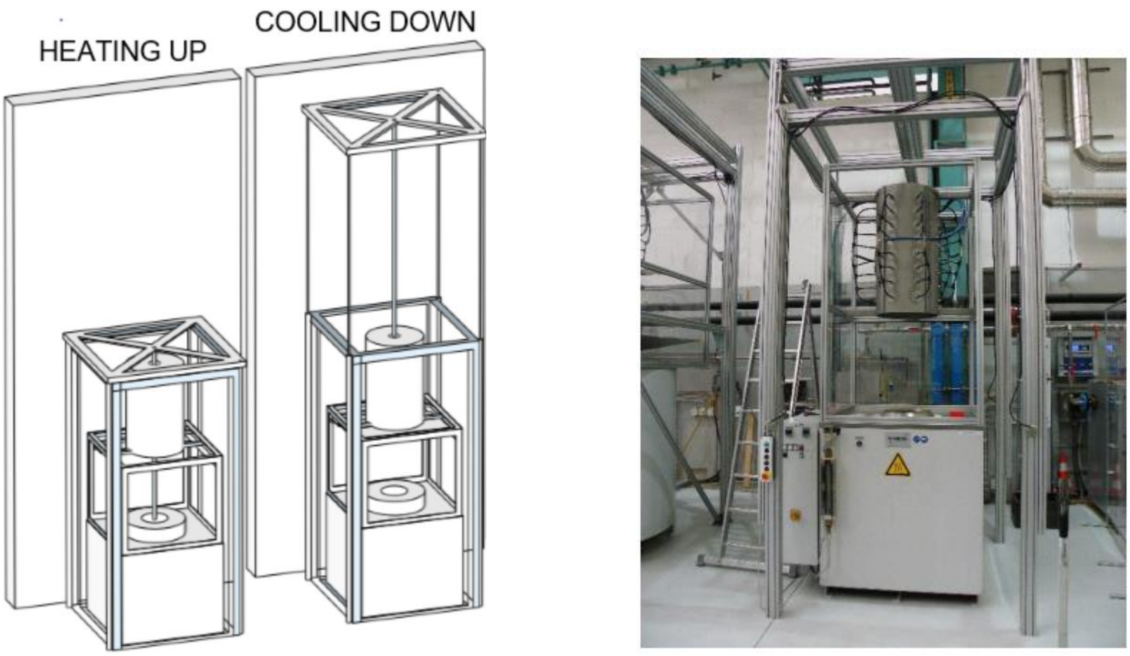


Figure 5: Operation concept of new fluidized bed test rigs (left) and lifting device (right)

Small and large fluidized test beds produced slightly different thermal profiles. Nevertheless, the thermal cycles results obtained in the new (large) facility indicated that the temperature profile can be matched for the heat up phase, while the cooling rate is longer in the new (larger) fluidized bed compared to the smaller one. This can be explained by the lower cooling efficiency of the large rig because of the larger cooling sleeve. However, this is deemed acceptable and is a key milestone and prerequisite for the comparability of tests between both test rigs. [Figure 6] shows a test sequence of four cycles with a minimum target temperature approaching ambient and maximum target temperature above the operation temperature in service simulating cold start conditions in a field application.

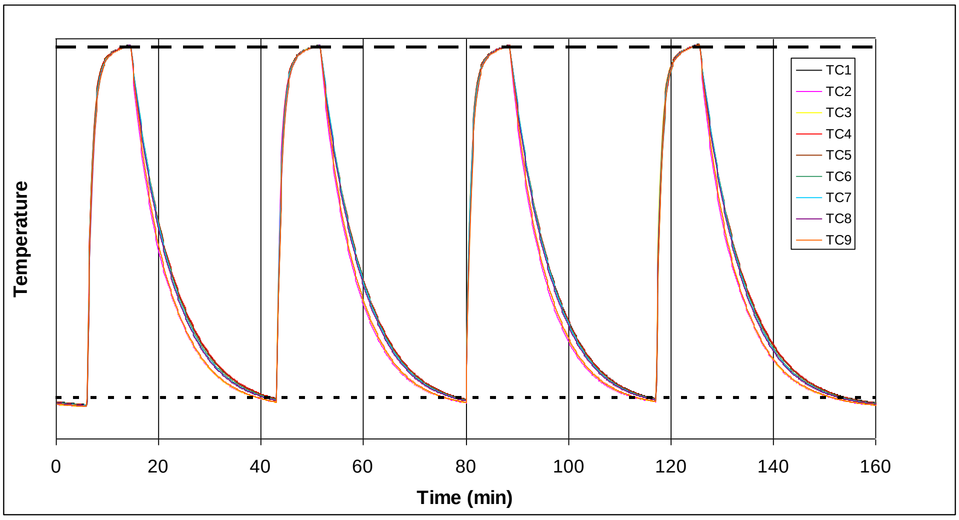


Figure 6: Example of temperature profiles achieved in large fluidized bed test rig.

Prior to each test campaign the transient temperature distribution of each test position in the rig was recorded with temperature calibration probes equipped with four to six type-K thermocouples in 2 to 3 planes of the sample. These probes had the same geometry, material combination and surface roughness as the test samples helping to ensure comparability of the pre-tests with the final test samples. The pre-tests were also used to improve the test machine settings and ensure long term stability of test conditions during the whole test campaign.

2.3 DMW Material Testing Process and Methodology

ASME Boiler and Pressure Vessel Code guidelines for DMWs are advisory in nature and are clarified to be based on a situation where failure is dominated by creep. However, GE's experience in HRSGs is that the most likely failure mode is fatigue driven due to different coefficients of thermal expansion between austenitic and martensitic stainless steels rather than creep. GE's view therefore is that the fatigue lifetime of DMWs should be improved to increase life.

In the frame of WP1 several different DMW configurations were evaluated – the parameters investigated included material choice, weld metal, weld angle, weld process and post-weld machining. The summary of test program is shown in Table 2. The first part of the program was to test weld joints between a martensitic 9% Cr steel and austenitic stainless steel using two types of Nickel base filler metal and different weld methods. The second part of the test program was to test weld joints of the same martensitic 9% Cr steel and a Nickel base material using two types of Nickel base filler metal. In the third part of the program friction welds and GTAW's of the martensitic steel with the Ni-base spool piece and the austenitic stainless steels were tested (so called 3 metal welds).

Material 1	Filler	Material 2	Material 3	Nominal Bevel Angle	Weld Method	PWHT	Machined profile	Number of samples tested per condition
Martensitic SS	Ni-base 1	Austenitic SS		high	GTAW	Yes	No / Yes	2/1
Martensitic SS	Ni-base 1	Austenitic SS		high	GTAW	Yes	Yes	3
Martensitic SS	Ni-base 1	Austenitic SS		low	GTAW	Yes	Yes	2
Martensitic SS	Ni-base 2	Austenitic SS		low	GTAW	Yes	Yes	3
Martensitic SS	None	Austenitic SS		low	Friction weld	Yes	Yes	3
Martensitic SS	Ni-base 1	Ni-Base		low	GTAW	Yes	Yes	2
Martensitic SS	Ni-base 2	Ni-Base		low	GTAW	Yes	Yes	2
Martensitic SS	Ni-base 2	Ni-Base		high	GTAW	Yes	No	3
Ni-Base	Ni-base 2	Austenitic SS		high	GTAW	No	Yes	2
Martensitic SS	None	Ni-Base	Austenitic SS	low	Friction weld	Yes	Yes	3
Martensitic SS	Ni-base 2	Ni-Base	Austenitic SS	low	GTAW	Martensitic SS side	No / Yes	2/1

Table 2: Overview of combinations tested in the frame of WP1.

The test specimens are of tubular form with dimensions representative of those used in GE’s OT HRSGs [Table 2]. All welds were stress relieved with the same PWHT temperature suitable for the 9% Cr steel.

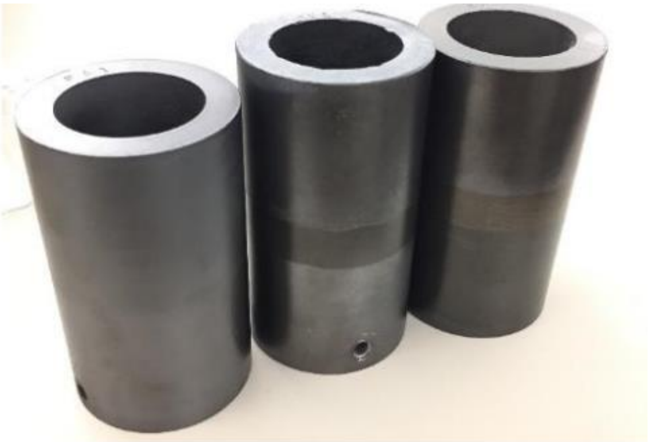


Figure 7: Welded samples.

Figure 8: DPI results on sample HU1 after first indication, after test continuation and test finish.

In total 29 specimen assemblies were tested with a total of more than 100’000 cycles. The test pieces were examined using dye-penetrant examination (DPI) after each 150 cycles to determine the onset of cracking. Specimens were removed from the test rig either when cracking had been identified or after reaching the run-out duration [Figure 8]. The number of cycles to crack initiation was recorded together with crack location. Thermal cycling was continued after the first crack was observed to allow crack growth and development of cracks in other locations.

After test completion the specimen were sectioned and prepared for metallographic examination. [Figure 9] shows examples of cracking on both the martensitic and austenitic sides of the DMW. The crack appearance is in-line with field experience and the location of the initial crack is consistent with FE calculations.

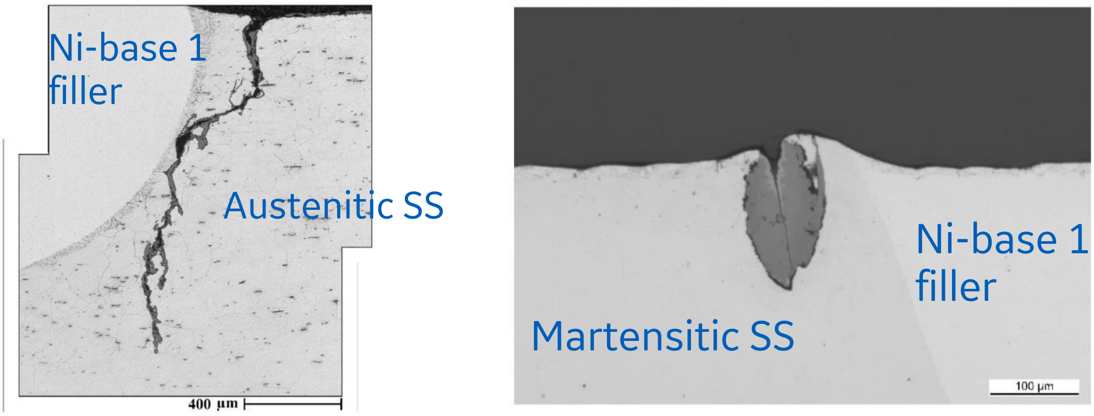


Figure 9: Microstructural images showing the typical crack appearance on the austenitic (left) and martensitic steels side (right).

2.4 DMW Lab Testing Results & Discussion

As the operating steam temperatures of HRSGs increase above 600 °C the strength and oxidation resistance of 9% Cr martensitic steels becomes inadequate and it is advantageous to consider the use of austenitic stainless steel in the hottest regions of the superheaters (and reheaters). In consequence, DMWs between the austenitic and martensitic steel components are required.

Comparing the different samples with regard to number of cycles till crack indication, the influence of different variables of interest become visible. [Figure 10] shows the cycle to crack indication for two metal welds (martensitic welded to austenitic stainless steel) and [Figure 11] shows all test data determined on samples relevant for three metal welds (austenitic SS welded to Ni-base and martensitic SS welded to Ni-base and martensitic SS welded to Ni-base welded to austenitic SS).

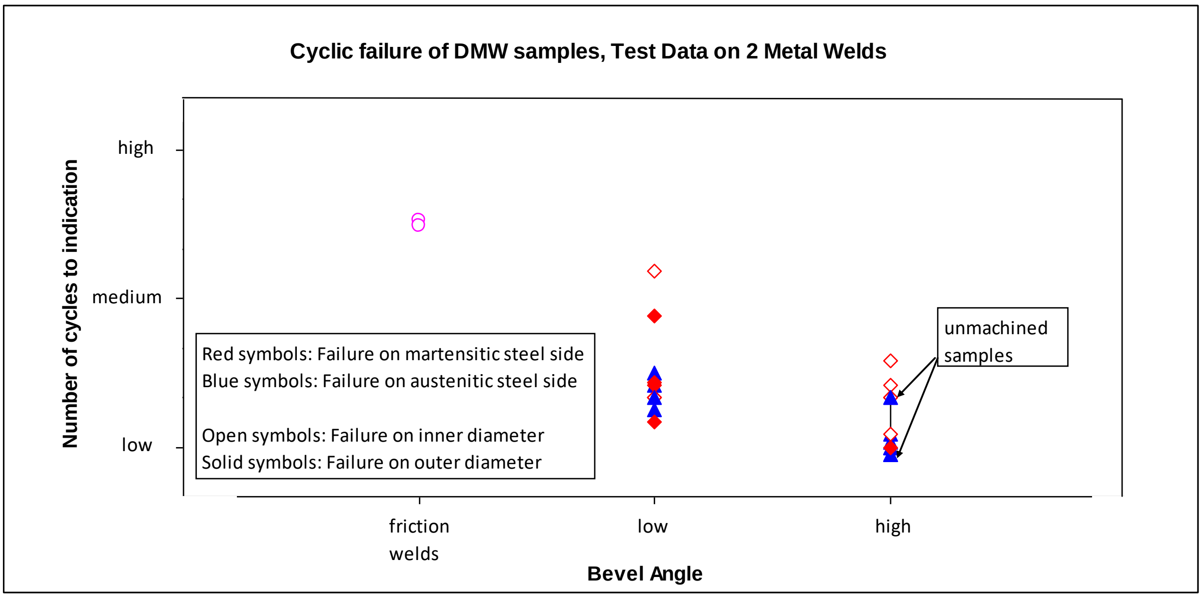


Figure 10: Number of cycles to indication for all two-metal DMWs

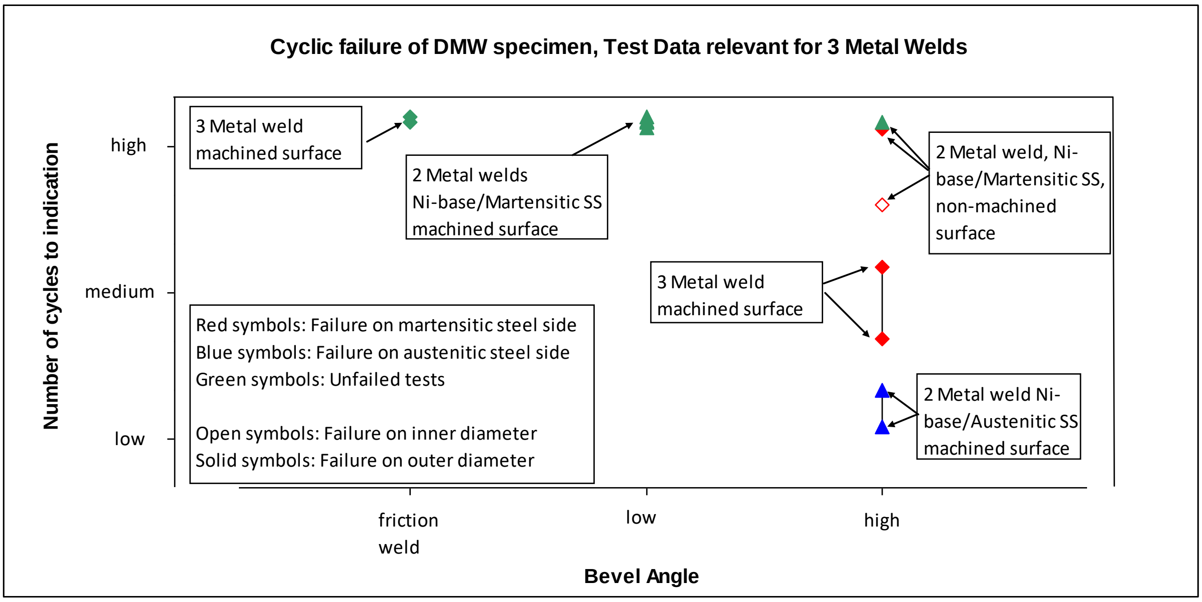


Figure 11: Number of cycles to DPI indication as a function of bevel angle for weldments to Inconel 617

In both figures each test sample can have multiple failures, i.e. on the two metal welds [Figure 10] crack indications were usually observed first on interface of austenitic stainless steel to Ni-base filler metal at the outer diameter (OD). During test continuation those samples showed predominantly failures at the interface between the martensitic stainless steel and the Ni-base filler metal at the inner diameter (ID). The primary failure on the austenitic stainless steel side can be explained by the higher mismatch of coefficient of thermal expansion (CTE) between austenitic SS and the Ni-base filler material and the higher thermal transients on OD leading to the highest thermal stresses in this location. Why the samples on the interface between martensitic SS and Ni-base metal failed earlier on ID than on OD remains unexplained. [Figure 10] also shows the beneficial effect of low bevel angles. This beneficial effect was observed independently on the type of Ni-base filler metal. The highest number of cycles to crack initiation was observed on the friction welds.

Comparing [Figure 10] and [Figure 11] shows the benefit of welding the martensitic stainless steel to a Ni-base material rather than welding martensitic stainless steel to the austenitic stainless steel. This effect can be explained with the lower mismatch of CTE between the martensitic SS and Ni-base material compared to martensitic SS and austenitic SS. However for the high bevel angle the weldment between Ni-base material and austenitic SS showed similar low cycles to indication than previously observed on the martensitic SS to austenitic SS welds despite the lower mismatch of CTE for the Ni-base to austenitic SS combination. The poor behavior of the Ni-base to austenitic SS steel weld could be partially explained by the fact that this weld was not stress relieve annealed and depending on the cool down conditions from welding could have developed high thermal stresses. However, usually austenitic stainless steels don't require stress relieve anneal and the austenitic SS side of the three-metal weld with high bevel angle [Figure 10] also didn't receive an anneal and didn't show a crack indication until test completion. On [Figure 10] the beneficial effect of the lower bevel angle on crack indication on the Ni-base/ martensitic SS weld is visible too with the GTAW with the low bevel angle samples and the friction welds showing no crack indications until test completion.

The findings of this assessment are shown in [Table 3].

Material 1	Weld Metal	Material 2	Material 3	Parameter changed	Conclusion
Martensitic SS	Nickel-base 1	Austenitic SS		Bevel Angle low/high	Low bevel Angle gives longer life
Martensitic SS	Nickel-base 1	Austenitic SS		Machined/unmachined	Unmachined samples failed at lower bound of the scatterband of machined samples
Martensitic SS/ Nickel base	Nickel-base 2	Austenitic SS		Material 1	Longer life in Nickel-base variant
Martensitic SS	Nickel-base 1 /Nickel-base 2	Austenitic SS/ Nickel-base		Material 2 / Weld Metal	Longer life in Nickel-base variant, less impact of weld metal
Martensitic SS	Nickel-base 2	Nickel-base		Bevel Angle low/high Weld profile machined/ unmachined	Lower bevel angle and machined profile gives longer life
Martensitic SS	Nickel-base 1 / Nickel-base 2	Nickel-base		Weld metal	For low bevel angle no crack in either weld metal variant
Martensitic SS	Nickel-base 1 / None	Nickel-base	Austenitic SS	Welding Method/Bevel Angle	3 metal friction welds superior to 3 metal TIG welds
Martensitic SS	None	Austenitic SS / Nickel base	None / Austenitic SS	Material 2	3 metal friction superior to 2 metal friction welds

Table 3: One-to-one comparison of test results and conclusions derived.

As a conclusion the main findings from Table 3 can be summarized as follows:

- The main contributing factors to the cyclic lifetime of the DMW's tested in WP1 are the difference in the coefficient of thermal expansion between the weld partners and the weld bevel angle.
- By lowering the weld bevel angle the cyclic lifetime of the two metal welds could be increased significantly. For the three metal welds the improvement was even stronger producing only run outs with the low bevel angle.
- Different Ni-base weld metals had little impact on cyclic lifetime.
- The unmachined test samples for the austenitic SS/martensitic SS combination failed at the lower band of the machined samples. For the three metal welds a similar effect was not observed.

- Friction welds showed equivalent or better cyclic lifetime than TIG welds with low bevel angle.

3 Combined Cycle Plant Selected for Validation

The on-site validation of technologies developed in WP2 and WP3 took place in a Combined Cycle Power Plant (CCPP) in South East Asia [Figure 12].

The power plant configuration consists of two single-shaft units (later called unit 1 and unit 2) based on GE 9HA.02 Gas Turbines. Each single-shaft CCPP is equipped with a dedicated HRSG. The HRSGs are based on the OT (Once-Through) technology and produce steam at three pressure levels; the high-pressure steam is generated at 600°C and 185 bar pressure under nominal conditions. Each unit can generate 720 MW at a net efficiency > 64%. The water-steam cycle chemistry is based on the improved water chemistry concept as described in WP2. The control system contains the next generation logic as per WP3. The Dissimilar Metal Weld Technology (WP1) has not been applied at this validation site.

Figure 12: GE's 1st CCPP with GE's evolved OT HRSG technology located in South East Asia.

The validation program defined in WP4 integrates technologies which have been developed under WP2 and WP3 to collect and analyze data on GE's first OT HRSG behind a H-class gas turbine.

Dedicated instrumentation and an on-site test program have been set-up with key performance indicators to assess the success of the new technologies. The measured key indicators are different for WP2 and WP3 and are discussed in more detail in [Chapter 4] and [Chapter 5].

Overall, the defined key performance indicators cover the startup and load changes and the control of the steam temperature for the Plant and the steam temperature distribution within the HRSG with the new OT HRSG controls system developed under WP3. A further set of indicators are used to monitor and validate the water consumption at startup and the control of the water steam chemistry and «impurity cleaning» capability of the updated impurity cleaning concept.

To cover the validation requirements for both WP2 and WP3, a test program summarized in [Table 4] has been integrated into the overall commissioning plan of the new built power plant.

Component/feature⇨ **Tests ⇩**	**OT filling**	**Dynamic Feed Fwd Controls**	**Controls Integration**	**Water-/Steam Chemistry**
Cold commissioning checks	X			X
Step tests mapping		X	X	
Start ups (fast, hot/cold/warm)	X	X	X	X
Load operation tests (cycling, park & shutdown)		X	X	X
Cycle cleaning			X	X
Robustness & failure modes		X	X	

Table 4: High Level Site Test Program

The main focus of the site validation program as defined in WP4 was on plant dynamic behavior (WP3) and on the water/steam chemistry (WP2) as discussed in the following sections. The advanced control concept for OT and reliable water chemistry are a prerequisite for the improved dynamic behavior of the OT technology.

The measurement of overall plant efficiency was not part of the site validation program as defined under this research program.

4 WP2: Water/Steam Chemistry Control

4.1 Water/Steam Chemistry Background

The targeted increase in CCPP efficiency can be achieved by operating at higher live steam pressure and temperatures. This requires controlling the impact of impurities in the water steam cycle at those conditions in terms of corrosion & oxidation on the boiler materials.

Water impurities are introduced into the water steam cycle through various means, such as:

- Makeup water: Makeup water is used to replace water lost due to leaks and normal drums blow-down. This makeup water may contain impurities such as dissolved minerals, organic matter, and microorganisms.

- Condenser leaks: The condenser is operated under vacuum and responsible for cooling the steam after it has passed through the turbine. If there is a leak in the cooling tubes of the condenser, impurities from cold side cooling water can enter the steam cycle. To be noted, that as cooling water typically river-, lake- or seawater is used.

- Chemical treatment: Chemicals are often used in the water steam cycle to prevent corrosion and scale build-up. However, if the chemical treatment is not properly managed, it can lead to the introduction of impurities into the system.

These impurities can cause various problems in the water steam cycle, such as corrosion, scale build-up, and decreased efficiency. To minimize these issues, special care must be taken, to maintain the impurity levels below acceptable levels. Generally, the allowed water impurity levels are defined by international standards and guidelines such as VGB-S-010-T-00.

As the application range is extended to higher pressures and temperatures, it was needed to verify whether the existing rules on both, the acceptable impurity levels as well as the cleaning capability of the advance OT cycle, are still applicable or within expected range respectively.

Therefore, Water/Steam chemistry laboratory testing is done to obtain baseline corrosion rates for different materials, impurity levels, and steam properties in autoclaves (pressure vessels). Based on these laboratory test data a specification of the allowable operating range for the Water/Steam Chemistry Parameters is derived to achieve the required performance and lifetime of the water steam cycle.

As mentioned in [Chapter 1], with the introduction of the OT technology the self-cleaning capability of the HRSG is reduced. Therefore, at the validation site an improved Water/Steam Cycle water impurity control concept was applied (see [Figure 13] and GE Patent US11199113B2), and the site testing was done to ascertain, that the Water/Steam chemistry parameters can be maintained within the allowable range.

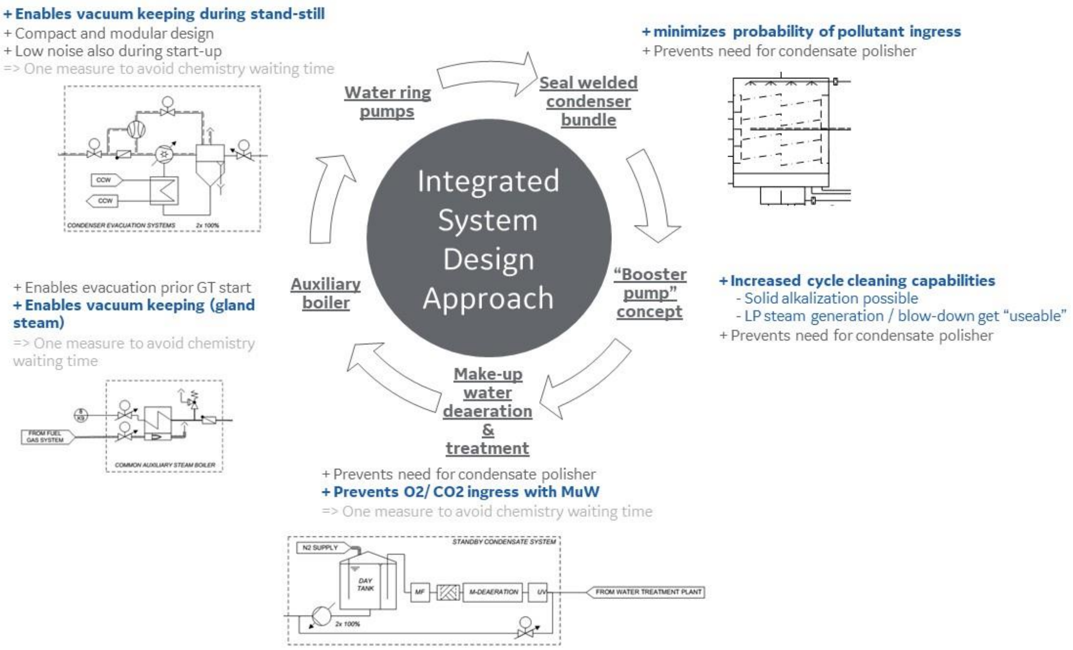


Figure 13: Improved water steam cycle impurity control concept.

4.2 Laboratory Chemical Testing (Autoclave Testing)

4.2.1 Chemical Testing Process and Methodology

The laboratory testing performed for WP2 (materials testing in autoclaves under different water/steam conditions) gives insight into the fundamentals of oxidation on materials exposed to water/steam conditions as found in industrial CCPP. In particular, the oxidation as a function of the steam impurity level is investigated for various parameters. This provides input to the water/steam specification for the field CCPP.

The samples to be subjected to the oxidation tests have been cut from new unused boiler tubes that have been received from the boiler manufacturing workshops. For cutting of the samples water jet erosion was applied to avoid change of the material structure of the samples by high temperatures. The samples were polished, cleaned and then suspended on the sample holder. After putting the sample holder with the samples in the autoclave, the autoclaves were closed, sealed and leak tested with high pressure nitrogen gas.

The aqueous test solution was prepared from demineralized water, to which sodium chloride was added until the required salinity as measure of the targeted impurity level has been reached. Then the solution was buffered at the necessary pH by addition of aqueous ammonia, followed by deaeration with a nitrogen gas stream until the required oxygen level has been reached.

The test solution was transferred under vacuum into the autoclave and then the autoclave was heated up to the testing temperature. After testing the autoclave were cooled down to ambient temperature and opened carefully. The test samples were taken out and stored in a dry ambient, whereas the test solution was transferred into suitable sample bottles.

The test samples were first weighted to record mass loss or gain, inspected visually and macroscopically and then cut parallel to the long edge, embedded in resin and polished for metallographic analyses of the thickness and morphology of the oxide layer by light microscopy.

The test solution after testing was analyzed by ion chromatography and spectrophotometric methods to detect changes with respect to the original test solutions.

The parabolic growth rate constant is calculated from the measured oxide layer thickness as a function of the testing parameters.

4.2.2 Chemical Testing Equipment

For the high pressure and high temperature chemical testing, commercially available autoclaves (Supplier: Parr) made of Hastelloy have been used. The autoclaves have been installed with the matching heaters and control equipment in an oven room adjacent to the GE water chemistry laboratory in Birr [Figure 14].

Figure 14: Autoclave container for water steam cycle testing.

Specific sample holders to fit into the autoclaves have been made by the GE Birr prototype workshop [Figure 15]. The samples for testing have been prepared by the Birr prototype workshop as well. For preparation of the aqueous test solutions as well as analyses of dissolved corrosion products, the infrastructure of the water chemistry laboratory has been used. Samples for testing have been manufactured as well in Birr [Figure 16]. After testing the oxidized samples were investigated metallographically in the Birr materials laboratory.

Figure 15: Autoclave with holder configuration and real samples (total capacity 16 samples).

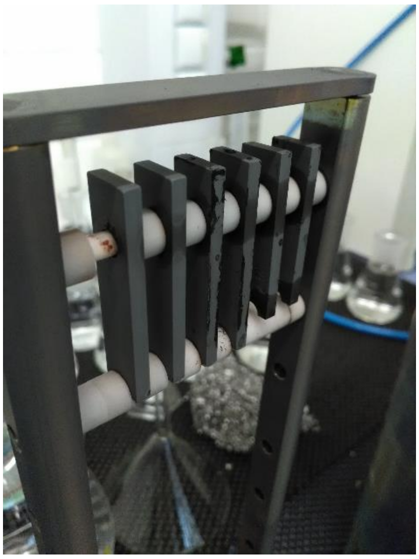


Figure 16: Sample holder with samples immediately after testing. The support structure of the holder is made from a nickel base alloy, whereas for sample fixation insulating ceramic material is used to suppress galvanic effects on the oxidation behavior.

4.2.3 Chemical Lab Testing Results

The oxidation behavior of selected HRSG materials has been tested in the autoclaves for different temperatures, pressures, impurity levels, pH and oxygen content as shown in [Table 5].

Test Nr.	1	2	3	4	5	6	7	8	9	10	11	12	13
Material	< 0.5% Cr	< 0.5% Cr	< 0.5% Cr	< 0.5% Cr	< 0.5% Cr		< 0.5% Cr	< 0.5% Cr		< 0.5% Cr	< 0.5% Cr		
	2-3% Cr	2-3% Cr	2-3% Cr	2-3% Cr	2-3% Cr		2-3% Cr	2-3% Cr		2-3% Cr	2-3% Cr		
	9% Cr (A)	9% Cr (A)	9% Cr (A)	9% Cr (A)	9% Cr (A)	9% Cr (A)	9% Cr (A)	9% Cr (A)	9% Cr (A)	9% Cr (A)	9% Cr (A)	9% Cr (A)	9% Cr (A)
	9% Cr (B)					9% Cr (B)			9% Cr (B)			9% Cr (B)	9% Cr (B)
	11% Cr			11% Cr	11% Cr	11% Cr	11% Cr	11% Cr	11% Cr	11% Cr	11% Cr	11% Cr	11% Cr
						DMW Martensitic-Ni Base			DMW Martensitic-Ni Base				
pressure											subcritical		
	supercritical	supercritical	supercritical	supercritical	supercritical	supercritical	supercritical	supercritical	supercritical	supercritical		supercritical	supercritical
Temperature	Evaporator	Evaporator	Evaporator	Evaporator	Evaporator		Evaporator	Evaporator		Evaporator	Evaporator		
						Superheater			Superheater			SH Outlet	Superheater
Impurity	low	low	low			low	low	low	low	low		low	low
				high	high						high		
O2	low		low		low	low	low						
		high		high				high	high	high	high	high	high
pH							low	low		low			
	high	high	high	high	high	high			high		high	high	high
Year	2019						2020						

Table 5: Test matrix of the autoclave oxidation tests.

The physical test conditions can be grouped into two categories

a) Testing at supercritical pressure with temperature close to the critical point as normally encountered in the evaporator (+ reference point at same pressure but below evaporation temperature). At these conditions strongest corrosion is expected due to possible dissociation of ionic impurities in supercritical fluid.

b) Testing at supercritical pressure with high temperature as found in the superheater. At these conditions, corrosion is expected to be low because fluid is dry, oxidation is mainly driven thermally.

The chemical parameters were selected as follows:

Parameter	Impurity	pH	Oxygen
LOW	10 x normal operation limit	Lower shut-down limit	Upper limit of normal operation band
HIGH	100 x normal operation limit	Upper limit of normal operation band	10 x upper limit of normal operation band

Table 6: Chemical Parameter settings applied in Autoclave testing.

Please note that both testing impurity levels, LOW as well as HIGH, are far above the normal operation band as defined per VGB-S-010-T-00; 2011-12]. The high levels have been chosen to get a clear indication about the effect of impurities on the corrosion rate already within the short testing period compared to the lifetime of the plant.

[Figure 17] shows a summary of the sample testing results.

The results of the laboratory material testing can be summarized as follows:

1) The oxide growth rate increases systematically with increasing impurity content, increasing oxygen content or decreasing pH of the test solution, see [Figure 17].

2) Requirements for the water and steam purity levels have been tested, criteria for safe operation at subcritical conditions and supercritical conditions have been defined and validated. The testing confirmed that application of existing operation limits as defined in international guidelines VGB-S-010-T-00; 2011-12 is allowed.

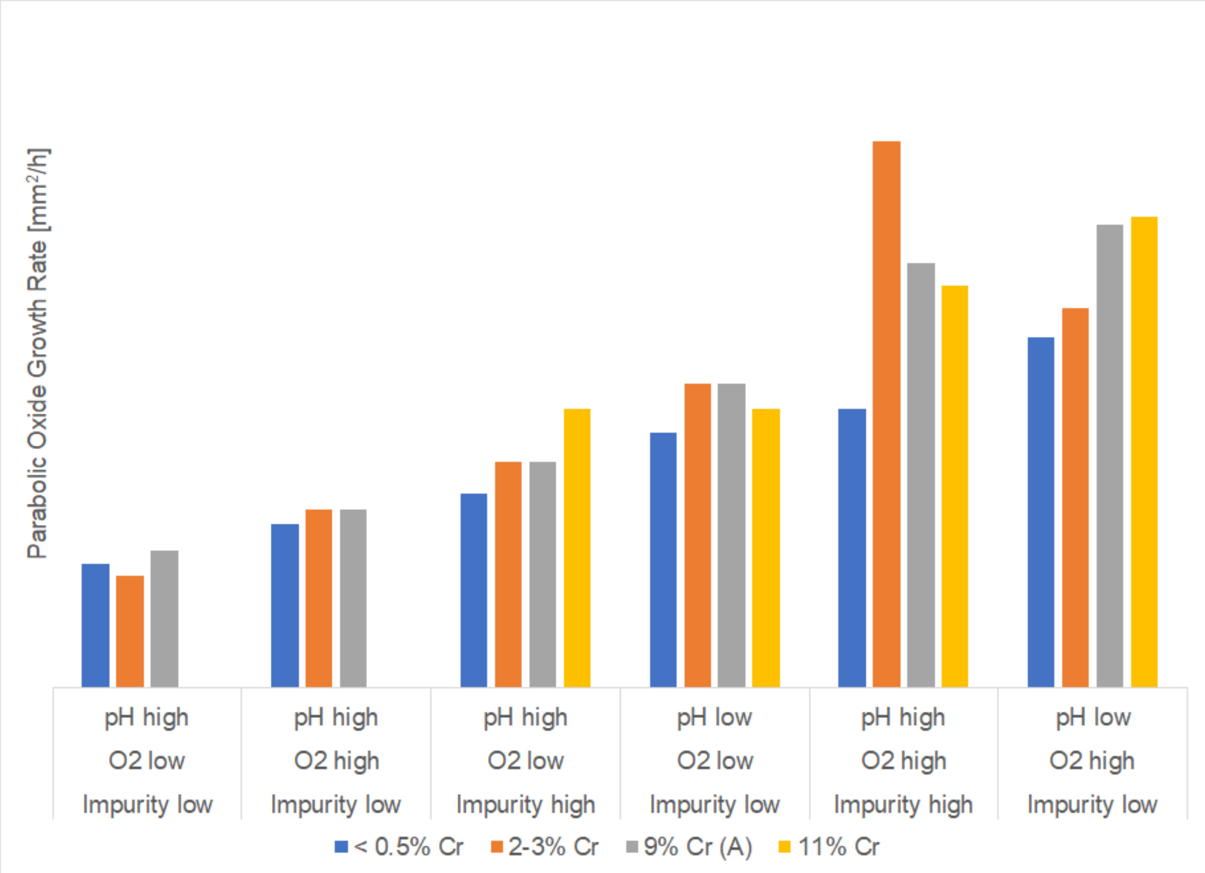


Figure 17: Measured parabolic oxide growth rate constants of different boiler materials in supercritical steam in dependence of the chemical test conditions.

Therefore, during the site validation [Section 4.3.2] the water impurities control was applied to conform with VGB-S-010-T-00; 2011-12.

4.3 Water-/Steam Cycle Chemistry Field Validation

4.3.1 Site Validation Goals

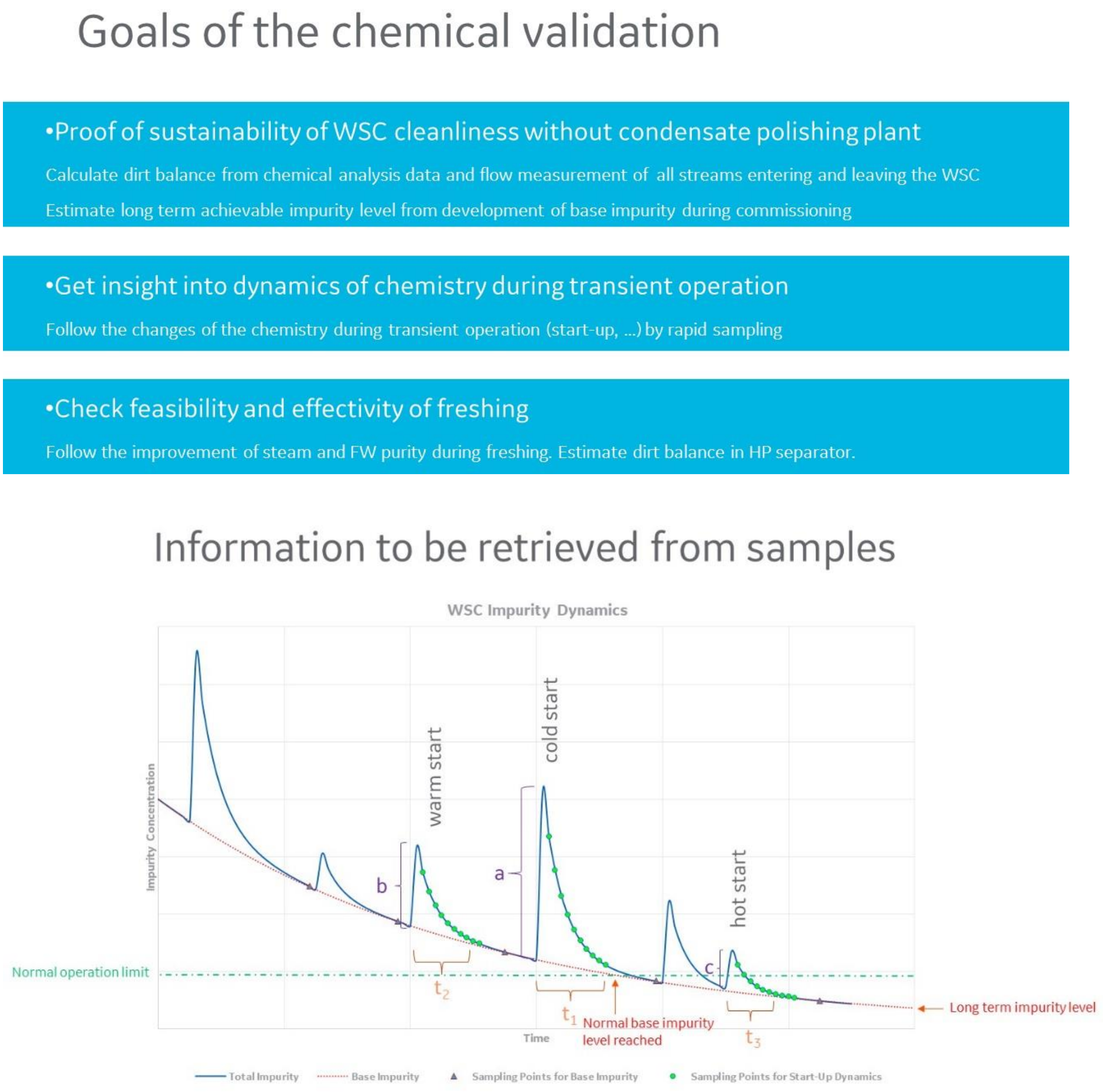


Figure 18: Expected impurity dynamics in the WSC

- The dotted red envelope reflects the decrease of the impurity originating from construction with ongoing operation.
- The peaks at the different starts reflect the expected increase of impurities due to ingress of air impurities during shut-down. Longer shut-downs result in larger inflow of impurities.
- The field validation shall establish the long term impurity level that can be reached as well as the dynamic behavior (Peak impurity values a, b, c as well as purity recovery times t1, t2 and t3) after cold, hot and warm start, respectively.

4.3.2 Water/Steam Chemistry Site Validation Results

During the final commissioning phase of the validation CCPP in South East Asia (see [Chapter 3]) the chemical behavior of Water/Steam cycle was monitored and compared to the requirements established in [Chapter 4.2.3]. The following sections give the details of the obtained validation results.

Standard chemistry supervision parameters of the water steam cycle of the power plant have been measured with permanently installed on-line sampling monitoring system which are part of the delivery scope of the power plant.. For the measurement of specific parameters as well as for quality control the permanently installed instrumentation has been complemented by temporary installed analyzers.

One of the main task of the site validation was to prove the normal impurity levels, given in the international guidelines, could be reached with the reduced cleaning capability (missing HP drum) of an Once Through HRSG.

Additional the impurity levels during start up of the steam turbine were monitored as described in [Figure 24].

The determination of the impurity level in the water steam cycle following parameters must be measured online or via grab sampling. These parameters are good indicators for determine the impurity level in the water steam cycle. This is also according international guidelines (e.g. VGB-S-010-T-00; 2011-12).

- Cation Conductivity (CC) via online analyzers
- Degassed Cation Conductivity (DCC) via online analyzers
- Silica via grab sample
- Iron via grab sample

The below [Table 7] lists the implemented sample points and the parameters measured at the different locations in the water steam cycle.

	Cation conductivity	Degassed cation conductivity	Silica	Iron
Condensate	x	x	x	x
Feedwater	x	x	x	x
LP Drum			x	
IP Drum			x	
LP Steam	x	x	x	x
IP Steam	x	x	x	x
HP Steam	x	x	x	x

Table 7: Sample points and measured parameters

4.3.2.1 Conductivity after cationic exchanger and degassed cation conductivity in the water steam cycle

The cation conductivity and degas cation conductivity are the main parameters to determine the impurity rate in the water steam cycle. They are indicator of the impurity level evoked from anions and carbon dioxide in the system. Higher anion or carbon dioxide levels could let to high corrosion rates in the system and would impact the performance / life time of the equipment. For this reason, the cation / degas cation conductivity must be measured in the system.

The target values for the normal operation limits are following:

- Cation conductivity the normal operation limit is < 0.3 µS/cm.
- The degassed cation conductivity the normal operation limit is <0.2 µS/cm.

[Table 8] and [Table 9] indicate the cation conductivity and degas cation conductivity for different sample points.

Unit 11	LP Steam	IP Steam	HP-Steam	Feedwater	Condensate
Cation conductivity [µS/cm] normal operation limits	<0.3	<0.3	<0.3	<0.3	<0.3
Cation conductivity [µS/cm]	<0.20	<0.20	<0.20	<0.20	<0.20
Degas Cation conductivity [µS/cm] normal operation limits	<0.20	<0.20	<0.20	<0.20	<0.20
Degas Cation conductivity [µS/cm] *	<0.10	<0.10	<0.10	<0.10	<0.10

Table 8: Cation Conductivity and Degas Cation Conductivity - Unit 1

Unit 21	LP Steam	IP Steam	HP-Steam	Feedwater	Condensate
Cation conductivity [µS/cm] normal operation limits	<0.3	<0.3	<0.3	<0.3	<0.3
Cation conductivity [µS/cm]	<0.20	<0.20	<0.20	<0.20	<0.20
Degas Cation conductivity [µS/cm] normal operation limits	<0.20	<0.20	<0.20	<0.20	<0.20
Degas Cation conductivity [µS/cm] *	<0.10	<0.10	<0.10	<0.10	<0.10

* Measurement with portable degassed conductivity analyzer

Table 9: Cation Conductivity and Degassed Cation Conductivity - Unit 2

[Figure 19] shows some typical cation and degassed cation conductivity value of a HP steam sample measured with an degassed conductivity analyzer.

Figure 19: Typical cation and degassed cation conductivity reading HP-Steam

For both parameters cation conductivity and degas cation conductivity the normal operation limits could be reached, which means the anion and carbon dioxide impurity in the water system cycle are very low.

4.3.2.2 Silica values in the Water Steam Cycle

Higher Silica levels in the water steam cycle can lead to deposits on the steam turbine, which would effects the performs from the steam turbine. For this reason, Silica must be measured in the system.

The Silica target values for the normal operation limits are following:

- Silica the normal operation limits for the water and steam areas are < 20ppb.
- Silica the normal operation limits for the LP/IP drum water is < 2000ppb.

[Table 10] lists the Silica values for different sample points.

SiO_2 [ppb]	LP Steam	IP Steam	HP-Steam	Feed-water	Conden-sate	LP Drum	IP Drum
normal operation limits	<20	<20	<20	<20	<20	<2000	<2000
Unit 11	5-15	10-15	10-15	10-20	10-20	<300	<300
Unit 21	10-15	10-15	10-15	10-20	10-20	<400	<400

Table 10: Silica values

At the end of commissioning phase the Silica levels in the water and steam cycle are reached the normal operation limits.

4.3.2.3 Iron Values in the Water Steam Cycle

Higher iron levels in the water steam cycle would be an indication for higher corrosion rates in the water steam cycle. For this reason, Iron must be measured in the system.

The iron target value for the normal operation limits is following:

- Iron the normal operation limits for the water and steam areas is < 20ppb.

For the iron measurement for Unit 11 was performed with an portable Fe analyzer. For Unit 21 the iron was measured via a grab sampling.

[Table 11] lists the iron values for different sample points at the end of the hot commissioning.

Iron [ppb]	LP Steam	IP Steam	HP-Steam	Feed-water	Conden-sate	LP Drum	IP drum	LP eco outlet
normal operation limits	<20	<20	<20	<20	<20			
Unit11*	<2	<2	<2	<5	<5	<300	<50	<15
Unit 21**	<10	<10	<10	<10	<10			

* The Portable Fe analyser was only used in Unit 11
** For Unit 21 the Iron was measure with portable spectrophotometer (Ferrozine measurement)

Table 11: Iron values at the end of commissioning [ppb]

[Figure 20] shows some typical Iron values for a HP steam after a view hour after restart of the Unit.

Figure 20: Portable Iron measurement HP Steam - Unit 1

At the end of commissioning phase the iron levels in the water and steam cycle have reached the normal operation limits.

All chemical parameters at the end of hot commissioning period for Unit 11and 21 reached the normal chemical operation values as mentioned in [Figure 18] and were in-line with the international guidelines. The impurity levels in water steam cycles were very low. The values were reached without the use of the temporary polishing plant and despite of a substantial sea water leakage into condenser of U11. This gives evidence that operating an once through cycle/HRSG is possible from chemical perspective without a condensate polishing plant. The removal of impurities over the LP and IP drum blow down is sufficient to reach the required normal operation limits.

4.3.2.4 Start-up times for the steam turbine

For the release of start up the steam turbine, the chemical parameters in the steam system needs to reach certain values. In this chapter the start up time for the chemical release of the steam turbine and the time until the normal cation conductivity operation limits are reached is recorded.

Depending on the shut down time of the plant different start up types (hot, warm and cold) are defined.

In [Table 12] the chemical release times for the steam turbine, for the different start ups and the time until the normal cation / degas cation conductivity operation limits are reached, are mentioned. The release condition for the steam turbine is defined for a cation conductivity of <1 µS/cm in the HP steam.

The below tabled limits “Release Time” are required to achieve the contractual overall start-up times of the cycles. The time frames to reach <0.2 µS/cm reflect the duration achieved in drum type installations:

	Hot Start	**Warm Start**	**Cold Start**
Release Time ST CC <1 µS/cm	30min	50min	70min
Typical Time until normal operation limits CC <0.2 µS/cm	120-135min	120-150min	210-240min

Table 12: Start-Up times

4.3.2.5 Hot Start

[Figure 21] shows a typical behavior of the cation conductivity steam values during a hot start of Unit 1. The cation conductivity values of the LP, Reheat and HP steam are recorded. Also the turbine speed and the plant load are shown.

30 min after start of the Gas turbine the chemical release for the steam turbine was given. After 2:15 h the cation conductivity in the steam reached the normal operation limit of <0.2 µS/cm.

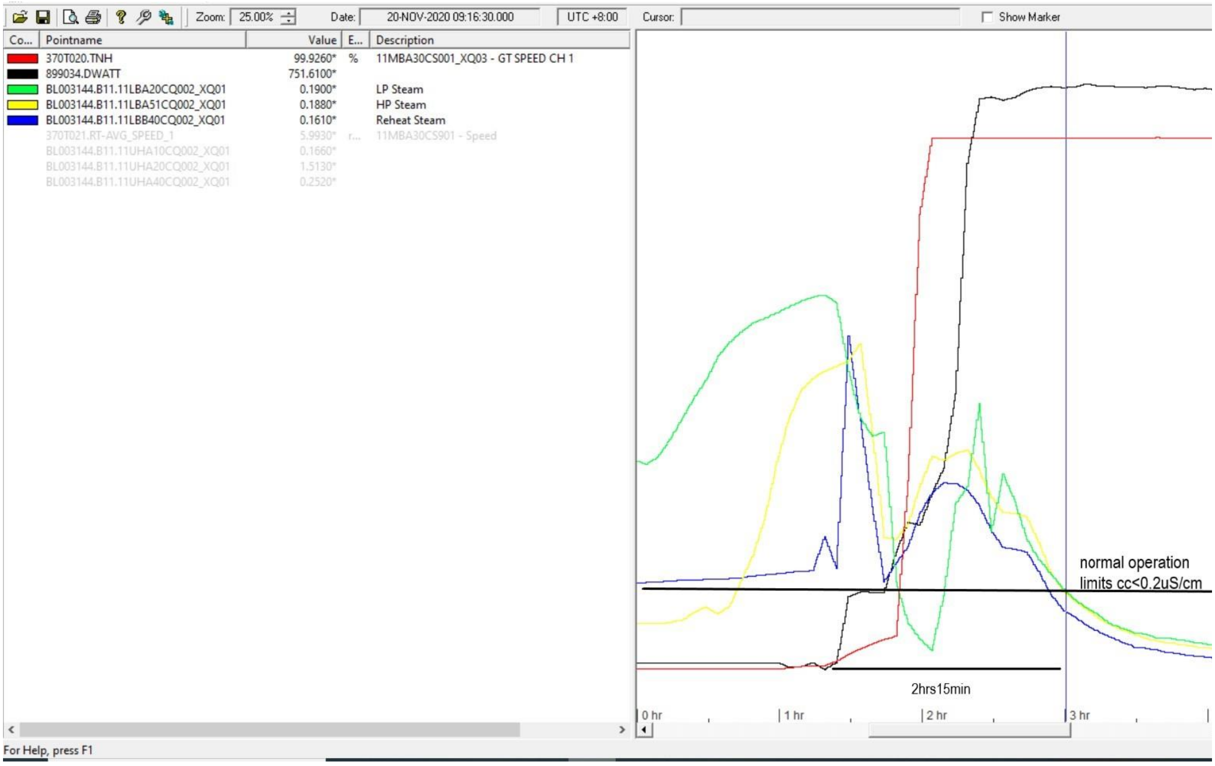


Figure 21: Cation Conductivity Transients during a typical Hot Start Unit 1

4.3.2.6 Warm Start

[Figure 22] shows a typical behavior of the cation conductivity steam values during a warm start of Unit 1. The cation conductivity values of the LP, Reheat and HP steam are recorded. Also the turbine speed and the plant load are shown.

50 min after start of the Gas turbine the chemical release for the steam turbine was given. After 2:45 h the cation conductivity in the steam reached the normal operation limit of <0.2 µS/cm. The normal cation conductivity values were reached before the plant reached his maximum load.

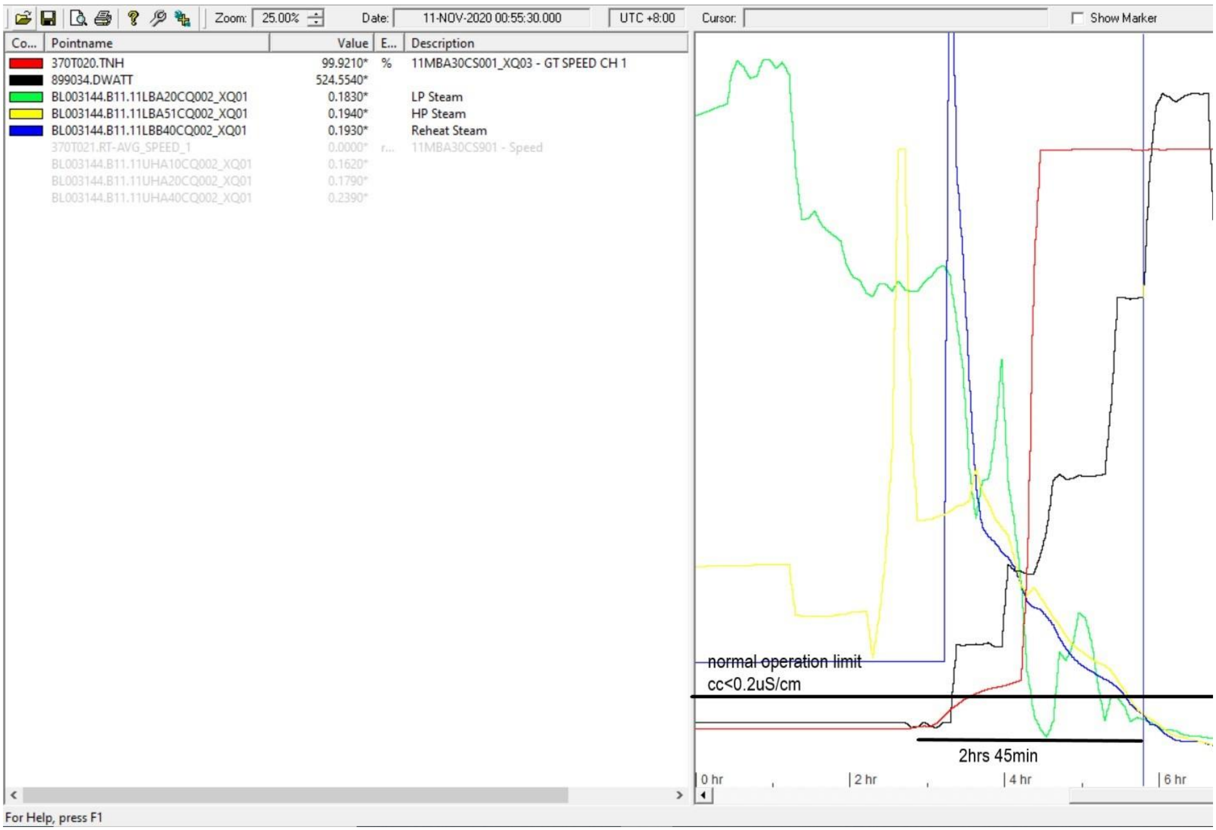


Figure 22: Cation Conductivity Transients during a typical Warm Start Unit 1

4.3.2.7 Cold Start

Figure 23 shows a typical behavior of the cation conductivity steam values during a cold start of Unit 1. The cation conductivity values of the Reheat and HP steam are recorded. Also the turbine speed and the plant load are shown.

70 min after start of the Gas turbine the chemical release for the steam turbine was given. After 3:50 h the cation conductivity in the steam reached the normal operation limit of <0.2 μS/cm. The normal cation conductivity values were reached short after the plant reached his maximum load.

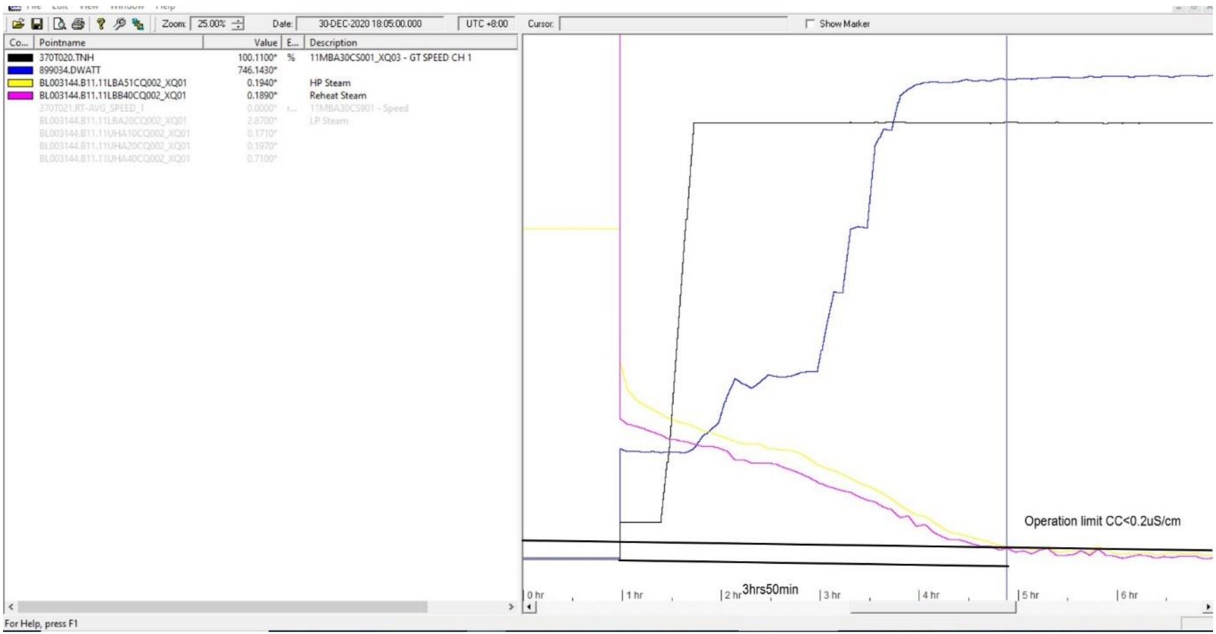


Figure 23: Cation Conductivity Transients during a typical Cold Start Unit 1

All contractual start up times for the steam turbine could be reached. The chemistry values were always reached before the steam turbine process parameters (Temperature, Pressure) were achieved. There was no hold up in the steam turbine start process due to the chemistry.

The times until the normal operation conditions were reached are similar to cycles based on conventional drum-type HRSGs.

4.3.3 Evaluation Water/Steam Chemistry Field Validation

With the results of the field validation the following dynamic of the impurity removal from the water/ steam cycle could be established:

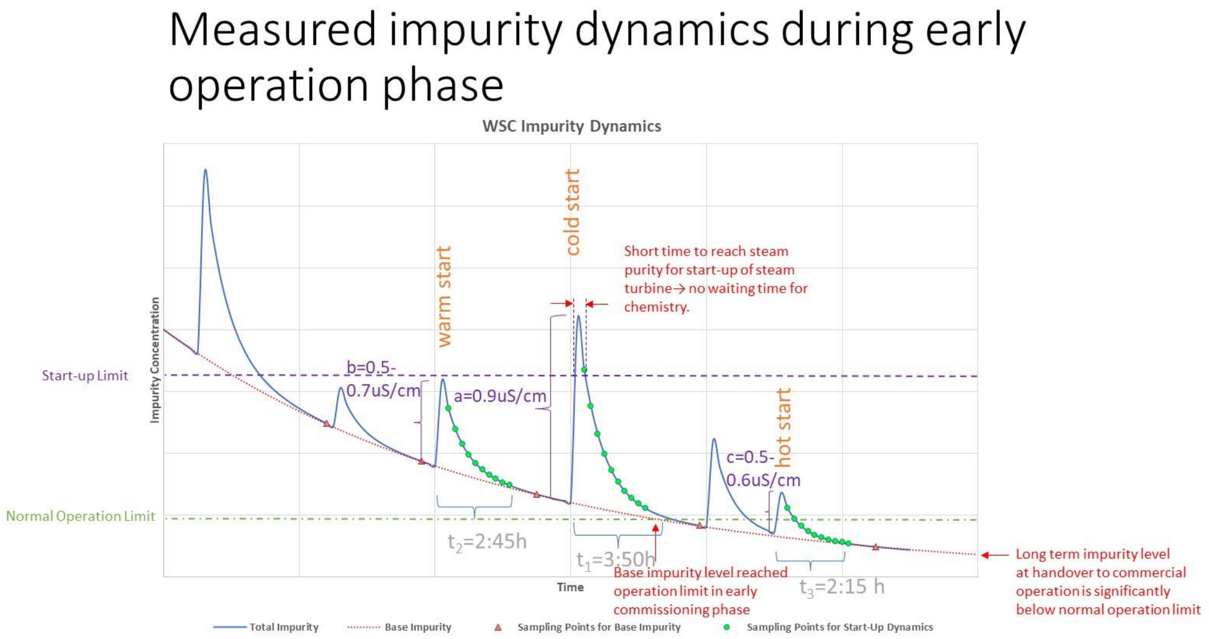


Figure 24: Schematic presentation of the measured impurity dynamics in the water steam cycle.

The impurity limit for normal operation – represented by the green dotted line - has been reached already during early commissioning, proving that the impurity removal from the cycle compensates by far the impurity inflow. For short or medium shut-down periods, corresponding to hot or warm restarts after, respectively, the according ingress of air impurities was normally lower than the steam purity limit for start-up of the steam turbine. During longer shut-downs larger amount of air impurities may ingress, leading to steam impurity levels above the steam turbine start-up limit at the subsequent cold start. However, these impurities could be purged from the system quickly enough without additional waiting time for steam turbine operation release.

Criteria	Description	Success criteria	Status
Control of impurities & cleaning capability	Achieve the required cleanliness) without condensate polisher, but by use of LP and IP blowdown only	Degassed cation conductivity of feedwater and steams below normal operation limit.	Achieved.
Control of impurities & cleaning capability	Steam purity recovery after start-up is fast enough to allow for unrestricted operation.	The steam purity limit for start-up of the steam turbine is reached within the agreed start-up-time of the cycle.	Achieved

Criteria	Description	Success criteria	Status
Refreshing mode (purging impurities by overfeeding the OT sections)	Refreshing efficiency: get step change of > 10% within 2 hours of operation	Measurable step change decrease of impurities in condensate during refreshing mode	Step change observed for silica and also slightly for sodium. Purity recovery within two hours achieved. No step change observed for degassed conductivity since impurity level is already very low
Mapping of chemical impurities	Balance of impurities in the cycle (flow meters in blow down and make up water) - delta to get condenser leakage - how much impurity can be achieved by HP separator, blowdown and (refreshing mode) to validate the water chemistry system	The flows and principal impurities of all streams have been measured and fed into impurity balance calculation. Balance is achieved or sources / depots have been identified and confirmed	Balance has been estimated with site measurement data, However measurement error is large due to low impurity concentration in samples.

Table 13: Final Status of key performance indicators for chemical validation.

5 WP3: Process Dynamics & Controls of OT HRSG in Combined Cycle Plant

5.1 Simulation Environment

For controls and dynamics of the OT HRSG, the development platform used is the APROS software simulation environment. The APROS model is used to model both, the physical behavior of the equipment and the controls software as it will be used at the real plant. By this way, costly iterations on site can be avoided. If the simulation of the physical behavior is realistic, only minor parameter modifications are needed at site for fine-tuning. A significant effort was made to upgrade the APROS process model to be able to replicate the observed behavior in Birr 2 in the simulation and to include a two-dimensional gas path to be able to simulate gas temperature spread. The revised HRSG model contains just over 2200 thermal hydraulic nodes.

APROS is a commercial simulation package by Fortum and VTT (www.apros.fi) used by GE for process simulation.

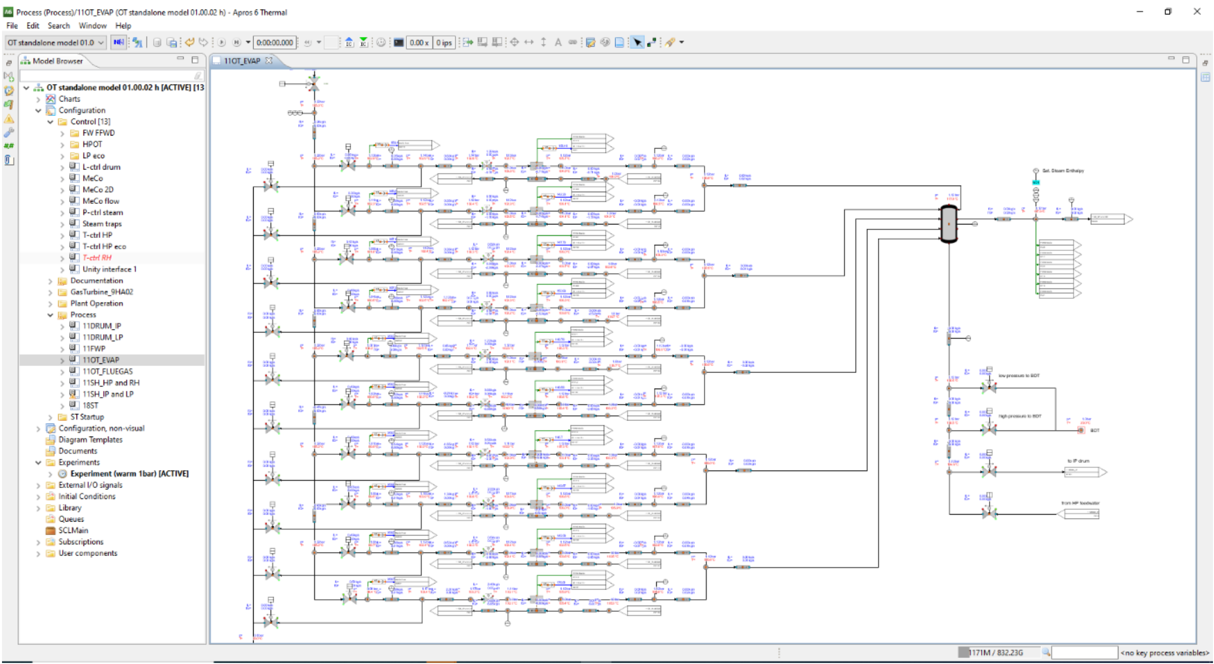


Figure 25: OT evaporator process model in APROS simulation environment.

Refer to Figure 25 representing a screenshot illustrating the APROS environment used, programmed to model the behavior of the 10 sections.

The model developed in this project is based on an expanded version of Birr 2 to include 10 sections [Figure 25]. Modelling and simulation environment. The picture describes the flow network with all the main process elements (e.g. control valves, heat exchangers, pipes, steam/water separator, instrumentation). The main parameters are steam outlet Temperature measured at the OT separator outlet (refer [Figure 26]) and to minimize the spread of the individual sections Temperature (refer [Figure 30]).

5.2 Process and Methodology

The controls system for the GE OT HRSG has been initially developed and tested in a prototype environment Birr 2. This was successful though the test environment was limited in scope with a scaled HRSG with only 3 sections. The generated steam was discharged to the atmosphere.

The control concept applied in this program was implemented for the first time to a commercial CCPP in a so called 1-on-1 configuration: one gas turbine, one OT HRSG and one steam turbine coupled with a single generator. The main advantages of GE's OT HRSG technology are: higher efficiency at part load and off design conditions, capability of high load gradients and enabler for higher up to supercritical operating pressures:

Horizontal Drum vs Horizontal OT HRSG:

GE's OT HRSG technology utilizes a heating surface section that heats water to produce superheated steam without the need for recirculation during normal operation. Steam is produced without the need for a mechanical water steam separation device [Figure 26]. The key consideration is to adequately size the OT section to ensure that steam is completely evaporated at the separator outlet and stability is maintained across the operating range.

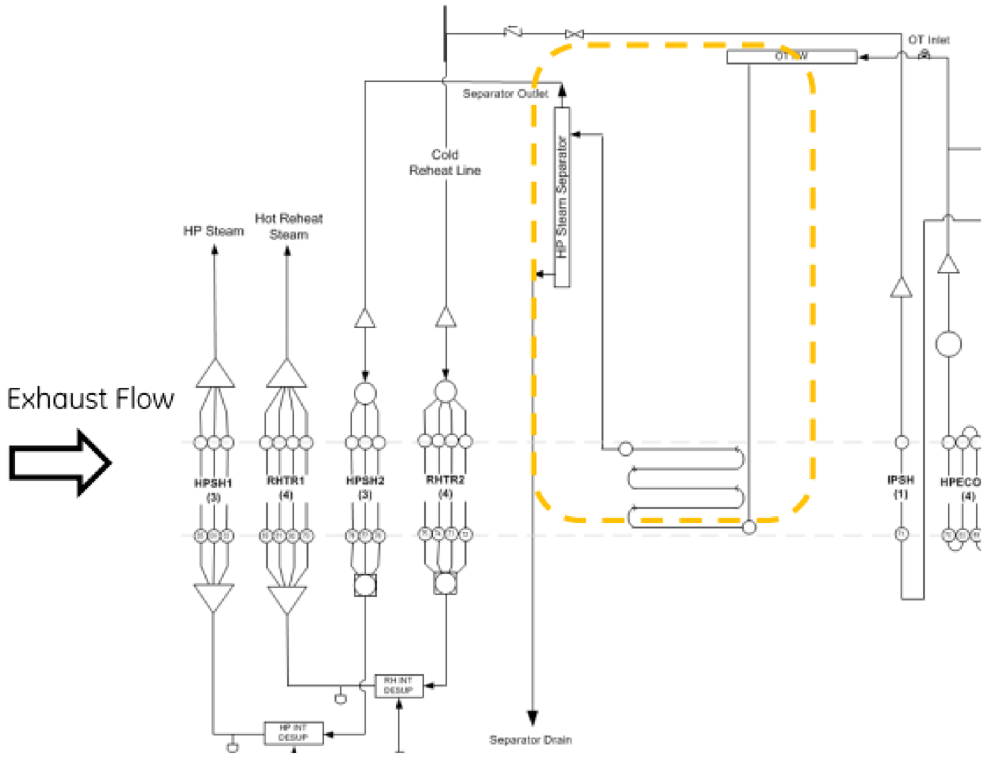


Figure 26: Process Diagram of GE's HP OT Circuit within the HRSG

In contrary, the horizontal drum type HRSG [Figure 27] is comprised of a drum, evaporator and interconnecting piping and configured to ensure a suitable water/steam circulation ratio to produce saturated steam at the drum outlet.

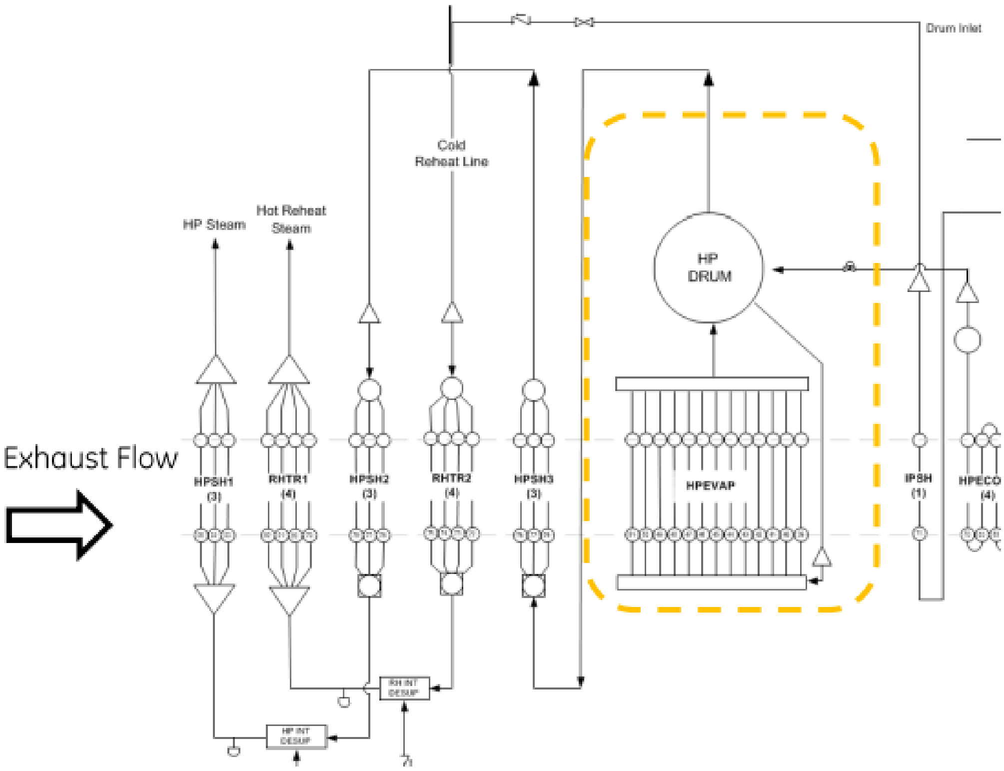


Figure 27: Process Diagram of GE's Horizontal Drum Type HRSG.

The Birr 2 program & test campaign (BfE, SI/501004-01) validated the mechanical design of the GE OT HRSG. The controls used during the test campaign were intentionally very basic.

For the application at a commercial site new control loops had to be developed in this program:

- Feedforward control of OT average outlet temperature (DFFWD): The control loop is programmed such that the OT outlet Temperature is controlled through the mass flow of feedwater at the OT common inlet, see [Figure 30]/(6).

- Steam temperature outlet spread (Section temperature control). Additional section loops to control individual section Temperature (10 loops), see [Figure 30].

- Transient HP steam temperature control. The OT feed water control needed to be integrated into the overall HRSG steam Temperature control to condition the Steam at the inlet of the Steam Turbine.

The Birr 2 test unit results indicated the need for an improved feedforward control of the OT average outlet steam temperature in response to disturbances in flue gas temperature and mass flow caused by GT load changes. In particular, the time constant of the OT steam temperature was different in response to flue gas temperature (B in [Figure 28]), flue gas mass flow (A in [Figure 28]) and feedwater temperature (D in [Figure 28]) changes. Temperature spread and excursions (over/underswing) reduce component lifetime.

In order to predict the response of the OT to these 3 disturbances (A, B, D, in [Figure 28]) a simplified macro heat balance model of the OT evaporator was developed to integrate into the OT controller.

The introduction of a local heat balance model (= dynamic FFWD control = model based control) is required to compensate the 3 disturbances with the feedwater flow (C in [Figure 28]) being the main control parameter.

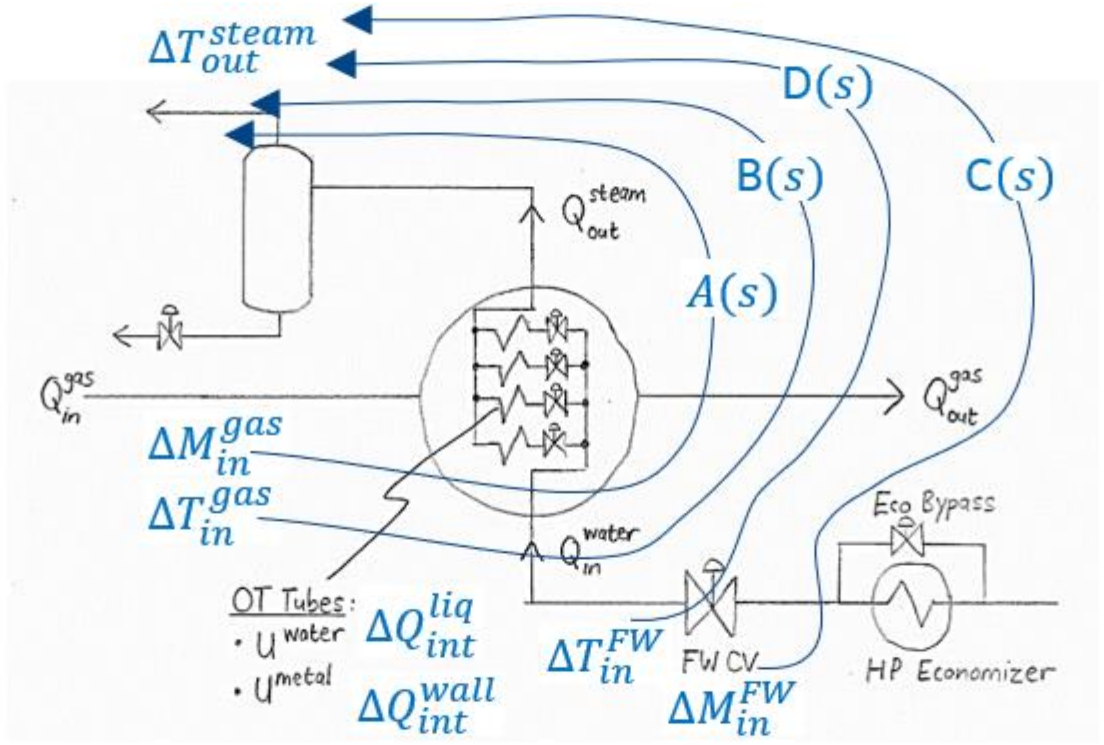


Figure 28: Schematic of OT evaporator heat balance model for Feedforward control.

In the OT evaporator heat balance model, the transient response dynamics of the OT steam temperature to the three main disturbances and feedwater flow was captured by the formulation of the A, B, C and D(s) first order time constants. In the simulation model, standard open loop step tests were performed to identify values of the time constants. Note for clarity: there are 3 disturbances and one main control parameter (feedwater flow).

This establishes a feedforward or model based control method for the OT which is driven by measurements of the disturbances in the simulation and actual plant.

The empirical time constants underlying the predicted OT dynamics are intended to be validated with step tests on the actual plant during pre-commissioning.

The Gas Turbine exhaust gas (hotgas) leaves the Gas Turbine with a certain, load dependent temperature profile. This hotgas temperature spread is further changed by the cross flow of steam (in the HRSG heat exchanger tubing) through super- and reheaters as well as the interstage attemperators. This complex modulation of the hotgas temperature profile (spread) puts additional demand on the OT section temperature controller [Figure 30]. Such a pronounced hotgas temperature spread was not present in the Birr 2 test unit which did not have superheaters, reheaters nor attemperators.

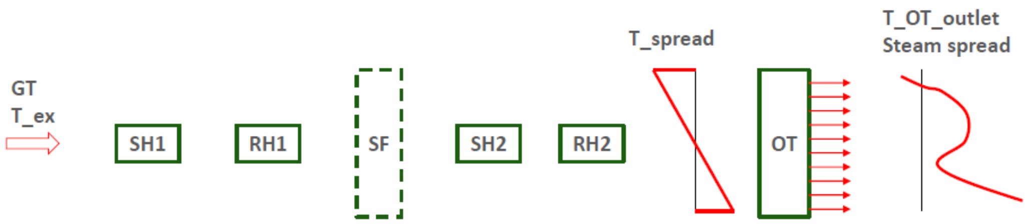


Figure 29: Schematic of HRSG High Pressure section with the OT water-/steam generator (OT). The red profile indicates inlet gas and OT outlet steam temperature distortions. SH = Superheater, RH= Reheater, SF = Supplementary Firing (optional).

For the development of the detailed control software and in preparation of the first site implementation the modeling parameters were adjusted using the transient behavior in the APROS simulation environment.

5.3 Results & Discussion

5.3.1 Simulation Results

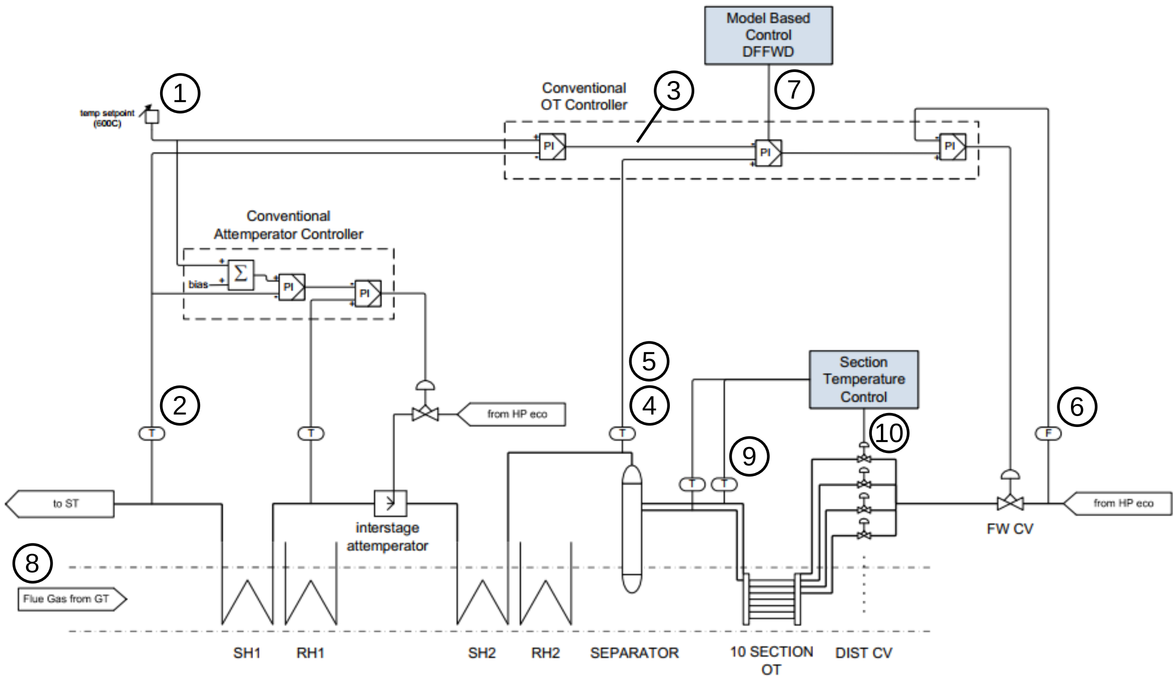


Figure 30: OT controller overview: Newly developed parts in the solid blue boxes, conventional parts in the dotted boxes.

The following items were developed and tested using the improved APROS process model:

1) Model-based control (Dynamic Feedforward, DFFWD) to accurately predict required feedwater flow based on gas temperatures, gas flow and other measurements. This improves both startup and onload temperature control as well as water consumption during startup (EP3495730A1).

2) Improved section temperature control with integrated model-based control (EP3495729B1).

The two newly developed OT control elements were integrated into an improved OT controller. The OT controller was placed in closed loop with the process model developed for the OT HRSG and dynamically simulated in APROS, as discussed in Chapter 5.1.

The objective in this Chapter is to show closed loop stability and dynamic compatibility of the elements by means of a typical plant load cycle test. Note: it is standard practice in Controls development to demonstrate the loop stability by applying a system disturbance and ensuring that all the controls responses are damped & stable.

The simulation results show the HP steam- and OT Separator outlet temperature [Figure 31] and the individual section outlet temperatures [Figure 32] being controlled during a GE 9HA.02 gas turbine load cycle from Base Load to MECL and then back to Base Load.

The OT variables in [Figure 31] and [Figure 32] are described in the list below. Refer to [Figure 30] for the measurement locations in the overall OT controller scheme.

1. T SP AFT SH1: HP Steam temperature setpoint at SH1 outlet
2. T AFT SH1: HP Steam temperature at SH1 outlet
3. T SP AFT SEP: OT Steam temperature setpoint at Separator outlet
4. T AFT SEP: OT Steam temperature at Separator outlet
5. Tsat: OT Saturation temperature at Separator outlet
6. F FW Actual: OT Feedwater flow measured
7. DFFWD: Dynamic Feedforward
8. GT Load: Gas Turbine Load (% of Base load)
9. T Sec01-10 out: OT section outlet temperature (10 Sections)
10. F FW Sec01-10: OT section feedwater flow (10 Sections)

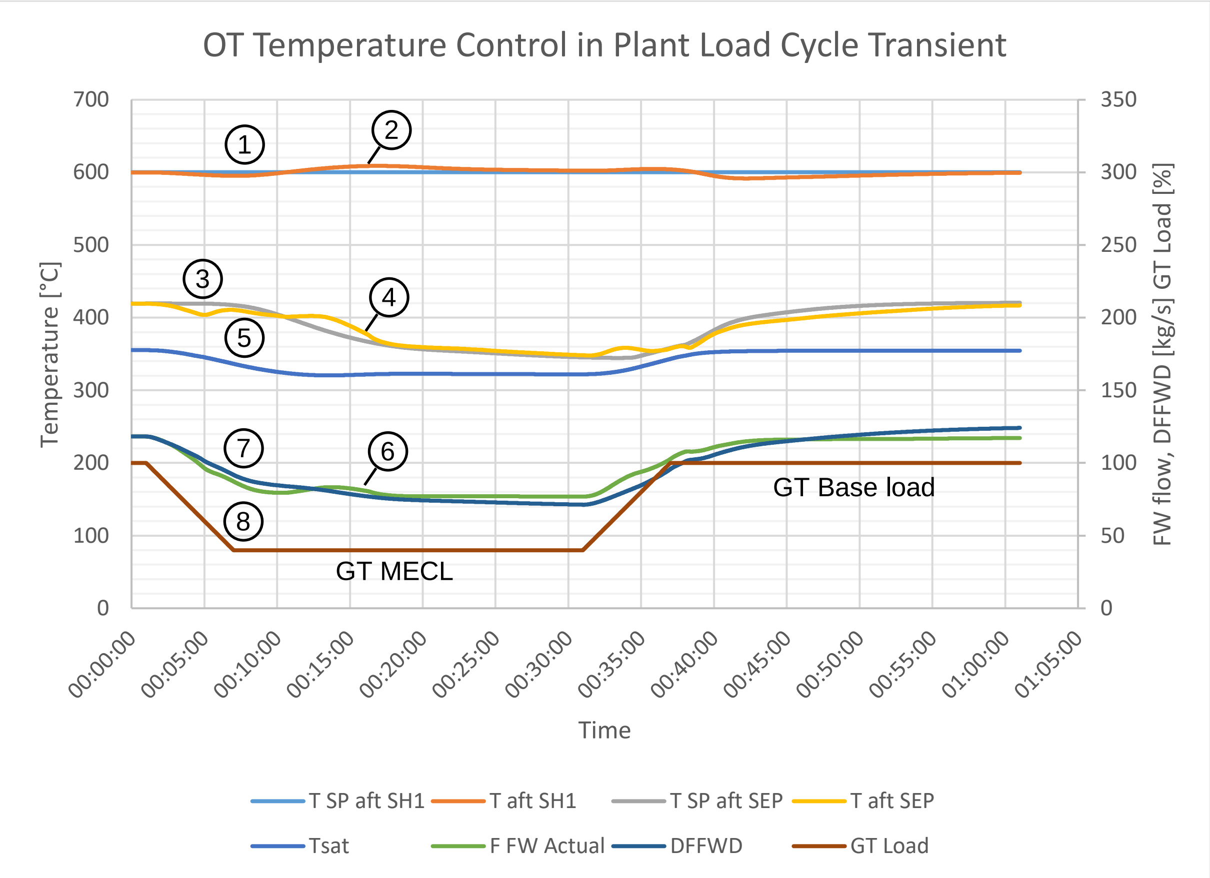


Figure 31: Plant load cycle simulation of improved OT control. Indicating the OT outlet Temperature and HP Steam Temperature response to a GT load change.

It is shown in [Figure 31] that the overall target to get a stable steam Temperature of 600°C at the inlet of the Steam Turbine in response to a GT load change has been achieved, e.g. compare (T aft SH1) (2) with (T SP aft SH1) (1).

In particular, the OT average outlet Temperature (T aft sep) (4) is adequately controlled to follow the set point curve (T SP aft sep) (3). The Controls also ensures that the steam is above the saturation point all the time during the load change, (Tsat) (5) is below (T aft sep) (3).

Please be reminded that all the above is mainly controlled by the OT inlet feedwater flow as shown by the curve (F FW) (6) actual, while the set line prediction is indicated by (DFFWD) (7).

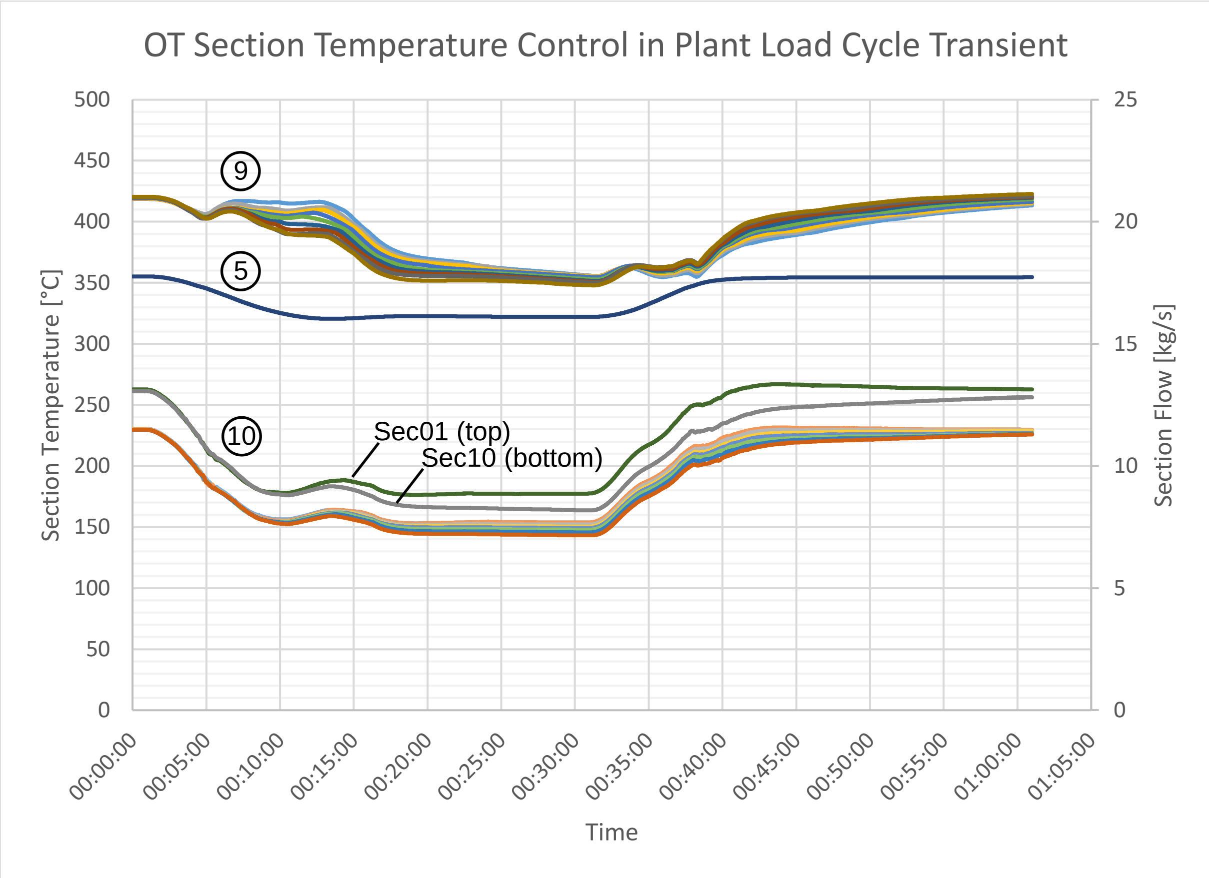


Figure 32: Plant load cycle simulation showing OT section temperatures in response to the GT load change from BL to MECL back to BL. (10 sections).

The Temperatures of the OT sections 1 to 10 (10) are shown in [Figure 32]), together with their respective feedwater flows (9). Note that the feedwater flows are the main control variables as explained above, and so these are controlled to ensure a minimum spread of the OT section Temperatures. Please be reminded that it is part of the section temperature control strategy to adapt the feedwater such that the OT section Temperatures spread is minimized.

The section Temperature spread stabilizes towards a few degrees with an acceptable max. spread of 30°C. Note that by design the top (section 1) & bottom (section 10) are designed with the largest. Feedwater.

In the following Section an overview of the process models used in the CCPP is provided to indicate how the OT process model simulated in APROS integrates with the overall GE CCPP process model simulated in Easy5.

For this project it was decided to integrate the APROS simulation of the OT evaporator model into the CCPP process model simulation in Easy 5 for software testing. This was done to assure consistency with the process work done for the newly developed and conventional controllers shown in Figure 30. This required some effort to solve interface and simulation stability issues. The following software packages were combined to simulate the controls:

- Mark VIe: GE’s Distributed Control System (DCS) used for power plant control (www.ge.com/power/gas/controls/mark-vie).
  Note: Mark VIe is also used to control the Gas Turbine and Steam Turbine

- APROS: simulation package by Fortum and VTT (www.apros.fi) used by GE for process simulation.

- Easy5: simulation package by MSC Software used by GE for process simulation for the purpose of control system software testing (www.mscsoftware.com).

The individual process models (GT, ST, HRSG and Plant) and the overall Mark VIe control system (MKVIe controlled devices) were linked in a unified simulation environment that enabled synchronized co-simulation. [Figure 33] shows the boundaries of the respective process models and the simulation software used to simulate them. The complex dynamics of OT evaporator model was simulated in the rigorous thermodynamic simulation software APROS (pink) and the rest of the CCPP in Easy 5 (yellow). The control actuators driven by the Mark VIe DCS, Mark VIe Gas Turbine- and Mark VIe Steam Turbine control systems are marked in blue and covers the water steam cycle of the plant and the rotating components Gas Turbine and Steam Turbine.

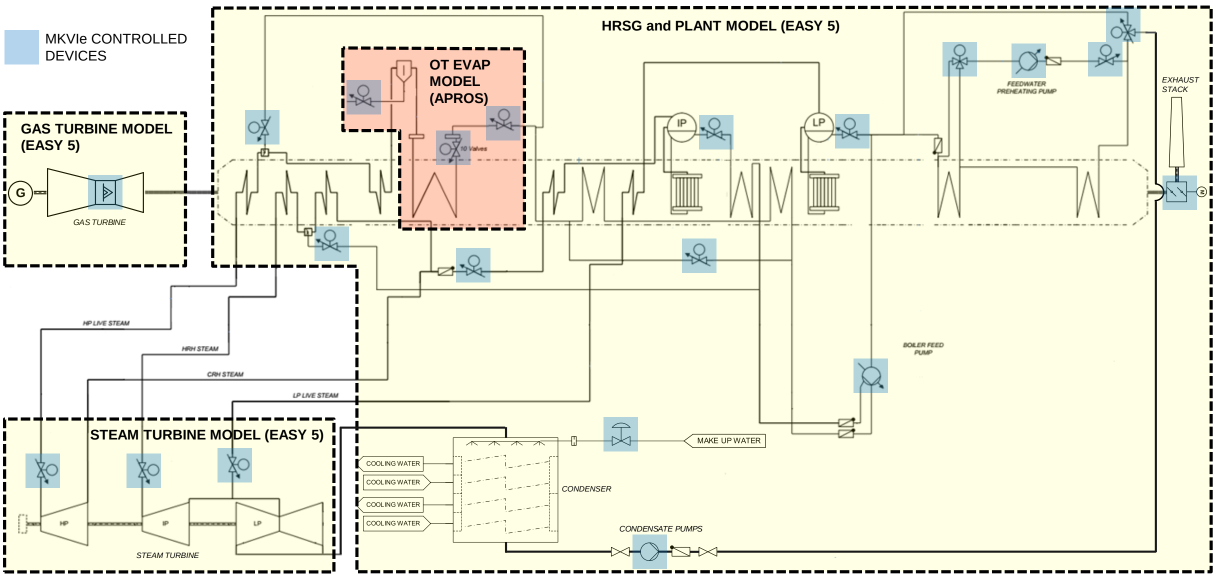


Figure 33: Software test simulator showing process models and simulation software boundaries.

Software coding and extensive testing of the new controllers followed on this software test simulator.

The simulator was also used to test modifications of the software that were found necessary during the commissioning and validation testing of the front-runner plant.

5.3.2 OT Controls Validation in Combined Cycle Plant

1) The list of validation tests, their sequencing and duration as well as the state of the CCPP during the testing has been defined and included in the commissioning test plan of GE’s front-runner unit in South East Asia as per [Table 4].

2) A “Test Readiness” review for the on-site validation has been conducted on May 14, 2019.

3) Plant Control validation - OT open loop response tests.

The validation tests OT-OP-1 to OT-OP-4 [Table 14] form a series of open loop step tests to identify the process dynamics of the OT in response to the disturbance variables and the main control variable, e.g. the OT feedwater flow rate. This data was used to validate the DFFWD empirical time constants to ensure the feedforward control dynamics matched the actual OT dynamics. Note that only the feedwater step tests (OT-OP-3 and OT-OP-4) are discussed in detail below.

A challenge in performing validation of the predicted OT dynamics from the plant response data is the fact that the OT disturbance variables are not independent but coupled through heat exchange between the flue gas and water/steam side. When any of the disturbance variables or main control variable is changed, the heat balance changes, and the OT flue gas temperature changes to reflect the new heat and mass balance equilibrium. The OT flue gas temperature effect must be de-convoluted out of the measured response data to isolate the effect of the stepped variable.

In each response test, a series of step changes were performed on one OT input variable and all other controllable variables kept constant. A case for validation was selected based on the amplitude and speed of change in the cross-coupled variables. In the validation cases the interference effect of cross-coupled disturbance variables were relatively small and could be de-convoluted from the step test response.

Date	**Start**	**End**	**NPI test**	**Description**
20/08/2020	16:50	20:05	OT-OP-1	GT exhaust temperature step test
20/08/2020	20:55	21:40	OT-OP-2	GT exhaust flow step test
20/08/2020	15:20	17:16	OT-OP-3	OT Feedwater temperature step test
20/08/2020	17:25	20:30	OT-OP-4	OT Feedwater flow step test

Table 14: OT open loop response tests conducted for OT dynamics validation.

a) Feedwater flow step test

The OT-OP-4 step test was conducted on 20 August 2020 from 17:25 to 20:30 local Malaysia time [Figure 34].

The first downward feedwater flow step was performed at 17:37 from 410 t/h to 390 t/h. The step size of -20 t/h proved to be aggressive, and the OT steam outlet temperature increased rapidly, causing the OT flue gas inlet temperature (after a lag) to rise because of the heat exchange occurring in the two upstream superheaters (SH1, SH2, Figure 30). In this example the OT flue gas temperature rise was too fast and the interference effect on the OT response too large to be useful.

At 19:47 the feedwater was stepped again with a reduced step size of +8t/h from 399 t/h to 407 t/h. In this case the OT steam outlet temperature showed a clear response and decreased at a moderate rate which kept the coupling with the OT flue gas inlet temperature to a minimum. This case was selected for further analysis.

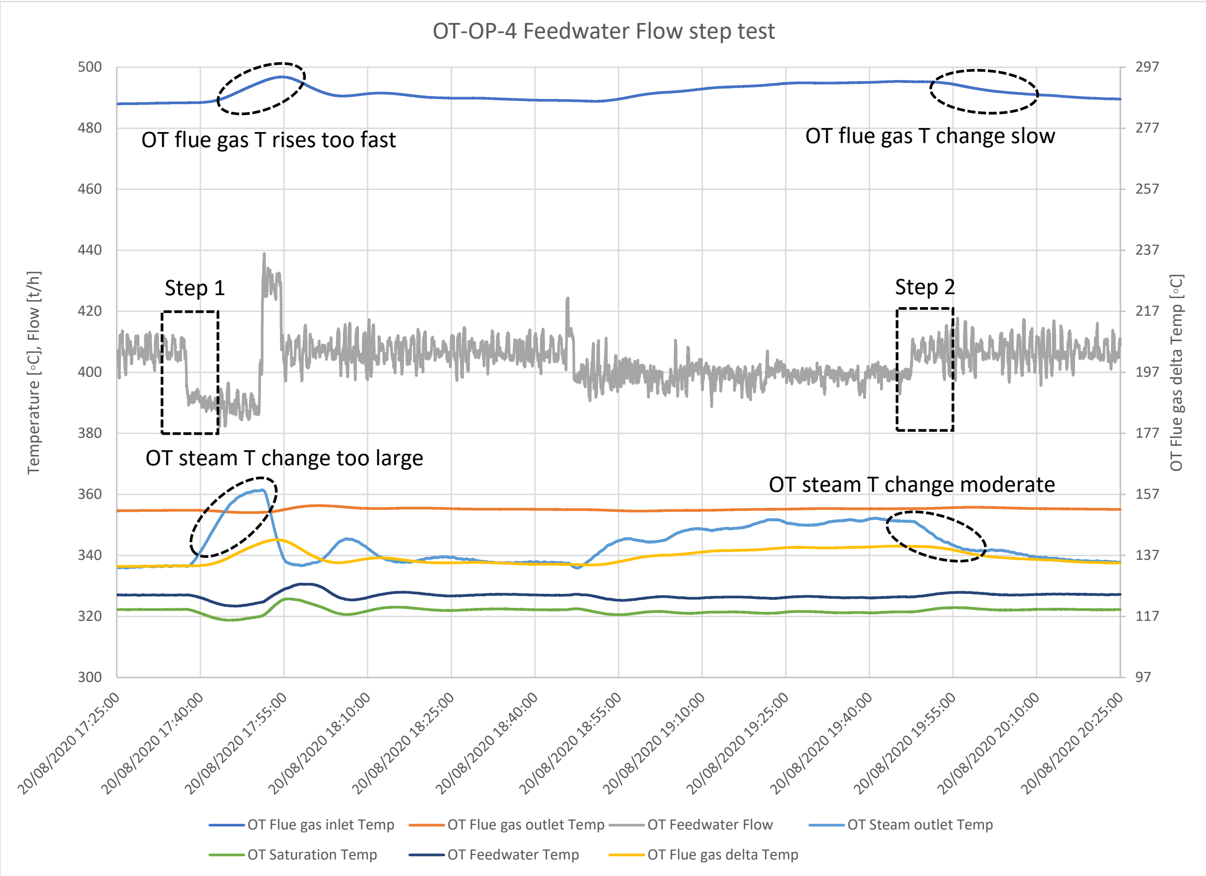


Figure 34: Feedwater flow step test series.

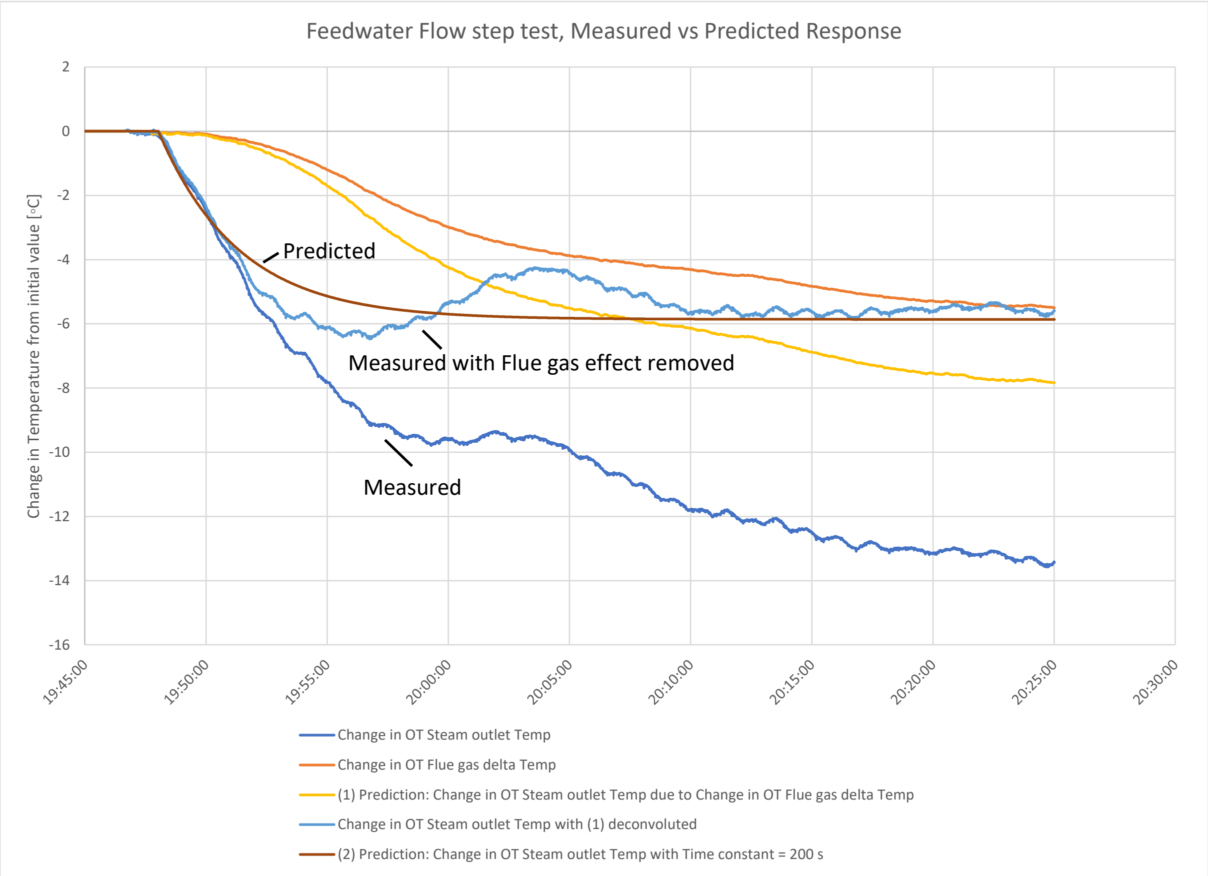


Figure 35: Feedwater flow step test transient response validation.

The response to the step at 19:47 [Figure 35] was analyzed by debiasing (e.g. by removing the absolute initial values to compare relative data) the measured OT steam outlet temperature and OT flue gas temperature. This step simplifies the prediction of linear first order dynamic models. First the effect of the change in OT flue gas temperature on OT steam outlet temperature was predicted according to the DFFWD model. The OT flue gas temperature effect was then removed from the measured OT steam outlet temperature. This result was the target variable against which the DFFWD prediction was compared. The DFFWD prediction with an assumed time constant of 200 s is shown to fit the measured response quite well in terms of both steady state change (-6°C) and first order transient dynamics (same initial slope).

In comparison, APROS simulation predicted an open loop time constant of 195 s for a change in feedwater flowrate to steam outlet temperature measured at the separator outlet.

b) Feedwater temperature step test

The OT-OP-3 step test was conducted on 20 August 2020 from 14:30 to 17:20 local Malaysia time [Figure 36].

A first step was made at 14:34 with the OT Economizer Bypass valve in automatic control. Inadequate tuning of the feedwater flow control in the early stages of commissioning caused a simultaneous decrease in feedwater flow to the OT. After an initial decrease, the OT steam outlet temperature started to rise rapidly at 14:40, making the step unsuited for analysis. A period was allowed for the feedwater flow rate to return to a normal operating range and the OT operation to stabilize. The OT Economizer Bypass valve was then switched to manual control with a fixed position in preparation for the next step test.

At 15:40 step 2 of the OT Economizer Bypass valve position was made from 25% to 100%. This fully opened the Economizer Bypass valve and the OT Feedwater temperature started to decrease immediately, as more feedwater bypassed the preheating occurring in the economizers. In response, the OT steam outlet temperature showed a temporary increase (inverse response) before it started to decrease to a colder final temperature, settling out at about 16:20. The inverse response was also observed in step tests performed on the process model in APROS to estimate the feedwater temperature disturbance time constant. It is due to the initial drop in OT steam flow rate of superheated steam which follows the step down in OT feedwater temperature.

As with the feedwater flow step test, the OT flue gas inlet temperature followed the OT steam outlet temperature after a time lag due to coupling in the front end superheaters of the HRSG. The rate of the OT flue gas temperature change was however slow enough to be suited for further analysis.

To obtain a bi-directional step response (e.g. first open then close), the OT Economizer Bypass valve position was stepped back at 16:22 from 100% to 25% (step 3). The OT Feedwater temperature started to increase immediately, as less feedwater bypassed the preheating occurring in the economizers. In this case the OT steam outlet temperature showed an immediate increase and continued to increase thereafter. The temperature response settled out at ca. 17:30 at a value of 336°C. This value was close to the starting value of the previous step, showing good repeatability.

The reason for the initial increase of the OT steam outlet temperature (in contrast to the inverse response earlier) is the increase in saturation temperature caused by the initial surge in OT steam flow. Since the OT steam outlet temperature started at a low temperature close to saturation temperature, there was no superheat margin to lose and the OT steam outlet temperature tracked the bump in saturation temperature. Note: In the steam phase the OT steam outlet Temperature cannot decrease below the saturation Temperature.

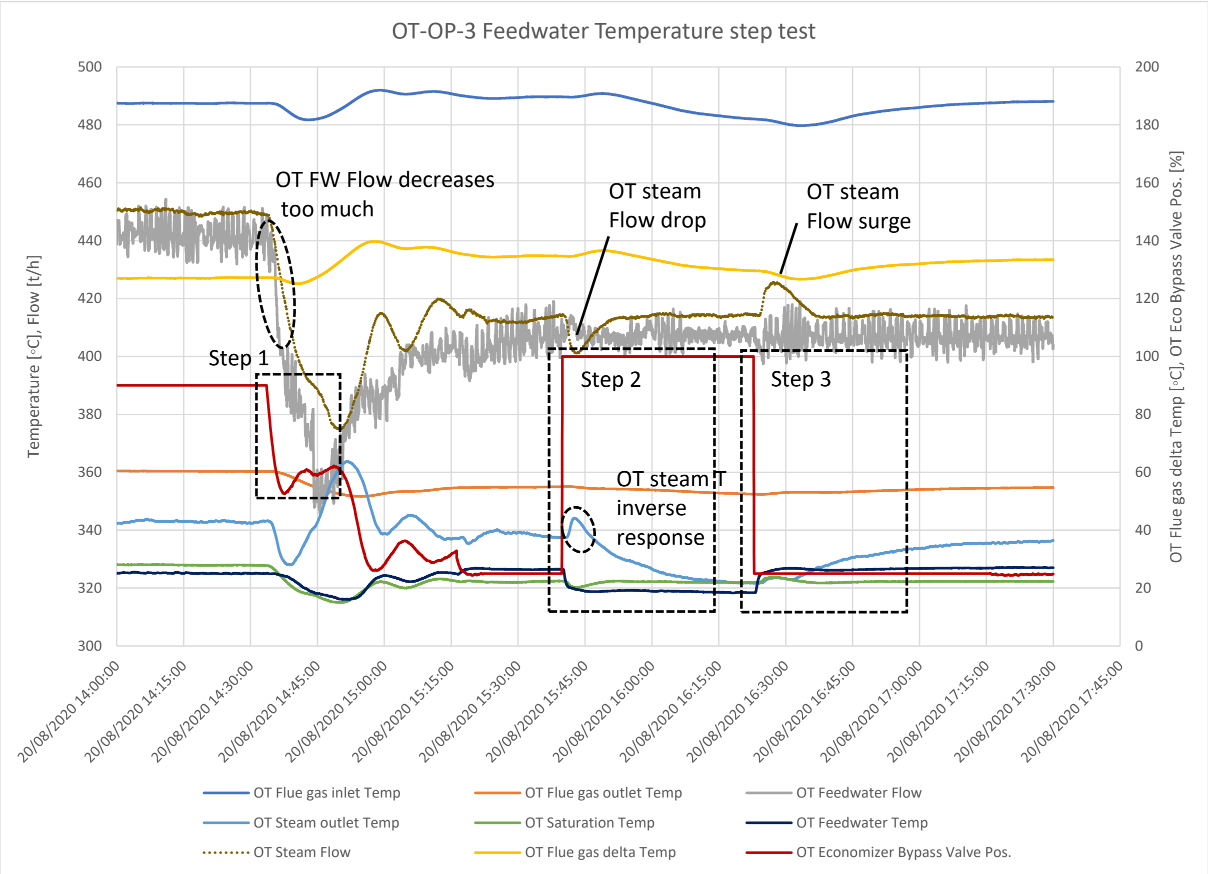


Figure 36: Feedwater temperature step test series.

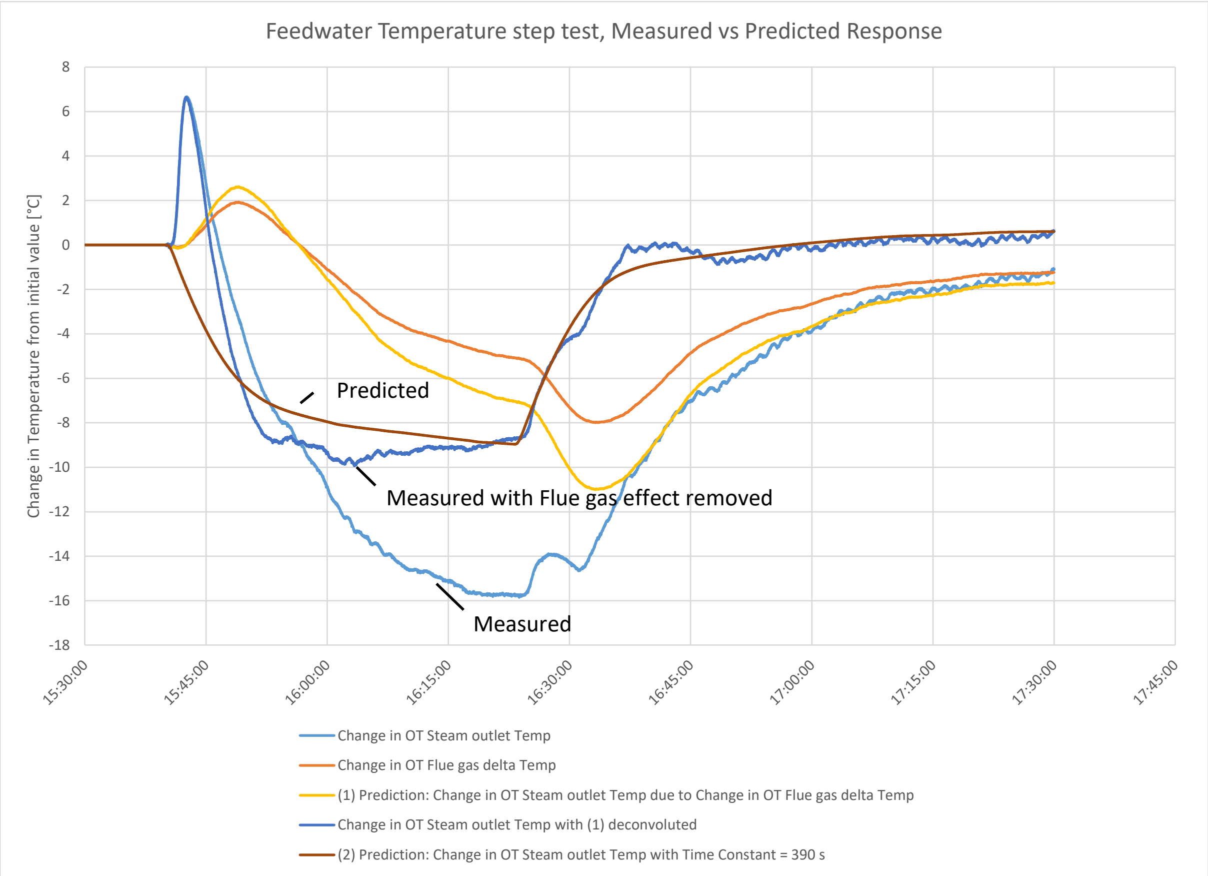


Figure 37: Feedwater temperature step test transient response validation.

The response to the feedwater temperature steps at 15:40 and 16:22 [Figure 36] was analyzed by debiasing the measured OT steam outlet temperature and OT flue gas temperature. First the effect of the change in OT flue gas temperature on OT steam outlet temperature was predicted according to the DFFWD model. The OT flue gas temperature effect was then removed from the measured OT steam outlet temperature. This result was the target variable against which the DFFWD prediction was compared, [Figure 37].

Since the DFFWD prediction is a simplified first order dynamic model, there is no dynamics to capture the inverse response as observed in step 2. In fact, inverse responses cannot be cancelled by inverting dynamics due to resulting controller stability issues and is typically ignored.

The DFFWD prediction with an assumed time constant of 390s is shown to fit the measured step responses quite well in terms of dominant time constant and steady state change. Refer to the time ranges 15:50 to 16:24 and 16:24 to 17:30 for similar dominant time constant behavior. Steady state changes are matched at 16:22 and 17:35 [Figure 37].

In comparison, the APROS simulation predicted an open loop time constant of 370s for a change in feedwater temperature to steam outlet temperature measured at separator outlet. A gap of less than 5% is excellent in these types of dynamic validation.

Plant data for the step tests was collected via OPC server from the GE Mark Vie DCS and recorded and archived in the GE Testman data historian (database) for future analysis. The Testman central server was updated once a day with an upload from the local data server in Malaysia.

5.4 OT Controls Validation Conclusions

Successful commissioning of the 1st commercial unit with GE's evolved OT HRSG technology and control concept developed in Switzerland as follow-up of the Birr 2 is a success: The startup performance and load changes are matching the acceptance criteria [Table 15]. The key performance criteria such as the steam temperature spread, the overshoot amplitude and the time for stabilization are well within design limits and confirmed the simulated behaviors.

Operating Condition	**Criteria**		**Status 2020-12-21**
HRSG OT operation, load changes ramps up, MECL to baseload	dry operation		ok
	SH1 steam temperature	overshoot	ok
	SH1 steam temperature	time to stability	ok
	OT section temperature	spread	ok
	OT section temperature	time to stability	ok
HRSG OT operation, load changes ramps down, baseload to MECL	dry operation		ok
	SH1 steam temperature	overshoot	ok
	SH1 steam temperature	time to stability	ok
	OT section temperature	spread	ok
	OT section temperature	time to stability	ok
HRSG OT cleaning	cleaning controls	flow spread	ok

Table 15: Acceptance criteria load changes and OT cleaning.

6 Conclusions

In **Work Package 1** a test facility for thermal cycling of DMW has been established. An experimental program to investigate the influence of different parameters on thermal cycling endurance was defined. Evaluation of the results showed that the main factors affecting thermal cycle endurance were weld bevel angle and the use of a transition piece. From the test results, the best candidates for the materials pairings in the OT HRSG configuration have been identified for the applications in supercritical conditions with thermal cycling loads. Extended lifetime cycles have been achieved when using the appropriate materials combination and weld geometry parameters. This key enabler for increasing CCPP efficiency through steam temperature & pressure levels above supercritical conditions has been successfully tested.

The DMW validated under this program have been implemented in an HRSG in Asia after conclusion of this program [Figure 38].

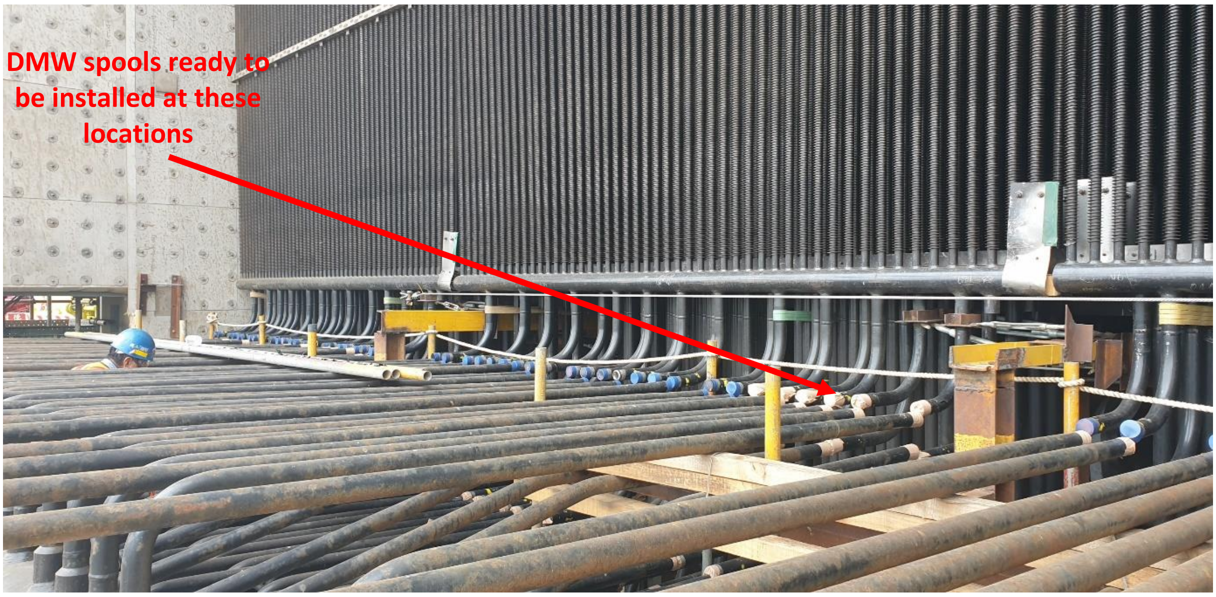


Figure 38: Photograph of an HRSG under construction in Asia where the DMW technology validated under this program is implemented.

In **Work Package 2** the influence of the water chemistry on the oxidation behavior of the boiler material has been evaluated for subcritical and supercritical operation conditions. It has been found that the water and steam purity levels and chemical operating schemes that have been defined for subcritical conditions are compatible with the necessary low oxidation rates. In addition, impurity levels above normal operation limits did not affect significantly the oxidation rates of the tested samples. The tests indicate that the water-/steam chemistry concept as defined for subcritical applications can be transferred for supercritical conditions. Another key enabler for cost effective CCPP cycling operation has been specified & quantified.

In **Work Package 3** the OT HRSG control concept has been completed and documented. Software testing and implementation has been conducted. The proposed feed-forward controls principle has been proven as robust and stable for controlling the steam temperature and the temperature spread at the OT HRSG evaporator outlet under different load transients as well as various load conditions. The advanced controls concept for OT HRSG which is required for supercritical operation has been successfully applied in a field unit.

Validation **Work Package 4**: Successful commissioning of the 1st commercial unit with GE’s evolved OT HRSG technology and control concept developed in Switzerland as follow-up of the Birr 2 is a success: The startup performance and load changes are matching the acceptance criteria. The key performance criteria such as the steam temperature spread, the overshoot amplitude and the time for stabilization are well within design limits and confirmed the simulated behaviors.

The chemical validation of the water-/steam cycle has proven that the necessary steady state feedwater purity for operation of GE’s OT HRSG can be achieved by alternative means without a condensate treatment unit. The dynamic test did also show that the impurity removal capacity of the cycle is sufficient to recover timely from a limited and controlled impurity ingress. The cleaning capabilities of the water-/steam cycle without condensate treatment have been fulfilled to ensure the startup times as expected in a state-of-the-art CCPP. During the validation, not all chemical systems of the plant have been operative yet. Also, the chemical analyses for the dirt balances are still in ongoing. Hence, the water-/steam cycle chemistry “cleaning” is promising but validation is still ongoing.

7 Outlook and Future Implementation

The technologies developed and applied in this program form the new standard applied in CCPPs with GE OT HRSGs; to date the developments are applied in at least five CCPP projects. In particular, the OT HRSG technology is well suited to be deployed in a changing electricity generation mix with high penetration of renewable electricity production with low predictability: the GE CCPP with OT HRSG has demonstrated the capability of producing fast power and complies to frequent load changes with high gradients and cutting edge CCPP efficiency. The OT HRSG technology program and this validation program, which were each co-sponsored by the BfE, have enabled GE Power to increase steam operating pressures and temperatures in the CCPP, resulting in plant efficiencies greater than 64% at base load operation. Improvement will be worked upon in these CCPP units with respect to further reducing water consumption and standardization of the controls system.

The technologies developed and validated with the support of this program allow already today to build CCPP with improved dynamic behavior without increasing plant cost for the owner. This is important in an environment with an increasing contribution of less reliable renewable energy sources such as solar or wind.

With the DMW technology an important enabler for even higher plant efficiencies was validated. In order to achieve the targeted step change in plant efficiency, a move to a supercritical steam conditions is needed. However, the increase of the steam pressure to a supercritical bottoming cycle will require the extensive development of new designs for the steam turbines for highly cyclic operation. It is important to note that the GE OT HRSG technology already demonstrated the operation at supercritical pressures at the Birr 2 Test Stand as part of the BfE OT HRSG technology program.

Through this BfE Validation program dissimilar metal welds (DMW) for steam temperatures at and above 600 °C have been tested under real thermal cyclic conditions and the optimal geometry, location and materials have been established. This effectively replaces multiyear field validation. All of this work and its inherent learnings will form the basis of GE Power future development programs to increase steam temperatures to 650 ˚C.

With the successful completion of this program GE is ready to support the current customer demands towards highest efficiency cycles. However, GE observes that the market focus for CCPPs is changing towards increased flexible operation and decarbonization, for example with carbon capture and H2-based fuels. The OT HRSG technology inherently leads to improved HRSG fatigue life due to rapid steam supply to the HP superheater enabling a more flexible operation of the CCPP. In addition, superior off design and part load performance results in higher CCPP efficiency since the OT varies feedwater flow minimizing the desuperheater spray flow. Both of these features lead to greater operational flexibility and better grid support.

8 National & International Cooperation

The forced ventilation, sanitary, heating & cooling systems infrastructure work for the installation of the autoclaves and fluidized beds in Birr are performed by Bayer Gebäudetechnik in Hausen /AG.

The cooling chambers and other equipment needed to operate the fluidized bed are acquired from Aerotech GmbH / Switzerland.

The controller for the lifting equipment & the Temperature thermocouple measurement of the fluidized bed for the DMW testing is acquired from Siemens Schweiz AG. The lifting concept was developed by GE Switzerland as well as the programming & implementation of the controller.

CE-conformity review & documentation produced by BDS Safety Management AG in Baden.

The electrical fitting to the autoclaves is performed by Eglin Elektro AG / Baden.

The registration of the autoclaves as pressure vessels is done with a collaboration to Swiss TS and SVTI (Swiss Association for Technical Inspections).

The engineering & manufacturing of the autoclaves holders as well as the test samples production is done by GE Prototype Design and Realization Laboratory in Birr.

The facility management for the Birr site is done by Engie Services AG /Schweiz.

New DMW with transition piece ("3 material") test samples design, development and manufacturing done in GE / Birr / Switzerland.

For the WP1/DMW the Baden/Birr cooperation extends to the GE material Lab in Rugby to get expert support for the set up of the test program. The specimen for testing (e.g. geometry of DMW) are based on actual HRSG designs developed in our Windsor/US facility.

The fluidized bed test system is acquired from Schwing Fluid Technik GmbH / Germany.

The compressor to operate the fluidized bed is acquired from Blitzrotary GmbH / Germany.

As mentioned above the autoclaves used for the water-/steam chemistry corrosion testing are transferred from GE Mannheim to our new chemistry Lab in Birr/Switzerland.

The autoclaves recertification is done in collaboration with SVTI and support from Parr Instrument Company/(USA & Germany) and Equilabo/France (Parr Europe representative).

The clamp-on flow meters are procured from Flexim / France.

A joint process Dynamics & Controls development team in Baden, Schenectady/US and South East Asia has been setup for aligning the validation development scope to the front runner units requirements.

The validation teams include GE Baden/Switzerland, Belfort/France, Schenectady & Windsor/USA as well as GE South East Asia.

9 Communication

GE Announces First Commercial Operation of GE's 9HA.02 Technology Globally at Southern Power Generation's Track 4A Power Plant in Malaysia | GE News

The story behind Track 4A and GE's FIRST 9HA.02 │ GE Power - YouTube

10 Publications

Commercialization and fleet experiences of the 7/9HA gas turbine. ASME Turbo-expo 2019, GT2019-91594.

GE Debuts Giant 9HA.02 Gas Turbines at 1.4-GW Plant in Malaysia. Sonal Patel, POWER magazine, February 2021.

Technology Triumph: Track 4A Is POWER's Plant of the Year. Sonal Patel, POWER magazine, July 2021.

GE & EDF unveil a game-changer at Bouchain: https://www.ge.com/gas-power/resources/articles/2016/power-plant-efficiency-record

GE Patent Application Publication EP3495730A1 *Once-through evaporator systems*. Pending.

GE Patent Publication EP3495729B1 *Once-through evaporator systems.* Granted.

GE Patent Publication US11199113B2 *Combined cycle power plant and method for operating the combined cycle power plant.* Granted.

Betriebsbewilligung Wasseranalytiklabor Gebäude 188N / Birr, Mai 8, 2018, Amt für Wirtschaft und Arbeit, Dpt Volkwirtschft und Inneres, Aarau/AG.