Liite I

Maija Vidqvist, Teollisuuden Vesi Oy- esitys:
TOC-kattilavesikierrossa, case: Kotka Laminating Papers

Teollisuuden Vesi

SKYREC TOCkattilavesikierrossa

Case: Kotka/Laminating Papers

Maija Vidqvist

Teollisuuden Vesi Oy

Taustaa

- Ilman esilämmittimien vauriot
- Mittaukset Pietarsaaressa (Andritz/Teollisuuden Vesi)
- Onko vedessä jotain sellaista, mitä siellä ei pitäisi?
- Lieriön paine ja lämpötila
- -> SKYREC-mittaukset Kotkassa; hyvä lisävesi, ei orgaanisia kemikaaleja

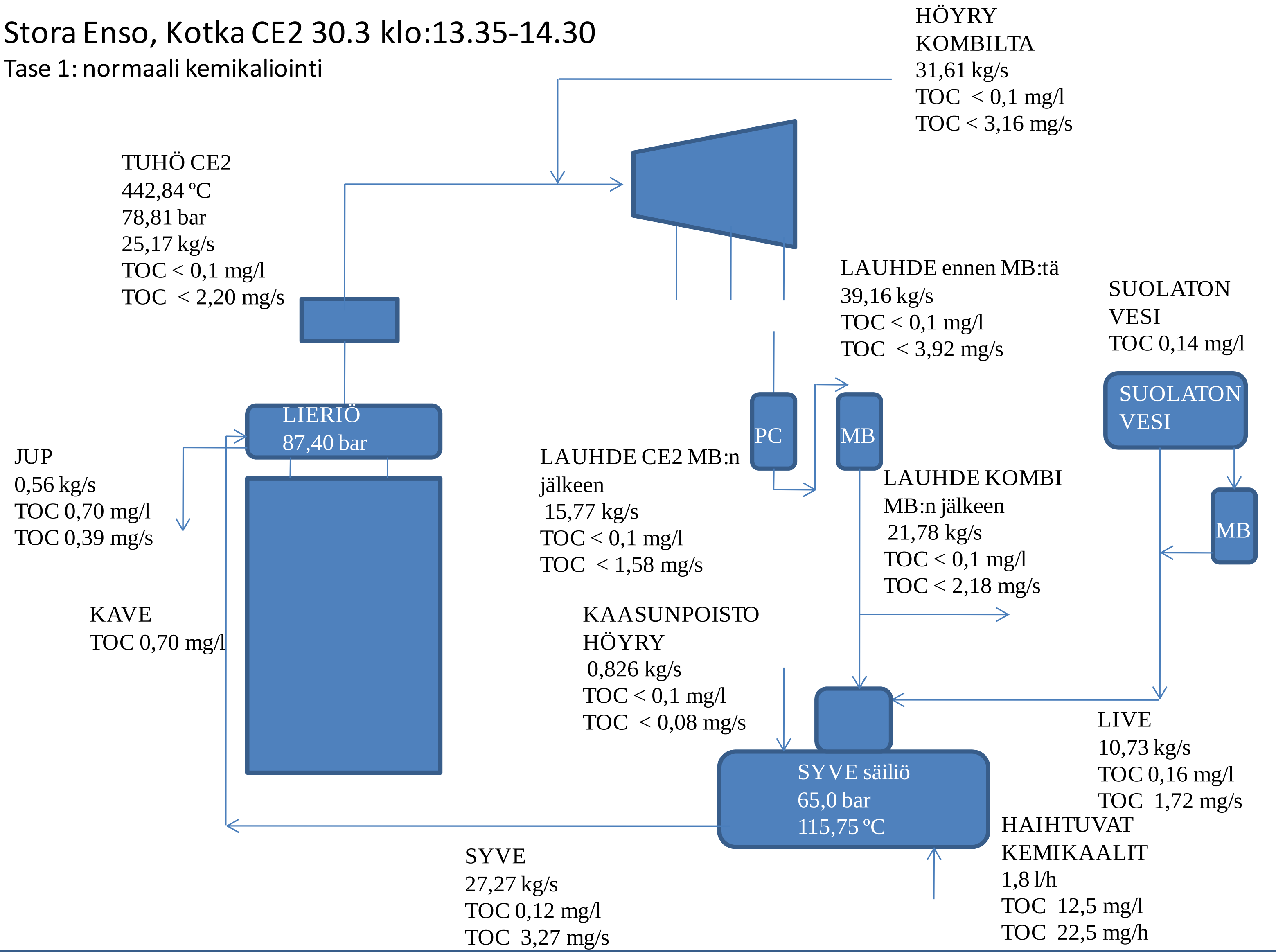
TOC vesihöyrykierrossa

- Lisävesi
- Kemikaalit
- Lauhde
- Vedenkäsittely (hartsit + lauhteenpuhdistus/precoat-massat)
- Tavoite:
  - kationivaihdettu johtokyky < 0,2 µS/cm

Teollisuuden Vesi

Stora Enso, Kotka CE2 30.3 klo:13.35-14.30

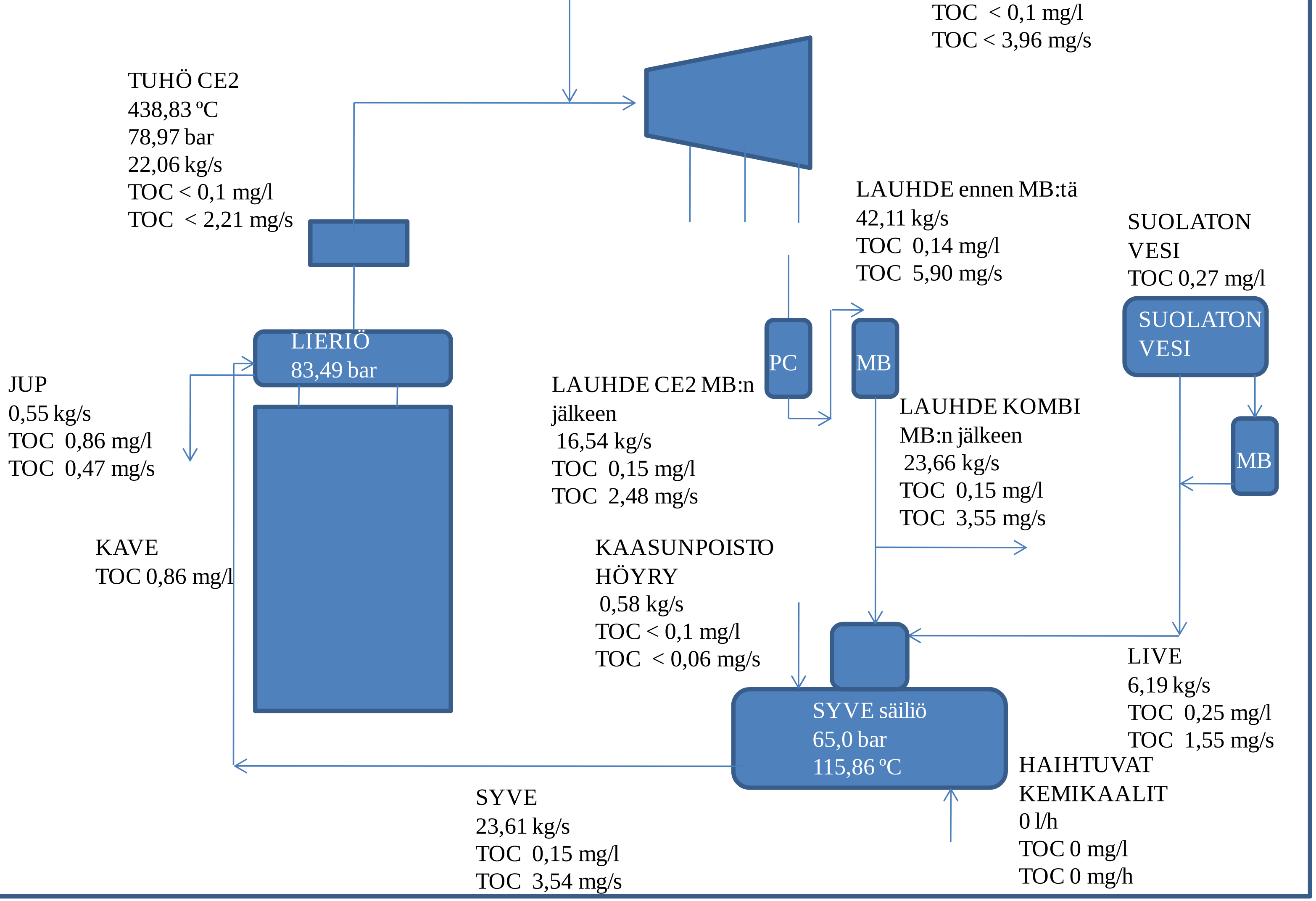
Tase 1: normaali kemikaliointi



Teollisuuden Vesi

Stora Enso, Kotka CE2 31.3 klo:11.00-13.30

Tase 2: ilman haihtuvia alkaleja



Teollisuuden Vesi

Näyte	TUHÖ CE2	Kokonaislauhde	Lauhde MB:n jälkeen	CE2 Syve	Live MB:n jälkeen	Suolaton vesi
Näytteenottoaika	30.3.2009 13:35	30.3.2009 14:30	30.3.2009 14:30	30.3.2009 13:35	30.3.2009 14:30	30.3.2009 13:35
F (µg/L)	< 0,4	< 0,4	< 0,4	< 0,4	< 0,4	< 0,4
Asetaatti (µg/L)	15,6	6,8	0,5	1,1	0,6	0,6
Formiaatti (µg/L)	< 0,4	3,2	< 0,4	0,7	0,4	0,4
Cl (µg/L)	0,4	2,9	0,3	0,6	0,4	0,4
NO_2 (µg/L)	< 0,4	< 0,4	< 0,4	0,6	0,3	0,3
NO_3 (µg/L)	< 0,4	0,4	0,5	0,3	0,3	< 0,4
SO_4 (µg/L)	2,2	4,2	0,8	< 0,4	< 0,4	< 0,4
HPO_4 (µg/L)	< 0,4	< 0,4	< 0,4	< 0,4	< 0,4	< 0,4
Oksalaatti (µg/L)	0,8	0,3	< 0,4	< 0,4	< 0,4	< 0,4
CO_2 (µg/L) *	< 10,0	20,0	< 10,0	< 10,0	< 10,0	< 10,0

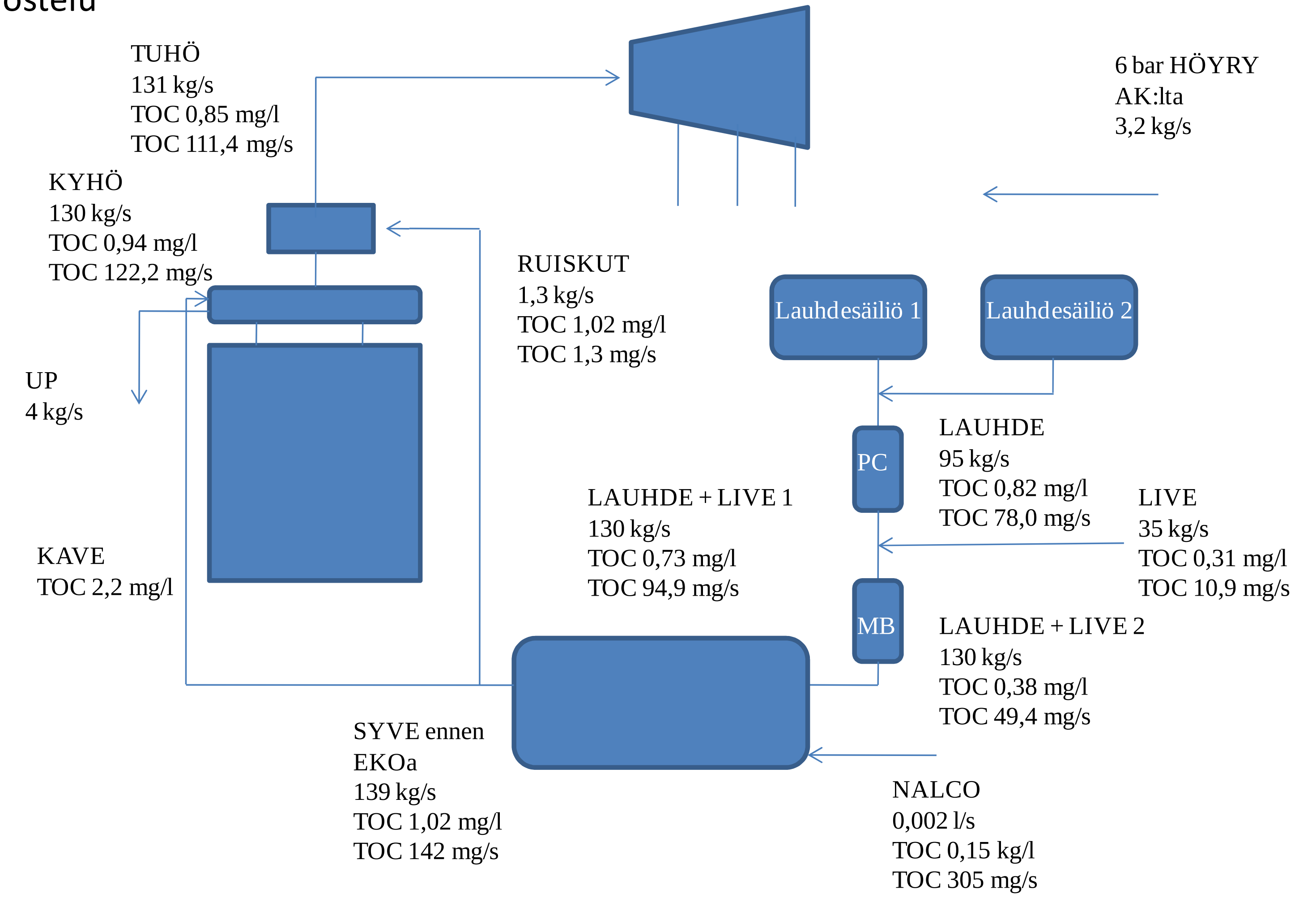
Näyte	TUHÖ CE2	Kokonaislauhde	Lauhde MB:n jälkeen	CE2 Syve	Live MB:n jälkeen	Suolaton vesi
Näytteenottoaika	30.3.2009 13:35	30.3.2009 14:30	30.3.2009 14:30	30.3.2009 13:35	30.3.2009 14:30	30.3.2009 13:35
kationivaihdettu johtokyky	0,24	0,31	-	0,07	-	-
suora johtokyky	**-**	**4,01**	**0,07**	**-**	**0,06**	**0,73**

Näyte	TUHÖ CE2	Kokonaislauhde	Lauhde MB:n jälkeen	CE2 Syve	Live MB:n jälkeen	Suolaton vesi
Näytteenottoaika	31.3.2009	31.3.2009	31.3.2009	31.3.2009	31.3.2009	31.3.2009
	9:40	13:30	13:30	9:40	13:30	9:40
F (µg/L)	< 0,4	< 0,4	< 0,4	< 0,4	< 0,4	< 0,4
Asetaatti (µg/L)	16,4	0,7	0,5	1,3	0,6	0,5
Formiaatti (µg/L)	< 0,4	0,6	0,4	0,6	0,4	0,4
Cl (µg/L)	0,8	8,6	< 0,4	0,4	0,4	0,4
NO_2 (µg/L)	< 0,4	< 0,4	< 0,4	< 0,4	< 0,4	< 0,4
NO_3 (µg/L)	0,3	0,6	< 0,4	< 0,4	< 0,4	0,3
SO_4 (µg/L)	5,1	6,8	< 0,4	< 0,4	< 0,4	< 0,4
HPO_4 (µg/L)	< 0,4	< 0,4	< 0,4	< 0,4	< 0,4	< 0,4
Oksalaatti (µg/L)	< 0,4	1,4	< 0,4	< 0,4	< 0,4	< 0,4
CO_2 (µg/L) *	< 10,0	< 10,0	< 10,0	< 10,0	< 10,0	< 10,0

Näyte	TUHÖ CE2	Kokonaislauhde	Lauhde MB:n jälkeen	CE2 Syve	Live MB:n jälkeen	Suolaton vesi
Näytteenottoaika	31.3.2009	31.3.2009	31.3.2009	31.3.2009	31.3.2009	31.3.2009
	9:40	13:30	13:30	9:40	13:30	9:40
kationivaihdettu johtokyky	0,20	0,22	-	0,07	-	-
suora johtokyky	**-**	**0,64**	**0,07**	**-**	**0,06**	**1,05**

Teollisuuden Vesi

15.10 klo:14:10
Nalco 68248 norm.
annostelu



Anionit/Pietarsaari

	Fluoridi	Asetaatti	Formiaatti	Kloridi	Nitraatti	Sulfaatti	Oksalaatti
1. TUHÖ T6 14.1.09 12.15	<0,5	35.8	3.1	1.5	<0,5	1.0	1.3
2. TUHÖ T6 14.1.09 15.00	<0,5	39.4	3.2	0.8	<0,5	0.8	0.9
3. TUHÖ T6 15.1.09 9.30	<0,5	36.9	2.8	5.2	<0,5	2.0	0.9
4. LAUHDE PRECOAT JÄLK. 15.1.09 9.30	1.0	39.9	1.2	3.8	<0,5	29.0	1.1

TOC lisävedessä

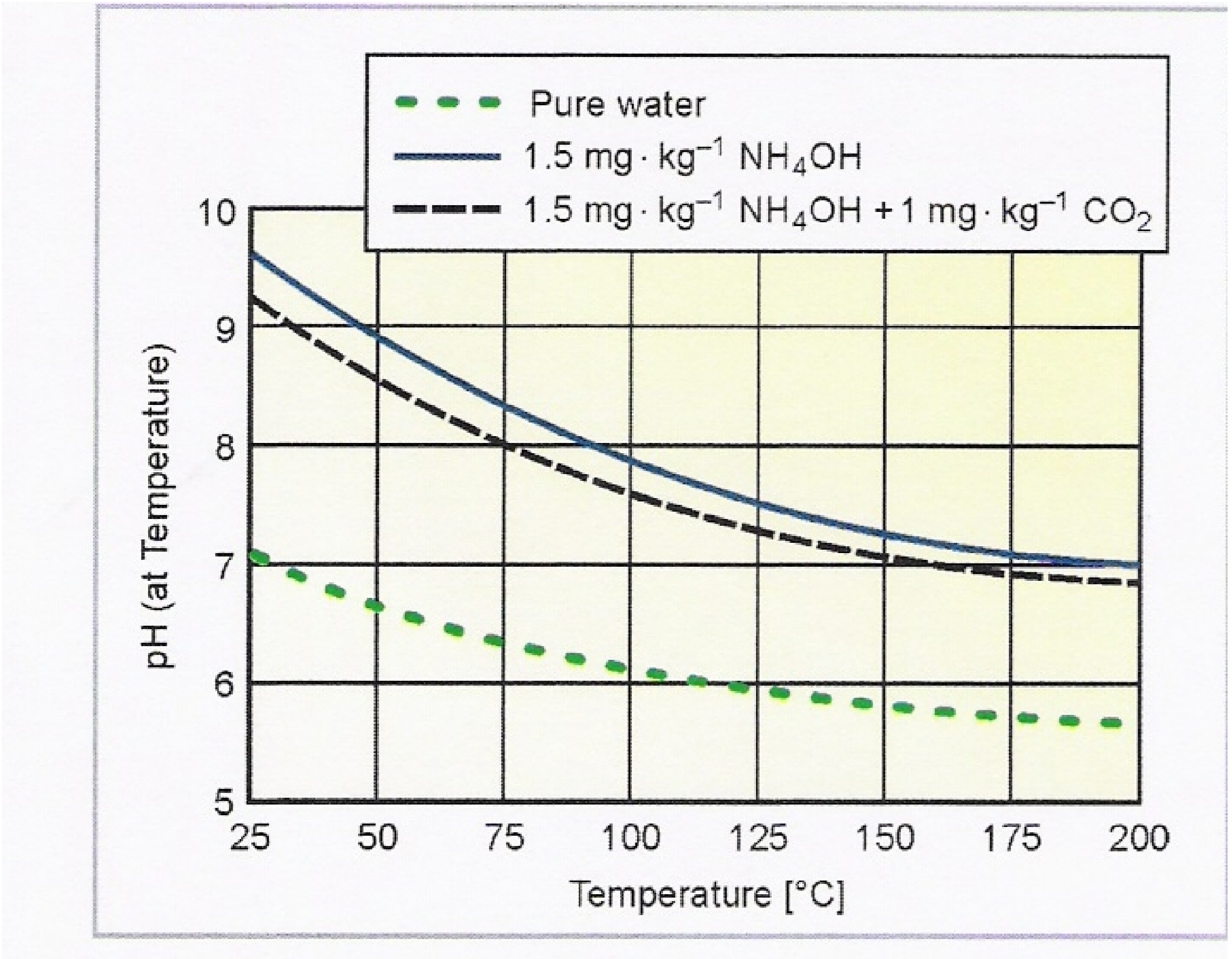
- Nostaa kationivaihdettua johtokykyä (esim. syöttövesi):

Kotka	Pietarsaari
0,07 µS/cm	0,7 µS/cm

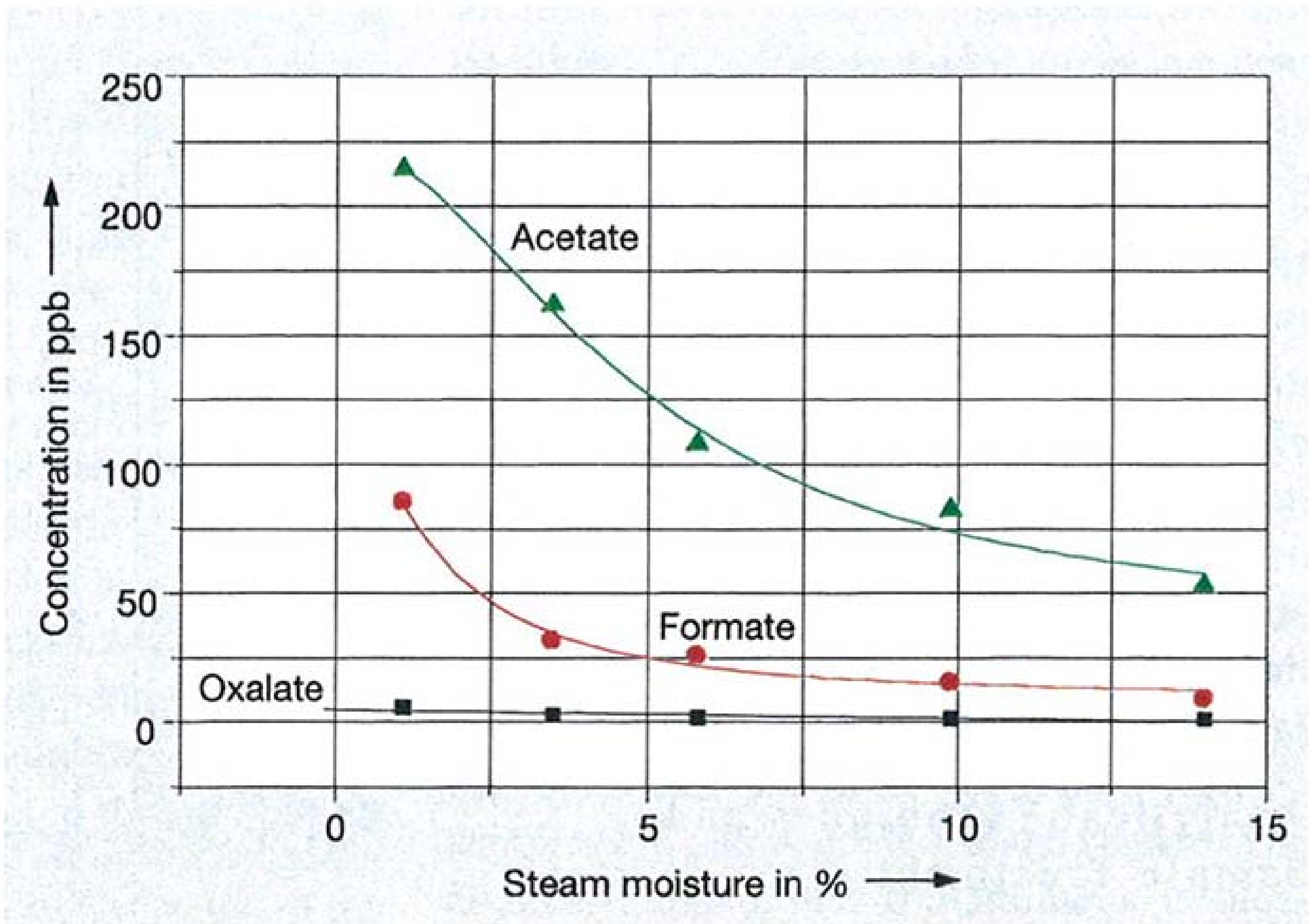
- Pudottaa ensilauhteen pH:ta -> riski korroosiolle kasvaa lauhdepiirissä
- Nostaa kemikaalien kulutusta
- Vaikeuttaa muutosten seurantaa

Teollisuuden Vesi

Hiilidioksidi ei ongelma



Muut hapot lauhtuvat helpommin

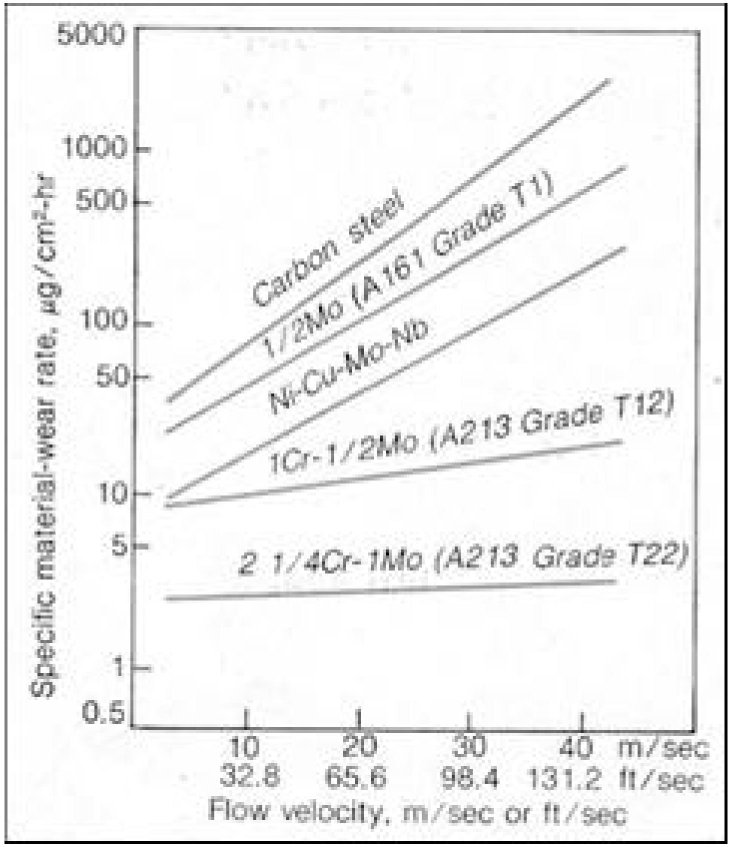


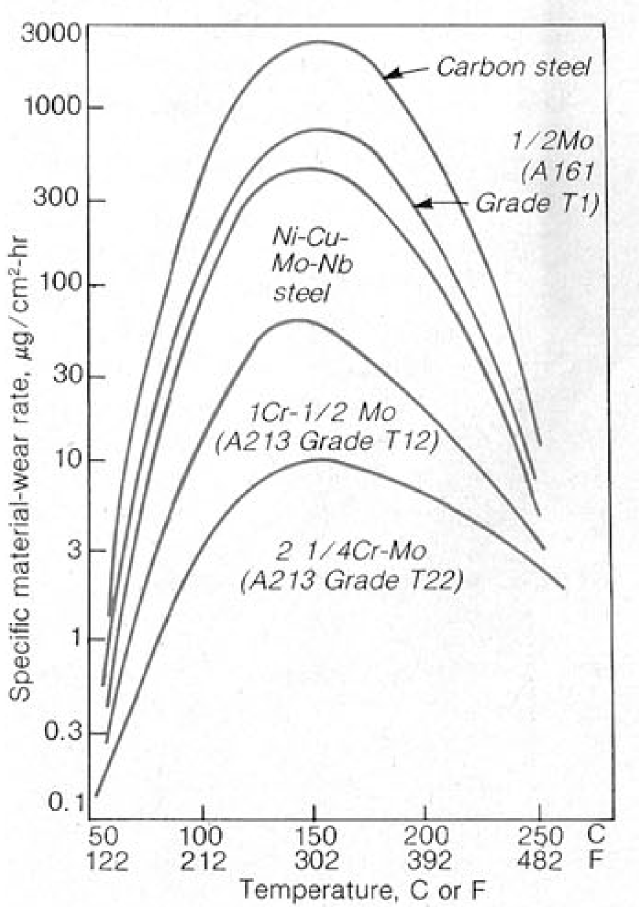
Haihtuvuus (volatility) ja liukoisuus (solubility)

Species	Unit	Boiler Water	Steam	Early Condensate
Chloride	$\mu g \cdot kg^{-1}$	72	2	16
Sulfate		190	2	8
Phosphate		390	< 5	< 5
Acetate		37	17	587
Formate		2	2	497
Carbonate		550	135	210
Ammonia		–	1 330	317
pH (25 °C)		–	9.4	5.7
pH (100 °C)		–	8.1	5.7

Teollisuuden Vesi

Muut muuttujat: Virtausnopeus ja lämpötila





Teollisuuden Vesi

Parannuskeinot

- Parempi lisäveden laatu
- Ei hapenpoisto-kemikaalia
- Paremmat materiaalit
- Virtausolosuhteet
  - tasaisempi virtausjakauma
  - Pienempi virtausnopeus

Teollisuuden Vesi

Jatkotilaus
Veden laadun parantaminen

- TOC ja perinteinen lisäveden valmistus
  - Ioninvaihto
  - Scavenger
  - Eri hartsityypit ja ioninvaihtoprosessit
- TOC-pitoisuutta pienentävät menetelmät prosessin eri vaiheisiin
  - Aktiivihiili
  - Kalvotekniikat
    - Nanosuodatus
    - Käänteisosmoosi
  - UV/AOP

Liite II

Maija Vidqvist, Teollisuuden Vesi Oy - tilanneraportti: TOC-poistomenetelmät ja niiden soveltuvuus soodakattiloiden lisäveden valmistukseen

Tilauksenne 16A0913/S88

TOC-poistomenetelmät ja niiden soveltuvuus soodakattiloiden lisäveden valmistukseen

Väliraportti

Teollisuuden Vedeltä on tilattu kirjallisuusselvitys TOC-poistomenetelmistä sekä selvitys ioninvaihtomassojen toiminnasta orgaanisten aineiden poistoon. Työt on aloitettu tarjouksen mukaisesti syyskuun alussa ja ne ovat edenneet suunnitelmien mukaan.

Kirjallisuusosassa tuodaan esille eri TOC-poistoon soveltuvat menetelmät (nanosuodatus, käänteisosmoosi, aktiivihiilisuodatus ja erilaiset UV-tekniikat mukaan lukien AOP-Advanced Oxidation Process) ja niiden tehokkuus. Investointikustannuksista annetaan arvio.

Ioninvaihtomassojen toimintaa selvitetään kirjallisuusosan lisäksi myös laboratorio-olosuhteissa niin, että sekä Rauman Botnian että Stora Enson Kotkan laitoksilta on hankittu näytteet anionivaihtomassoista. Massoille on tehty/tehdään seuraavat kokeet:

- TOC-likaantuminen (mg/g hartsia)
- Kokonaiskapasiteetti ja vahva kapasiteetti
- TOC-kapasiteetti ja elvyttyminen

Näiden kokeiden lisäksi molemmilta laitoksilta on lähetetty vesinäytteet laboratorioon Saksaan luonnon orgaanisen aineen jakautumisen määrittämiseksi vedenkäsittelyprosessin eri vaiheista mm.:

- liuennut hiili, DOC
- biopolymeerit (polysakkaridit, proteiinit)
- neutraalit orgaaniset aineet (alkoholit, aldehydit, ketonit)
- orgaaniset hapot

Työn alustavat tulokset esitellään 10.12.09 ns. projektipalaverissa Kotkan, Rauman ja Pietarsaaren käyttöhenkilökunnan kesken. Varsinaiseen jakeluun kommentteja varten raportti tutkimustuloksineen ja liitteineen toimitetaan viimeistään 9.1.2009.

Teollisuuden Vesi Oy
Y-tunnus1855496-8
www.teollisuudenvesi.fi
info@teollisuudenvesi.fi

Hyllyväntie 6-8
04600 MÄNTSÄLÄ
gsm 040 503 1258

Liite III

Tero Luukkonen, Oulun Yliopisto - tilanneraportti: Soodakattilalaitoksen lisäveden orgaanisen aineen (TOC) vähentäminen

Soodakattilalaitoksen lisäveden orgaanisen aineen (TOC) vähentäminen

20.11.2009
Tero Luukkonen

Mitä tähän mennessä tehty

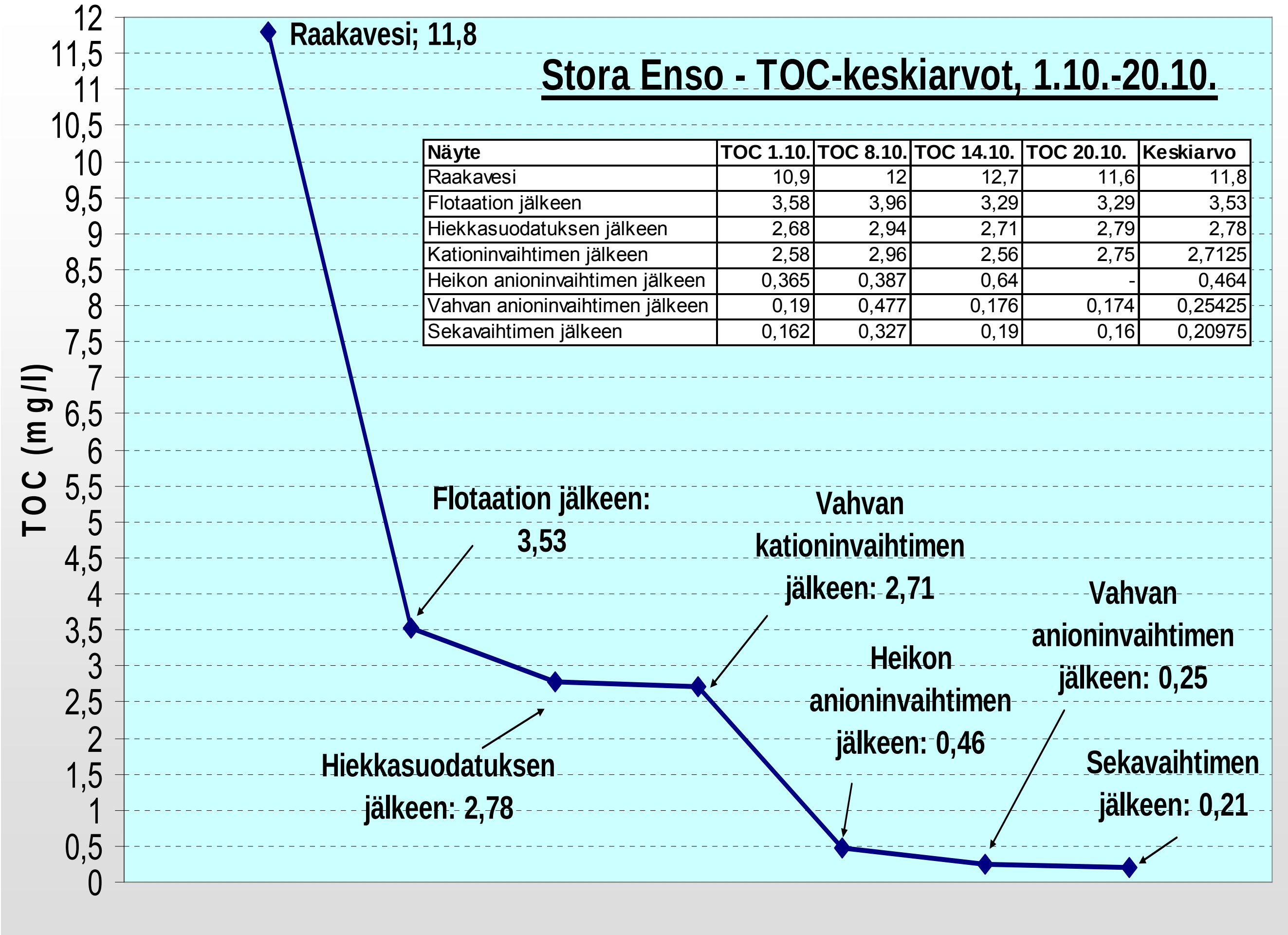
- TOC-mittaussarjat (4 kpl) tutkittavilta laitoksilta (Stora Enso, Kemira, Oulun vesi)
- Ioninvaihdon ajovaiheen vaikutus TOC-poistumaan
- Oulun veden valmistaman talousveden käyttö raakavetenä
- Mittaussarjat Veitsiluodon vedenpuhdistamolta sekä Kurkelanrannasta (Oulun veden toinen laitos)

TOC-mittaussarjojen tuloksia

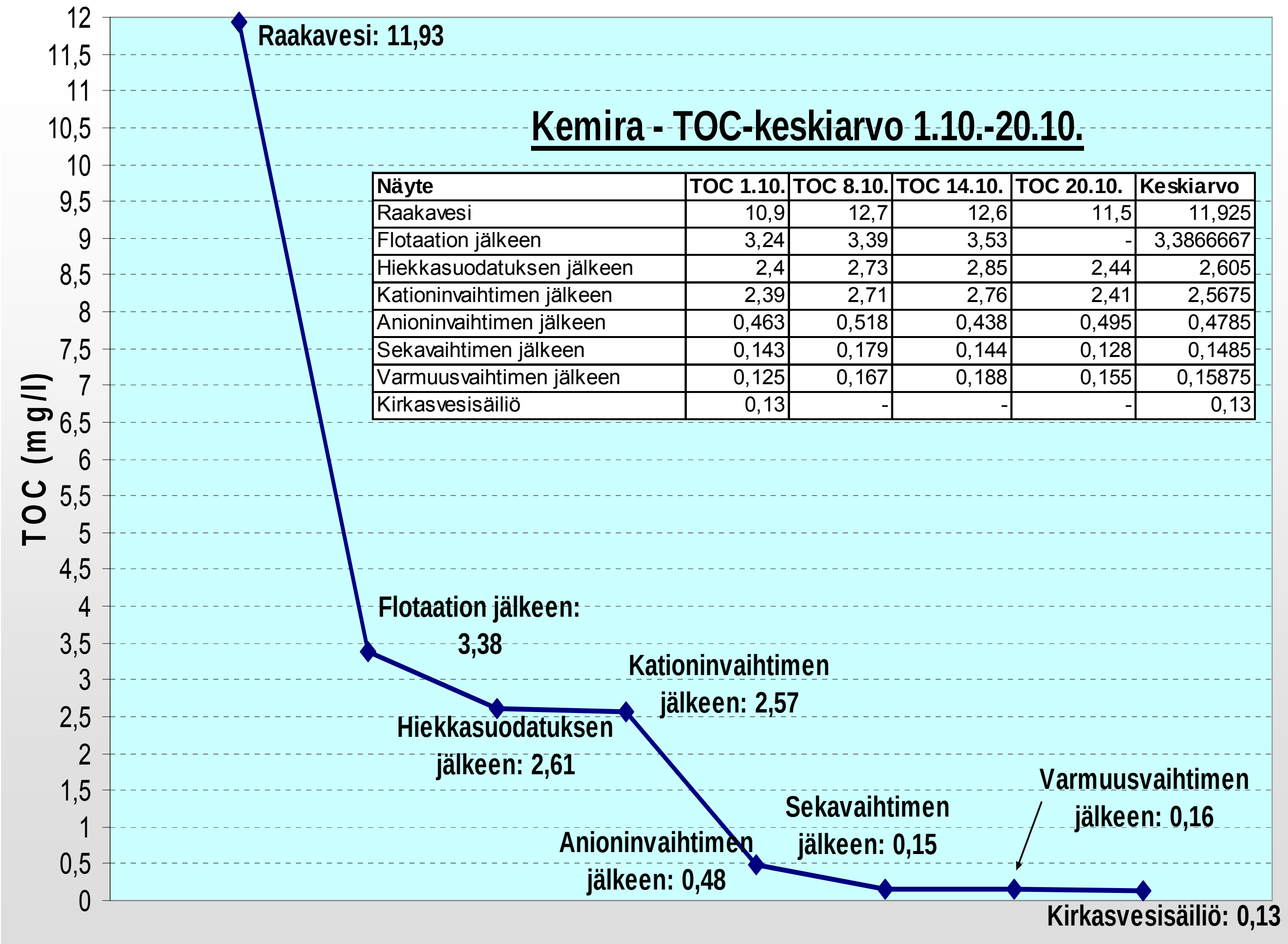
Näyte	**Stora Enso (keskiarvo) /ppm**	**Kemira (keskiarvo) /ppm**
Raakavesi	11,70	11,75
Flotaation jälkeen	3,41	3,47
Hiekkasuodatuksen jälkeen	2,62	2,57
Kationinvaihtimen jälkeen	2,40	2,28
Heikon anioninvaihtimen jälkeen	0,46	-
Vahvan anioninvaihtimen jälkeen	0,22	0,46
Sekavaihtimen jälkeen	0,19	0,24
Varmuusvaihtimen jälkeen	-	0,20

TOC-mittaussarjojen tuloksia

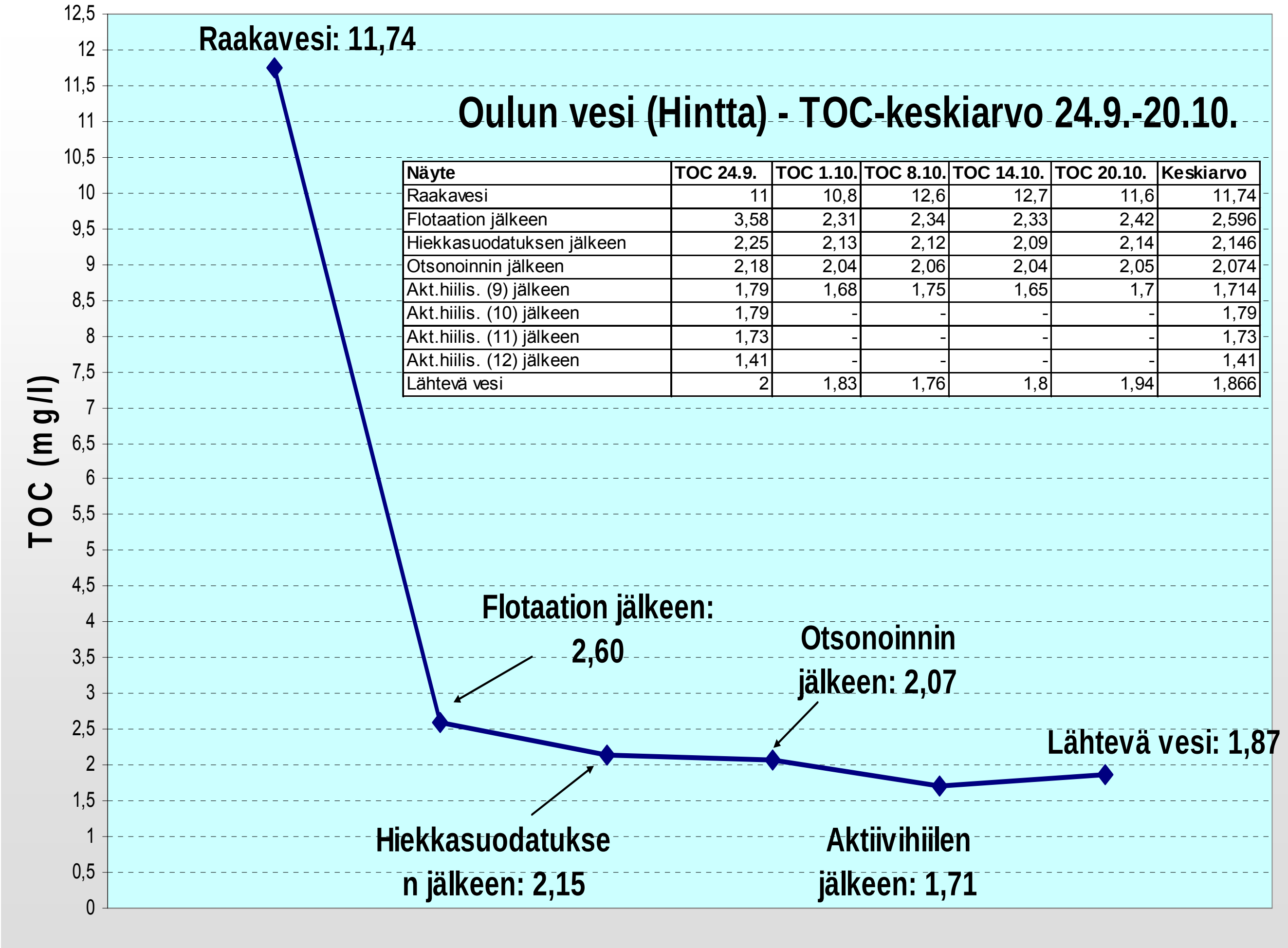
Näyte	**Oulun vesi (Hintan laitos), keskiarvo /ppm**
Raakavesi	11,67
Flotaation jälkeen	2,51
Hiekkasuodatuksen jälkeen	2,14
Otsonoinnin jälkeen	2,06
Akt.hiilis. (9) jälkeen	1,70
Akt.hiilis. (10) jälkeen	1,79
Akt.hiilis. (11) jälkeen	1,73
Akt.hiilis. (12) jälkeen	1,41
Lähtevä vesi	1,90



Näyte	TOC 1.10.	TOC 8.10.	TOC 14.10.	TOC 20.10.	Keskiarvo
Raakavesi	10,9	12	12,7	11,6	11,8
Flotaation jälkeen	3,58	3,96	3,29	3,29	3,53
Hiekkasuodatuksen jälkeen	2,68	2,94	2,71	2,79	2,78
Kationinvaihtimen jälkeen	2,58	2,96	2,56	2,75	2,7125
Heikon anioninvaihtimen jälkeen	0,365	0,387	0,64	-	0,464
Vahvan anioninvaihtimen jälkeen	0,19	0,477	0,176	0,174	0,25425
Sekavaihtimen jälkeen	0,162	0,327	0,19	0,16	0,20975



Näyte	TOC 1.10.	TOC 8.10.	TOC 14.10.	TOC 20.10.	Keskiarvo
Raakavesi	10,9	12,7	12,6	11,5	11,925
Flotaation jälkeen	3,24	3,39	3,53	-	3,3866667
Hiekkasuodatuksen jälkeen	2,4	2,73	2,85	2,44	2,605
Kationinvaihtimen jälkeen	2,39	2,71	2,76	2,41	2,5675
Anioninvaihtimen jälkeen	0,463	0,518	0,438	0,495	0,4785
Sekavaihtimen jälkeen	0,143	0,179	0,144	0,128	0,1485
Varmuusvaihtimen jälkeen	0,125	0,167	0,188	0,155	0,15875
Kirkasvesisäiliö	0,13	-	-	-	0,13



Näyte	TOC 24.9.	TOC 1.10.	TOC 8.10.	TOC 14.10.	TOC 20.10.	Keskiarvo
Raakavesi	11	10,8	12,6	12,7	11,6	11,74
Flotaation jälkeen	3,58	2,31	2,34	2,33	2,42	2,596
Hiekkasuodatuksen jälkeen	2,25	2,13	2,12	2,09	2,14	2,146
Otsonoinnin jälkeen	2,18	2,04	2,06	2,04	2,05	2,074
Akt.hiilis. (9) jälkeen	1,79	1,68	1,75	1,65	1,7	1,714
Akt.hiilis. (10) jälkeen	1,79	-	-	-	-	1,79
Akt.hiilis. (11) jälkeen	1,73	-	-	-	-	1,73
Akt.hiilis. (12) jälkeen	1,41	-	-	-	-	1,41
Lähtevä vesi	2	1,83	1,76	1,8	1,94	1,866

Veitsiluodon TOC-tulokset

Näyte	TOC 20.10. (ppm)
Raakavesi	9,58
Ennen humussuodinta	2,68
Humussuotimen jälkeen	0,912
Kationinvaihtimen jälkeen	0,834
Anioninvaihtimen jälkeen	0,186
Sandwich-suotimen jälkeen	0,204

Kurkelanrannan TOC-tulokset

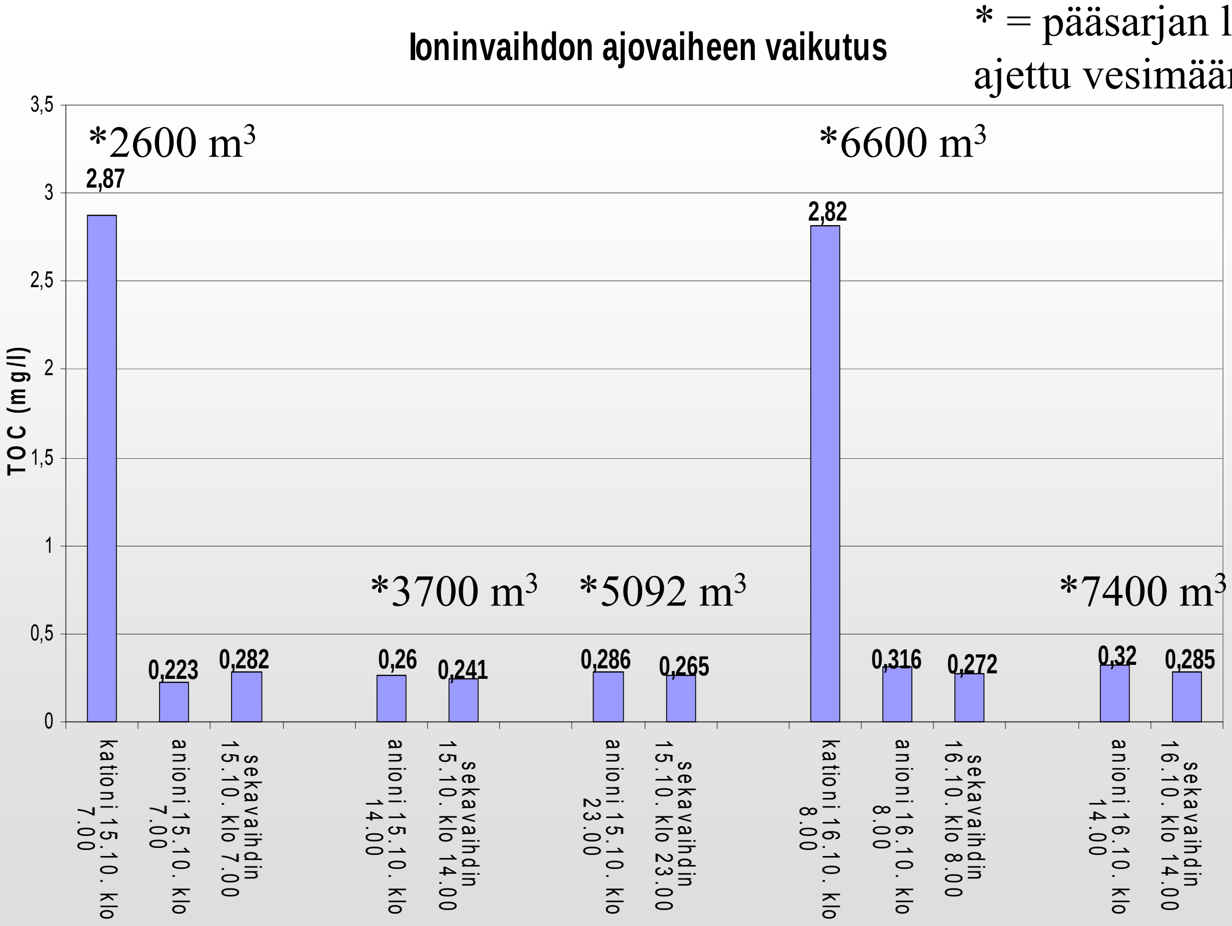
Näyte	TOC 14.10. (ppm)
Flotaation jälkeen	2,42
Hiekkasuodatuksen jälkeen	2,12
Otsonoinnin jälkeen	2,03
Biologisen akt.hiilis. Jälkeen	1,78
Akt.hiilis. jälkeen	1,6
UV:n jälkeen	1,6

- UV (aallonpituus 254 nm) ei vaikuta TOC-lukemaan

”Kaupunginvesi” raakavetenä Stora Ensolla

Näyte	TOC-keskiarvo 1.10.-20.10.	Kaupunginvesi raakavetenä 14.10.
Kationille menevä	2,78 ppm	2,31 ppm
Kationinvaihtimen jälkeen	2,71 ppm	1,73 ppm
Anioninvaihtimen jälkeen	0,254 ppm	0,253 ppm
Sekavaihtimen jälkeen	0,210 ppm	0,190 ppm

* = pääsarjan läpi ajettu vesimäärä



Aktiivihiilikokeet

- Oulun veden aktiivihiili pesty
- Käyttö mekaanisesti (adsorptio) vai biologisesti?
- Aktiivihiilen käyttökode?

Mitä seuraavaksi

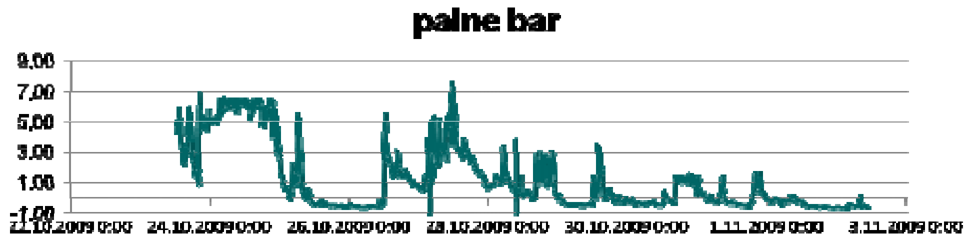
- Aktiivihiilikokeet
- UV-kokeet (pelkkä UV ja sopivan hapettimen kanssa)
- Flokkauskokeet (käytetään rautakoagulanttia)

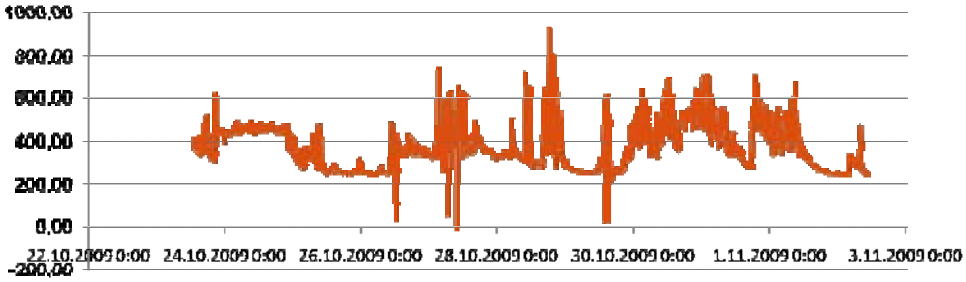
Aktiivihiilikokeiden koe-järjestely: viipymä pyritään saamaan samaksi kuin Oulun vedellä

Liite IV

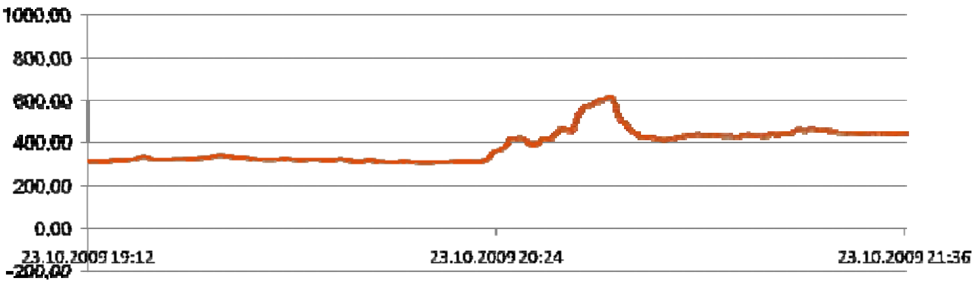
Timo Karjunen, Boildec Oy – tilanneraportti: Materiaalikokeet tulipesässä

Ensimmäisen kokeen paine ja lämpötila





Ensimmäinen lämpötilapiikki



Liite V

Timo Karjunen, Boildec Oy – esitys Konemestaripäivät 2010: Soodakattilan sisäpuolinen tarkastus

Soodakattilan sisäpuolinen tarkastus

Timo Karjunen

Boildec Oy

Soodakattiloiden räjähdykset Pohjoismaissa 1980 - 2007

9 räjähdystä 1 500 käyttövuoden aikana

8 räjähdyksessä syynä vuoto tulipesän putkessa

50 % vuodoista sisäpuolisen korroosion aiheuttamia

Räjähdysten ja niihin johtaneiden vaurioiden aiheuttamat seisokit 1980 - 2007

Seisokkien yhteispituus 300 vrk

200 seisokkipäivää liittyi räjähdyksiin, joiden aiheuttajana oli sisäpuolinen korroosio

Keskimääräinen menetetyn tuotannon arvo 600 000 t/a massatehtaalle 120 000 €/vuosi

Sisäpuolista tarkastusta koskevat vaatimukset

KTM:n päätös 953/1999, 14 §: Sisäpuolinen tarkastus

Painelaitteen sisäpuolisessa tarkastuksessa
on tarkastettava, että painelaitteessa ja sen varusteissa
ei ole vikoja tai ominaisuuksia, jotka
vaarantavat painelaitteen **turvallisen käytön**.

Sisäpuolisten tarkastusten aikaväli
saa olla enintään neljä vuotta

Soodakattilan seinäputken repeämä 2006

Vuodon seurauksena tulipesään
meni vettä useita kymmeniä kg/s

Sisäpuolinen syöpymä kattilan seinäputkessa

Vaurioiden jälkeen kattilassa tehtiin täystarkastus,
jonka tuloksena kattilasta vaihdettiin 300 kpl putken osaa

Käytettävissä olevat tarkastusmenetelmät

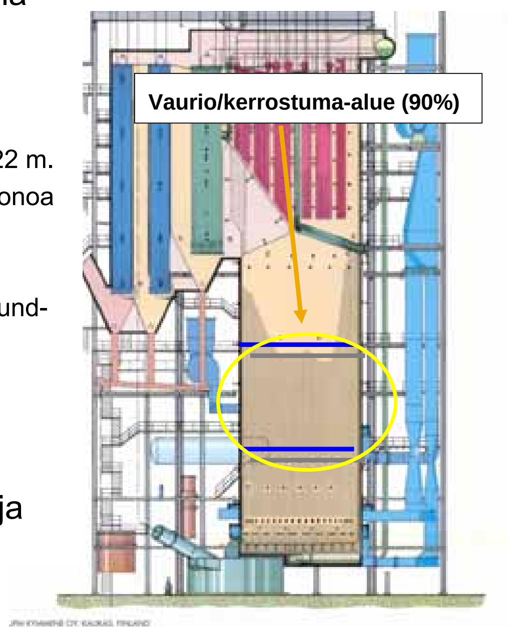
- Lieriön ja jakotukkien visuaalinen tarkastus
- Näyteputken otto ja sisäpinnan tarkastus
- Vetymittaus (käynnin aikana)
- Endoskooppitarkastus
- Ultraäänitarkastus

Tarkastukset ja vauriot

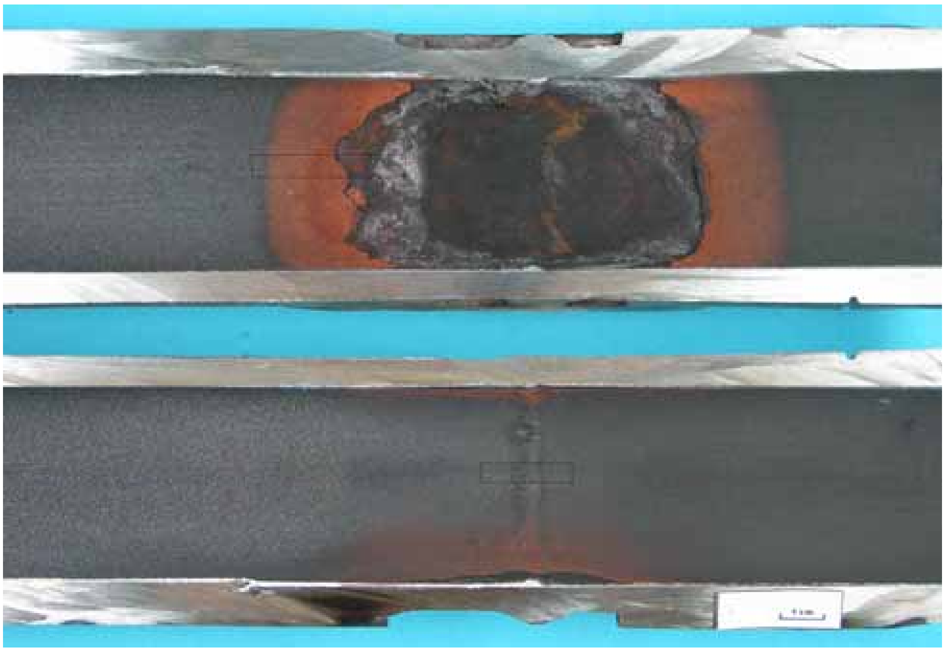
Kerrostuma- ja vauriokohdat pääosin kahdella tulipesän vaakasaumalla

- Alempi 10 m:n korkeudella, alkuperäisellä compound/musta-rajasaumalla
- Ylempi nykyisellä compound/musta-rajasaumalla 22 m.
- Myös saumojen väliseltä alueelta löytyi hieman huonoa putkea, muttei juurikaan muualta
- Compound-rajan nosto 7 v aikaisemmin, jolloin asennettiin uudet, asennuspaikalla peitatut compound-paneeliseinät
- Yli 90% nyt kerrostuman tai vaurioiden takia vaihdetuista putkista oli tällä välillä

Vaihdettua putkea tuli yhteensä noin 300 m ja vaihdettuja pätkiä noin 300 kappaletta.



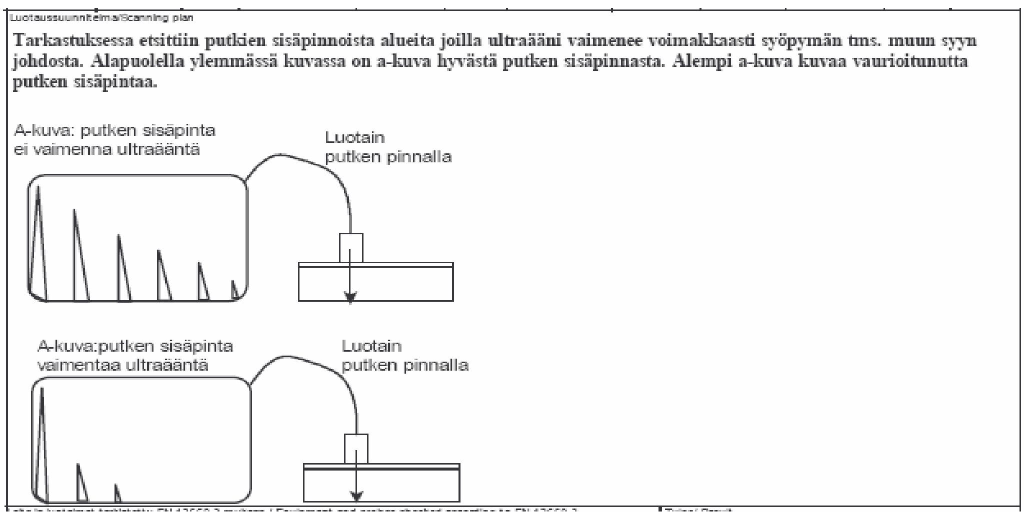
Kattilaputkien sisäpinnat lipeäkorroosiosta kärsineessä kattilassa



Vauriot rajoittuivat n. 10 cm matkalle, muualla putken sisäpinnan kunto erinomainen

Kerrostumien mittaus ultraäänellä

Seinämien paksuusmittaukseen käytettyjä ultraäänilaitteita on käytetty myös paksujen kerrostumien paikantamiseen



UÄ-tarkastukset lipeäkorroosiosta kärsineessä kattilassa

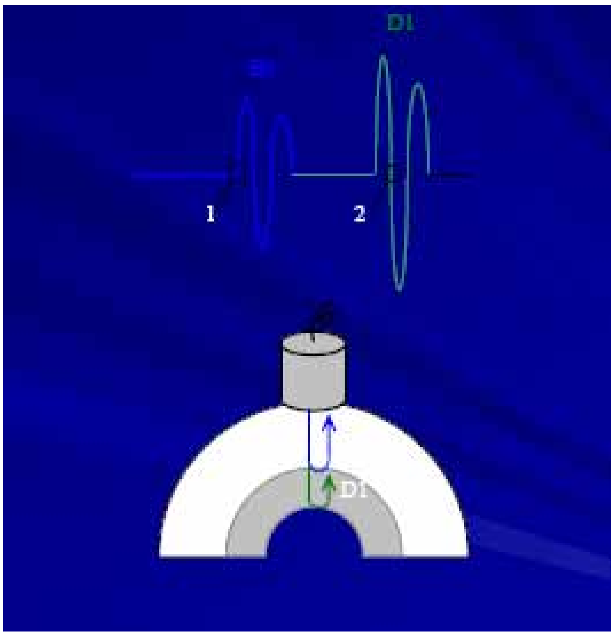
- Tarkastettiin pohja ja tulipesän seinät 23 m:iin asti 100%:sti, yhteensä noin 16,8 km. Ko. menetelmä osoitti "huonoksi" n. 160 m ja kun lisättiin hieman vaihdettavaa putkea, tuli vaihdetuksi n. 300 m putkea eli 1.8% compoundalueen putkista.

- Jokaisen vaihdetun putken pätkän kohdalta tarkastettiin putken sisäpuoli endoskoopilla molempiin suuntiin noin 6 m:n matkalta eli yhteensä noin 4 km:n matkalta, mikä on noin neljäsosa ko. alueen kokonaisputkimäärästä.
  - **Endoskooppitarkastuksilla löytyi neljätoista kappaletta sisäpuolista kerrostumaa omaavia kohtia, joita ei ollut ultraäänellä löydetty taikka ei ollut tulkittu huonoiksi**.
  - Kattilan pohjalla alue, joka ei täysin terve, mutta kaiku ei kunnolla vaimentunutkaan. Tältä alueelta tarkastettiin endoskoopilla 5 putkea pohjan syöttöputkien kautta sekä tutkittiin lisäksi yksi koepala laboratoriossa. Ei kerrostumia ja tutkittu putki täysin terve. Alue tarkastettiin peittauksen jälkeen uudelleen ultralla ja nyt putket näyttivät täysin terveiltä.

Sisäpuolisen kerrostuman paksuuden mittaus ultraäänellä – perinteinen menetelmä

Menetelmä toimii, kun putken sisäpinnasta ja kerrostuman pinnasta heijastuva aalto ovat erilliset

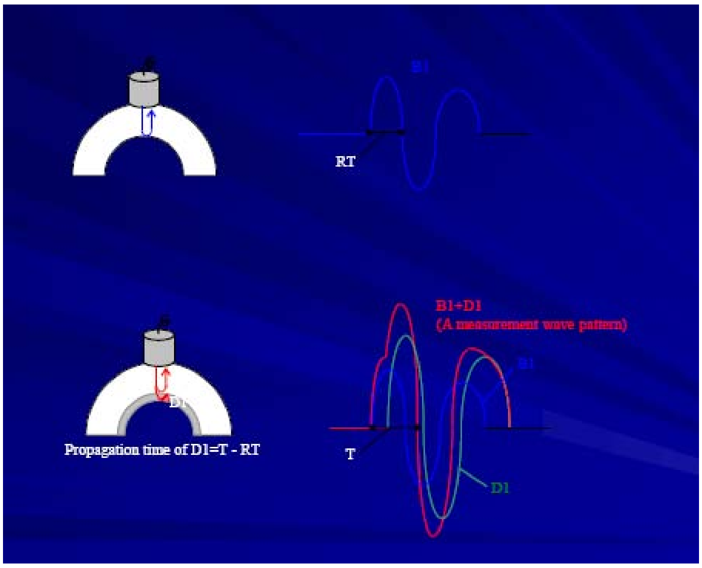
=> Kerrostuman paksuus > 150 µm



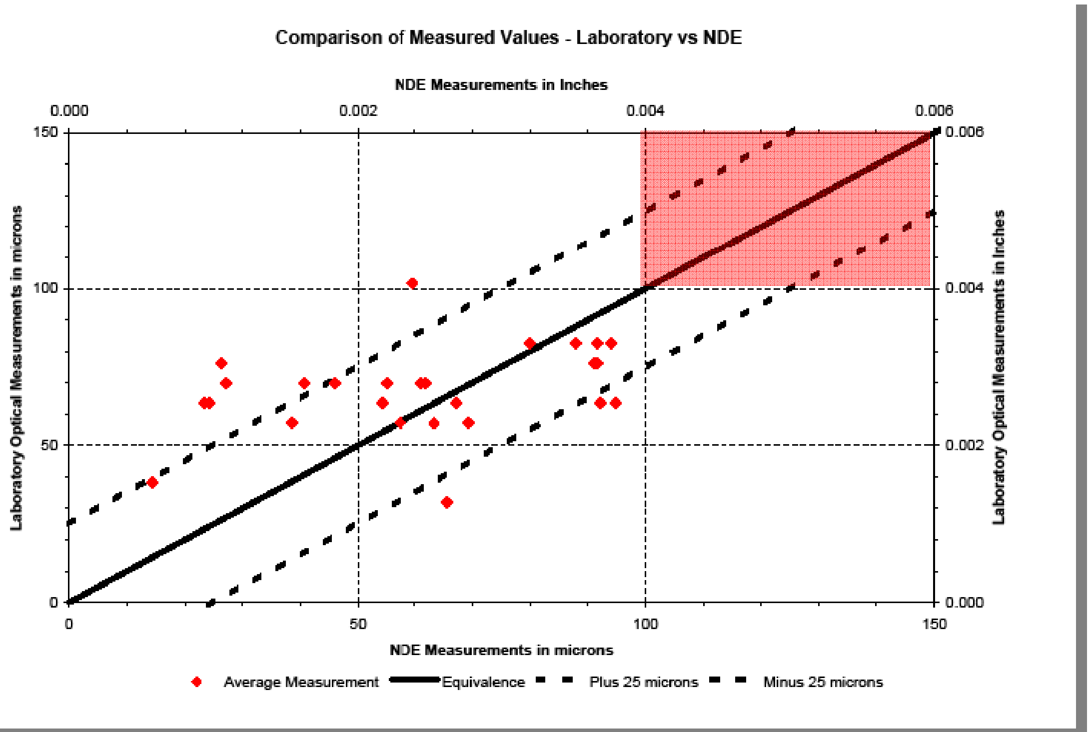
Sisäpuolisen kerrostuman paksuuden mittaus ultraäänellä – uusimmat menetelmät

Kerrostuman paksuus määritetään sen perusteella, kuinka paljon kerrostuman pinnasta heijastunut aalto leventää putken sisäpinnasta heijastunutta aaltoa

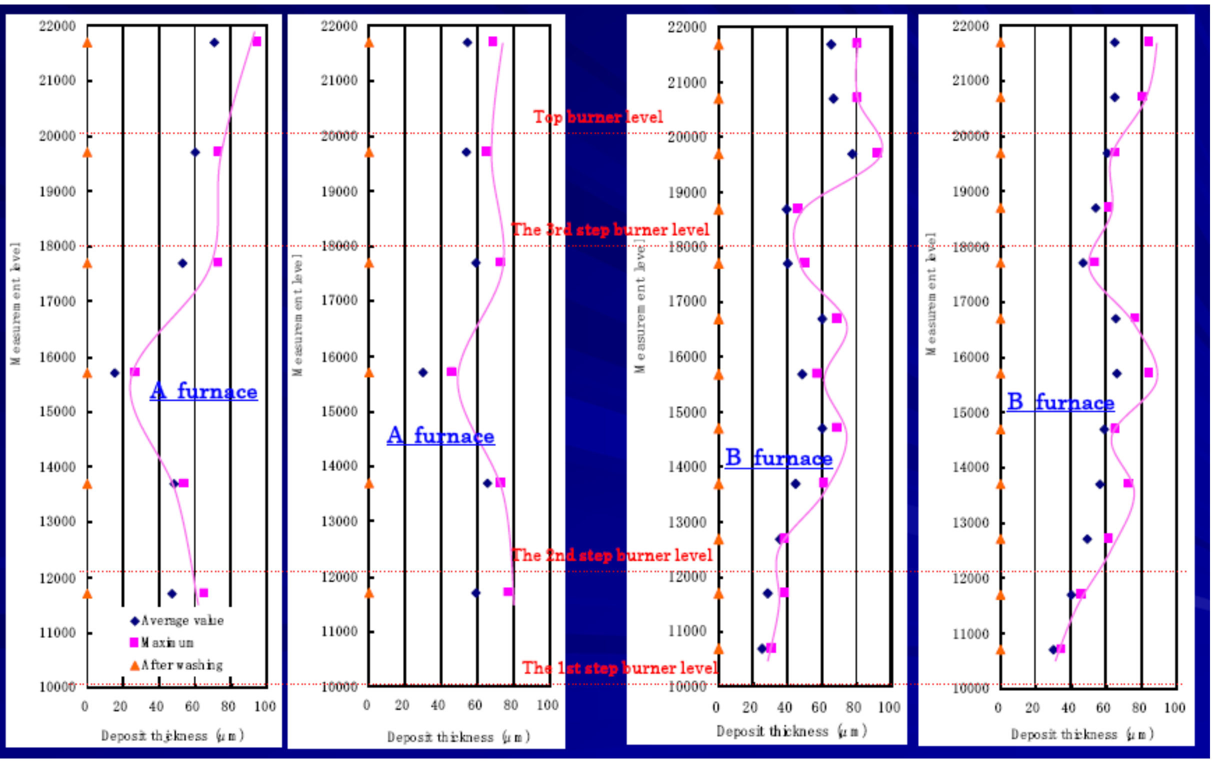
⇒ Kerrostuman paksuus on mitattavissa, kun sen paksuus > 20 µm



Kehittyneen UÄ-menetelmän tulosten ja mikroskooppikuvaustulosten vertailu

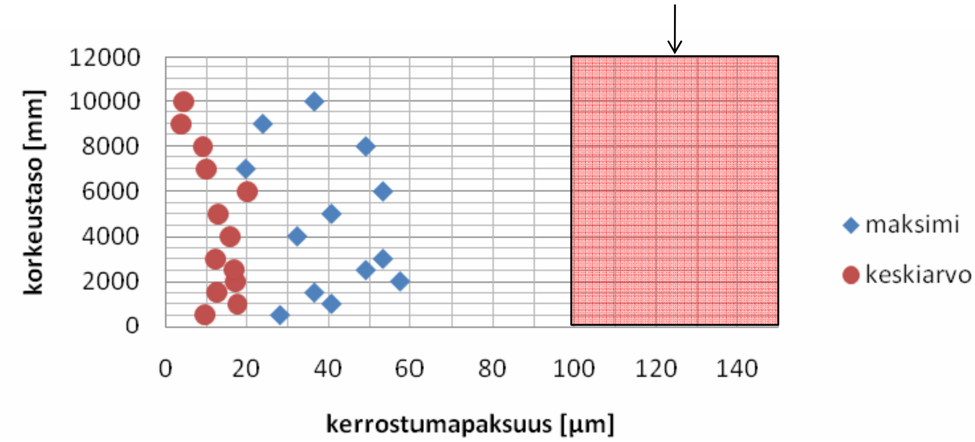


Kehittyneen UÄ-menetelmän käyttö



Boildecin tekemän sisäpuolisen tarkastuksen tuloksia

Kerrostumien poisto peittaamalla tai muilla keinoin
tarpeen varsinkin jos veden laatu on heikko
tai korroosiota voi olla tulipesän puolella



Nyt kattilaputken sisäpinnan kerrostumat ohuita

Ei tarvetta näyteputken ottoon, peittaukseen
tai muutoksiin vedenkäsittelyssä

Esimerkki turvallisuuden vaarantavasta ominaisuudesta ja viasta

Ehjän seinäputken sisäpinta

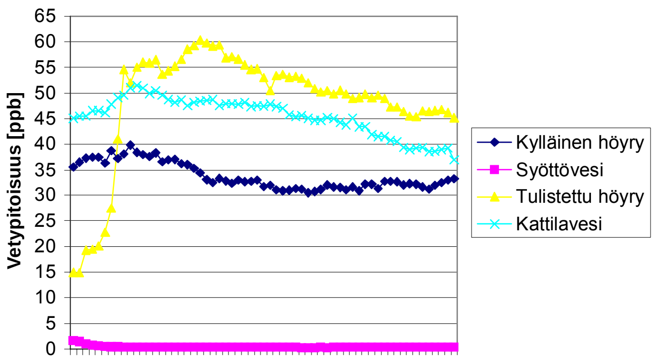
Kerrostuman paksuus keskimäärin ≈ 150 µm
Paikallisesti 200 – 300 µm
Kattila peittauskunnossa

Korrodoituneen seinäputken sisäpinta

Pitkälle edennyt vetyhyökkäys

Vetyhyökkäyksen tunnistus vetymittauksella

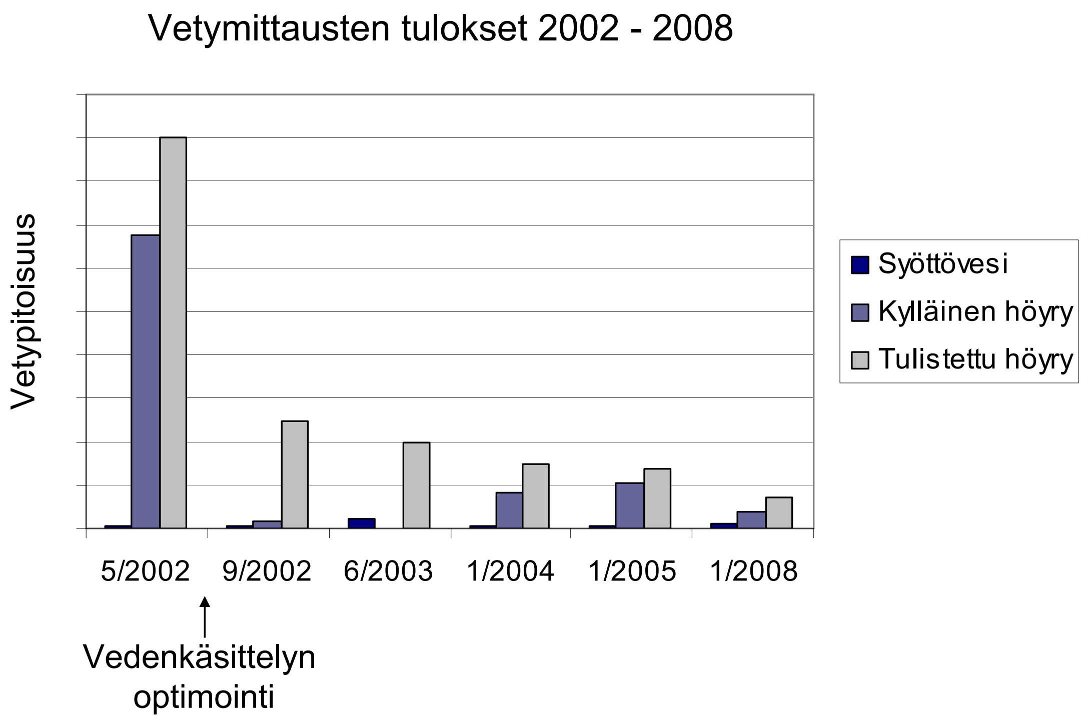
Mittaus huhtikuussa 2002



Putkinäyte kerätty kesäkuussa 2002

Vetyhyökkäys saatiin tunnistettua ajoissa niin, että se oli torjuttavissa pelkästään veden laatua parantamalla

Sisäpuolisen korroosion seuranta määräajoin tehdyillä vetymittauksilla



Yhteenveto

Kokemuksien mukaan suurin riski soodakattilan käytettävyydelle ja käyttö-turvallisuudelle on sisäpuolinen korroosio ja sen aiheuttamat kattilavuodot

Tätä riskiä voidaan pienentää määräaikaistarkastuksilla, joissa mitataan tulipesän seinäputkien sisäpuolisten kerrostumien paksuus tulipesän alaosassa sekä compoundin jatkosaumoissa. Tarkastusta voidaan täydentää vetymittauksella käynnin aikana.

Tarkastuksen tulosten perusteella voidaan

a) poistaa kattilasta putket, joissa kerrostumat ovat hyvin paksuja ja joiden seinämäpaksuus on vaarallisen ohut (vetyhyökkäyksen mahdollisuus ml.)
b) peitata kattila, jos kerrostumat ovat paksuja, mutta putkien seinämäpaksuus on vielä riittävä eikä vetyhyökkäys ei ole mahdollinen
c) parantaa vedenkäsittelyä, jos kerrostumat ovat normaalia paksumpia, mutta ei vielä niin paksuja, että kerrostumien poisto peittaamalla olisi tarpeen

Tarkastuksen avulla em. toimenpiteet voidaan tehdä oikea-aikaisesti

Tällä hetkellä ainoa yritys Pohjoismaissa, joka kykenee tällaisen tarkastuksen tekemään, on Boildec Oy

Liite VI

Esa Vakkilainen, LUT - esitys:
Läpivirtauskattila konseptit

Läpivirtaus ja välitulistuskattilakonseptit

Edistymisraportti 26.11.2009

Esa K. Vakkilainen

Edistyminen

- Määritykset uusiksi 26.6.2009
- Mitoitettu kattilat
- Tehty taseet tehtaille jossa biomassakattila
- Tehty taseet tehtaille jossa ei biomassakattilaa
- Vertailtu kannattavuutta
- Ajettu APROS ajoja
- Vertailtu esilämmityskonsepteja

Tutkitut tapaukset (uudet, 26.6.2009)

A. luonnonkierto 82 %, 490 °C, 9.0 MPa (Joutseno)

B. luonnonkierto 85 %, 505 °C, 10.2 MPa (Kymi)

C. luonnonkierto 85 %, 515 °C, 12.0 MPa (Yonago)

Tulevaisuuden kattila tapaus

D. avustettu kierto 85 %, 540 °C, 16.0 MPa (SoTu)

Välitulistus kattilat

E. luonnonkierto 85 %, 515/515 °C, 12.0/3.0 MPa (SkyRec)

F. läpivirtaus 85 %, 540/540 °C, 26.0/5.4 MPa (Skyrec+)

Case		**A**	**B**	**C**	**D**	**E**	**F**
Capacity	tds/d	5500	5500	5500	5500	5500	5500
capacity (virgin)	tds/d	5005	5005	5005	5005	5005	5005
Dry solids	%	82.0	85.0	85.0	85.0	85.0	85.0
ds (virgin)	%	80.6	83.8	83.8	83.8	83.8	83.8
recycle ash	%	9.0	9.0	9.0	9.0	9.0	9.0
HHV	MJ/kgds	13.00	13.00	13.00	13.00	13.00	13.00
LHV	MJ/kgds	12.28	12.28	12.28	12.28	12.28	12.28
O2 in dry flue gas	%	2.8	2.8	2.8	2.8	2.8	2.8
Primary air percentage	%	23.0	22.0	22.0	22.0	22.0	22.0
Primary air temperature	°C	150.0	190.0	190.0	190.0	190.0	190.0
Secondary air percentage	%	50.0	54.0	54.0	54.0	54.0	54.0
Secondary air temperature	°C	120.0	190.0	190.0	190.0	190.0	190.0
Tertiary air percentage	%	27.0	12.0	12.0	12.0	12.0	12.0
Tertiary air temperature	°C	30.0	190.0	190.0	190.0	190.0	190.0
Quartenary air percentage	%	0.0	12.0	12.0	12.0	12.0	12.0
Quartenary air temperature	°C	30.0	190.0	190.0	190.0	190.0	190.0
Total air temperature	°C	102.6	190.0	190.0	190.0	190.0	190.0
Reduction	%	95.00	96.00	96.00	96.00	96.00	96.00
Main steam pressure RB	bar(a)	91.0	102.0	120.0	160.0	105.0	260.0
Main steam temperature RB	°C	490.0	505.0	515.0	540.0	505.0	540.0
Main steam pressure PB	bar(a)	91.0	102.0	102.0	102.0	102.0	102.0
Main steam temperature PB	°C	490.0	505.0	505.0	505.0	505.0	505.0
Feedwater pressure	bar(a)	110.0	121.0	146.0	182.0	290.0	290.0
Feedwater temperature	°C	120.0	148.0	148.0	148.0	148.0	148.0
		511.3	630.9	632.5	634.8	641.8	641.8
Reheater inlet pressure	bar(a)					36	56
Reheater inlet temperature	°C					348	337
Reheater outlet pressure	bar(a)					34	54
Reheater outlet temperature	°C					400	460
HP FWpreheater inlet temperature	°C	200	200	200	200	200	200
HP FWpreheater outlet temperatu	°C	200	200	220	220	220	220
Flue gas temperature (eco out)	°C	155	197	197	197	197	197
Flue gas temperature (to stack)	°C		155	155	155	155	155
Sootblowing	kg/s	6.0	6.0	6.0	6.0	8.0	8.0

Sähkön tuotanto (voimakattila mukana)

Tapaus		A	B	C	D	E	F
Kapasitetti	tds/d	5500	5500	5500	5500	5500	5500
Kuiva-aine	%	82.0	85.0	85.0	85.0	85.0	85.0
HP höyry	bar(a)	94.0	104.0	124.0	164.0	124.0	264.0
HP höyry	°C	490.0	505.0	515.0	540.0	515.0	540.0
Höyryvirtaus (SK)	kg/s	215.0	226.4	232.5	232.0	224.0	218.5
	%	0.0	5.3	8.1	7.9	4.1	1.6
Sellutehdas käyttö	MW	87.6	88.1	88.9	90.2	88.2	93.2
Tehtaan käyttö	MW	95.5	96.1	96.9	98.2	96.2	101.2
Sähkön tuotanto	MW	234.4	239.5	249.8	262.9	250.1	263.4
Sähkö myyntiin	MW	138.9	143.3	153.0	164.7	153.8	162.2
Hyötysuhde	%	23.2	23.1	24.1	25.4	24.1	25.4
Lisäsähkö	MW	0.0	4.4	14.0	25.8	14.9	23.2
	%	0.0	3.2	10.1	18.5	10.7	16.7

Sähkön tuotanto (ei voimakattilaa)

Tapaus		A	B	C	D	E	F
Kapasitetti	tds/d	5500	5500	5500	5500	5500	5500
Kuiva-aine	%	82.0	85.0	85.0	85.0	85.0	85.0
HP höyry	bar(a)	94.0	104.0	124.0	164.0	124.0	264.0
HP höyry	°C	490.0	505.0	515.0	540.0	515.0	540.0
Höyryvirtaus (SK)	kg/s	215.0	226.4	232.5	232.0	224.0	218.5
	%	0.0	5.3	8.1	7.9	4.1	1.6
Sellutehdas käyttö	MW	87.6	88.1	88.9	90.2	88.2	93.2
Tehtaan käyttö	MW	91.1	91.7	92.4	93.8	91.8	96.8
Sähkön tuotanto	MW	149.3	153.9	161.8	175.6	162.3	177.9
Sähkö myyntiin	MW	58.2	62.2	69.4	81.7	70.5	81.1
Hyötysuhde	%	20.4	20.4	21.4	23.2	21.5	23.5
Lisäsähkö	MW	0.0	4.0	11.2	23.6	12.3	22.9
	%	0.0	6.8	19.3	40.5	21.1	39.4

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Soodakattila sähkönkäyttö

Tapaus		A	B	C	D	E	F
Ilmapuhallin	kW	2275	2296	2296	2296	2296	2296
Savukaasupuh.	kW	2570	2534	2534	2534	2534	2534
SV-pumppu	kW	3055	3556	4347	5719	4187	8606
Muu käyttö	kW	1500	1500	1500	1500	1500	1500
Yhteensä	kW	9401	9886	10677	12049	10518	14937

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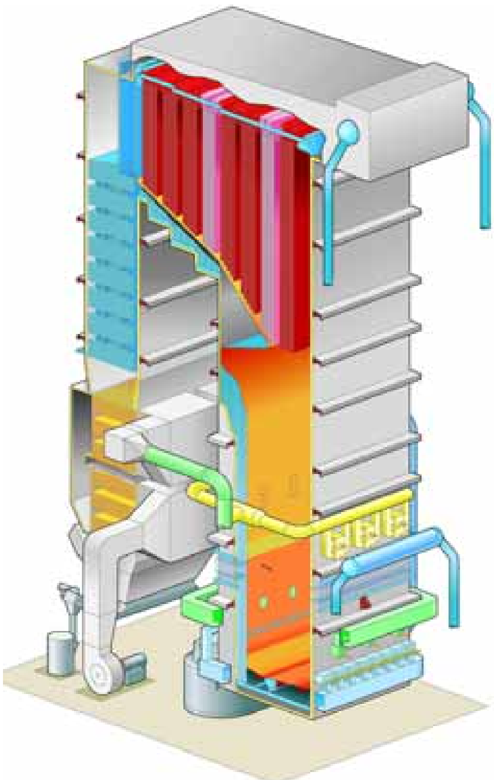
Välitulistus soodakattila



Välitulistus soodakattila tapaus

Toimittaja Babcock & Wilcox, kapasiteetti 4500 t ds/24h,

Mustalipeä ka 85 %

Höyry 130 kg/s 179 bar(a) 510 °C

Välitulistushöyry 62 bar(a) 443 °C

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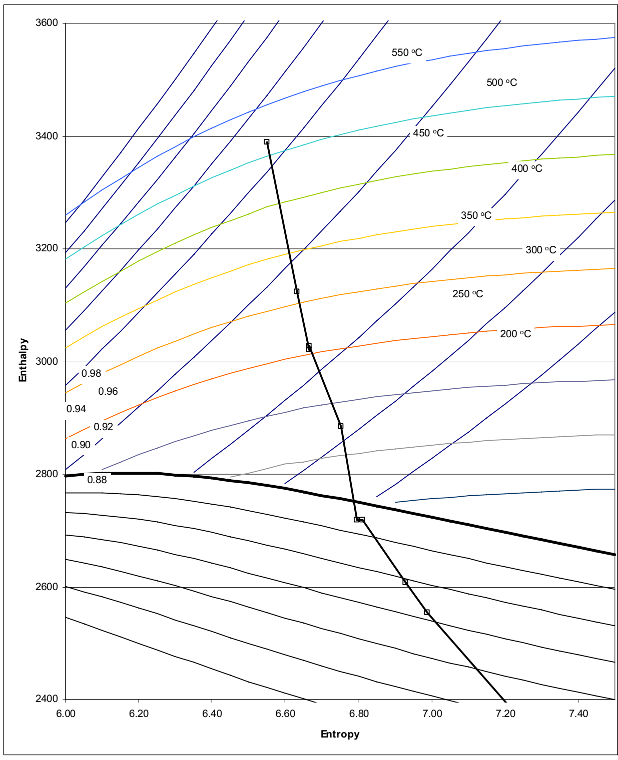
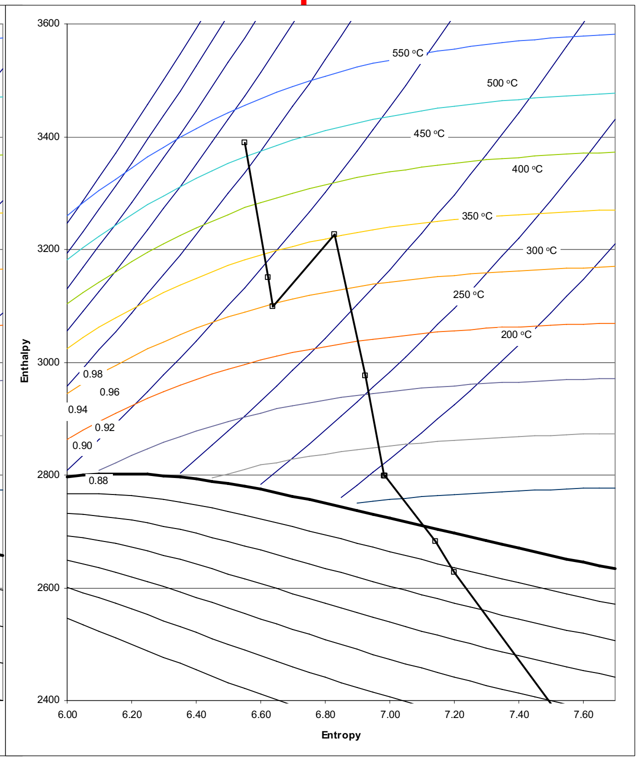
Tapaus C



Tapaus E



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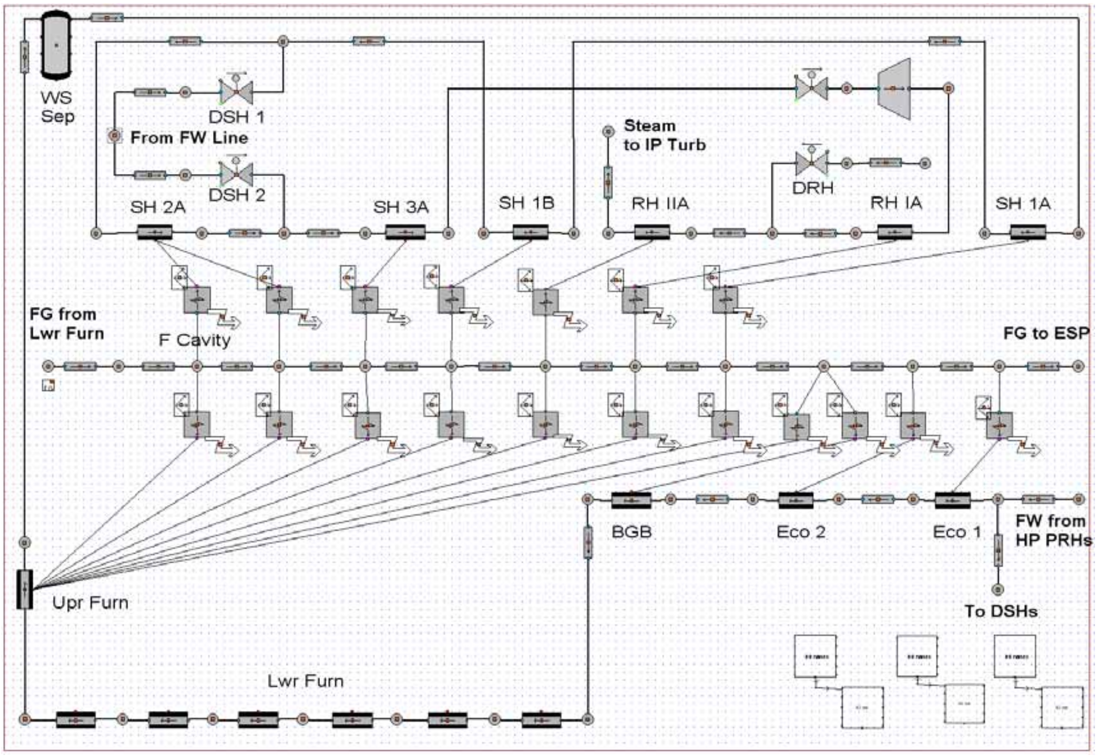
Välitulistusarvojen valinta

	480°C	460°C	440°C	420°C	400°C	380°C	360°C	340°C	320°C
5.4 MPa	182.7	***169.9***	***157.1***	***147.9***	147.9	147.9	147.9	147.9	147.9
	1.000	***1.000***	***1.000***	***0.994***	0.978	0.938	0.920	0.900	0.879
4.4 MPa	202.4	189.3	***176.1***	***162.8***	***147.9***	***147.9***	147.9	147.9	147.9
	1.000	1.000	***1.000***	***1.000***	***1.000***	***0.984***	0.967	0.934	0.914
3.4 MPa	228.2	214.5	200.8	187.0	***173.2***	***159.3***	***147.9***	147.9	147.9
	1.000	1.000	1.000	1.000	***1.000***	***1.000***	***0.995***	0.978	0.960
2.4 MPa	264.8	250.3	235.8	221.2	206.6	192.0	***177.3***	***162.6***	***147.9***
	1.000	1.000	1.000	1.000	1.000	1.000	***1.000***	***1.000***	***0.998***
1.4 MPa	326.8	310.8	294.8	278.7	262.6	246.5	230.4	214.3	198.1
	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

APROS laskennat

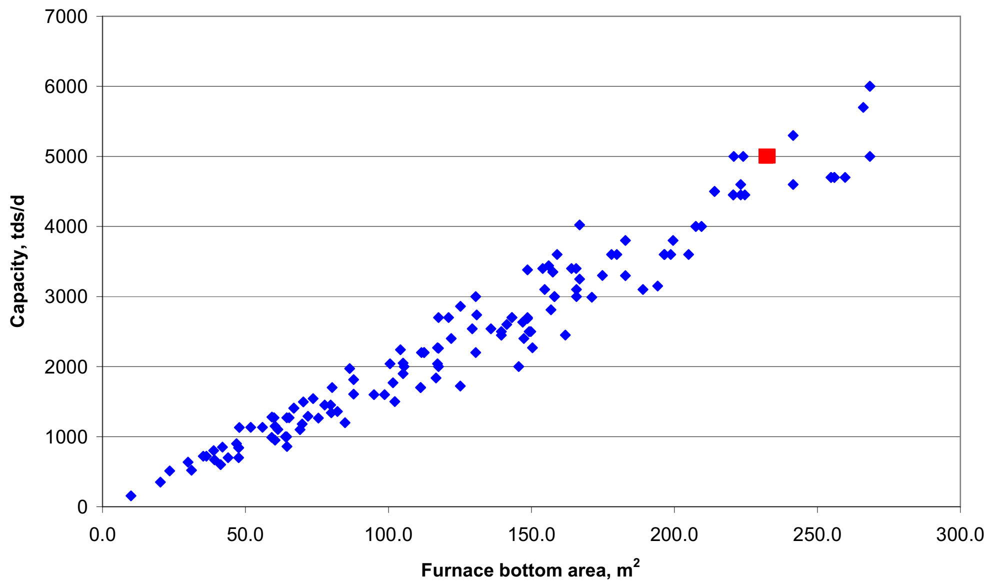
- laskennat 100 % ja 80 % Tapaus F
- Laskenta 100 % -> 80 %
- Esitetään myöhemmin



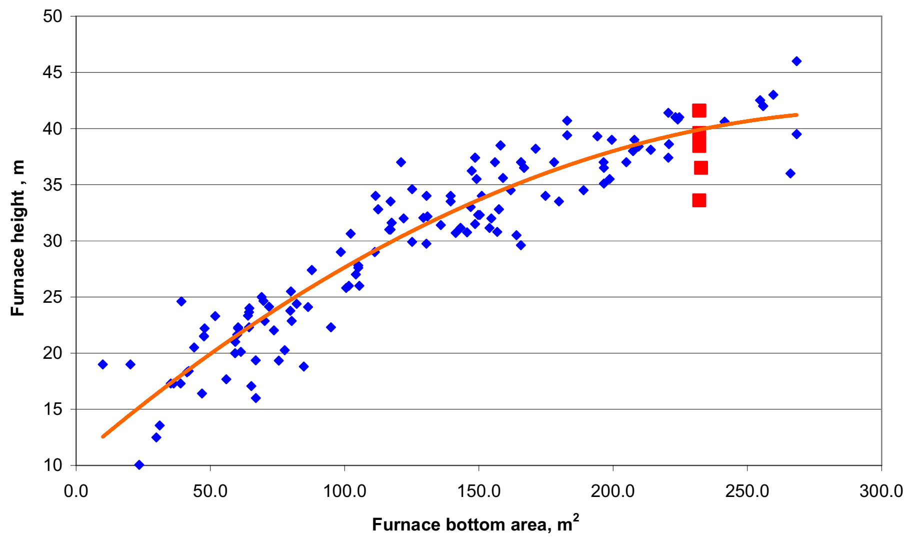
Mitoitus ja talous

- Dimensions for each Case
- Prices for each Case
- Economies for each Case
- To be presented

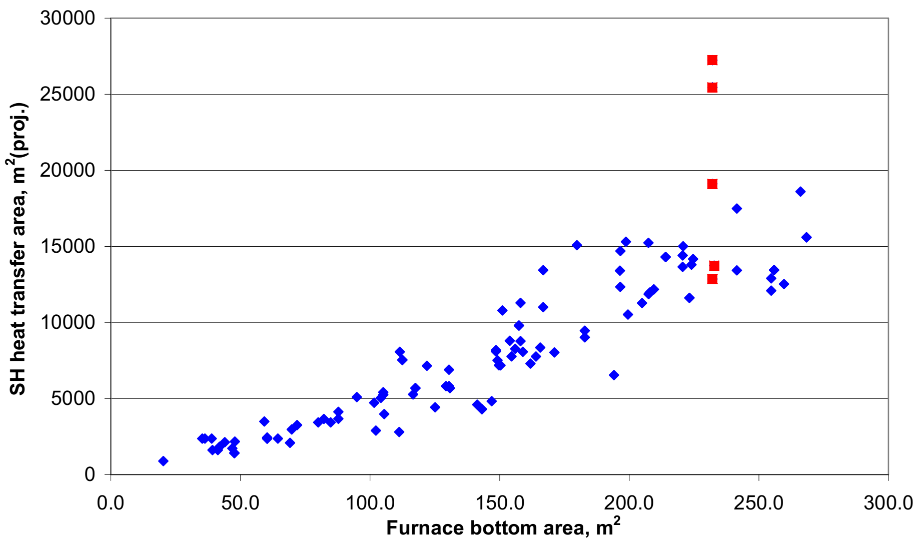
Kapasiteetti vs pohjan koko



Kattilan tulipesän korkeus vs pohja



Tulistinpinta vs pohja



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Soodakattilan lämpöpinnat

Tapaus		**A**	**B**	**C**	**D**	**E**	**F**
Kapasitetti	tds/d	5500	5500	5500	5500	5500	5500
Kuiva-aine	%	82.0	85.0	85.0	85.0	85.0	85.0
HP höyry	bar(a)	94.0	104.0	124.0	164.0	124.0	264.0
HP höyry	°C	490.0	505.0	515.0	540.0	515.0	540.0
Suunnittelu paine	bar(e)	130	129	148	186	148	289
Tulipesä	m2	233.6	232.1	232.1	232.1	232.1	234.4
Korkeus nokka	m	36.5	41.6	41.6	39.6	38.4	33.6
Kattilan korkeus	m	75.5	75.1	78.0	76.0	75.0	72.0
Tulipesä	m2	4417	5056	5056	4813	4672	4084
Verho	m2	0	796	0	796	796	796
Tulistin	m2	16004	12984	15446	19429	20437	23803
Keittopinta	m2	13600	10262	11982	11982	11982	12786
Eko	m2	40720	39676	39676	39529	39382	39235
Yhteensä	m2	98454	82310	88262	96804	98575	105075
Lisäsähkö	MW	0.0	4.0	11.2	23.6	12.3	22.9
	%	0.0	6.8	19.3	40.5	21.1	39.4

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Soodakattilan painot

Tapaus		**A**	**B**	**C**	**D**	**E**	**F**
Kapasitetti	tds/d	5500	5500	5500	5500	5500	5500
Kuiva-aine	%	82.0	85.0	85.0	85.0	85.0	85.0
HP höyry	bar(a)	94.0	104.0	124.0	164.0	124.0	264.0
HP höyry	°C	490.0	505.0	515.0	540.0	515.0	540.0
Paineosien paino							
Tulipesä	tons	1035	1085	1107	1157	1051	843
Verho	tons	0	465	0	588	503	543
Tulistin	tons	2254	1463	1827	2490	2417	2569
Keittopinta	tons	813	740	1041	1041	1041	1080
Eko	tons	1845	2080	2080	2072	2063	2057
Lämpöp. yhteensä	tons	5946	5832	6055	7348	7075	7091
Riippuva paino	tons	9250	8760	9270	10290	10170	10140

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Soodakattilan lisäsähkö

Tapaus		**A**	**B**	**C**	**D**	**E**	**F**
Kapasitetti	tds/d	5500	5500	5500	5500	5500	5500
Kuiva-aine	%	82.0	85.0	85.0	85.0	85.0	85.0
HP höyry	bar(a)	94.0	104.0	124.0	164.0	124.0	264.0
HP höyry	°C	490.0	505.0	515.0	540.0	515.0	540.0
Kustannus							
Kustannusero	M€	9.2	0.0	6.5	17.1	24.3	27.0
Sähköero	MWe	-4.0	0.0	7.3	19.6	8.3	19.0
Lisämegawatti	k€/MWe	-2310	0	890	875	2921	1422
Lisäsähkö	€/MWh	-57.8	0.0	22.2	21.9	73.0	35.6

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Soodakattilan lisäsähkö

		tapaus C	nuohous	Ei KPEL	<SVLT	Ilma 150	Ilma 120
Tapaus		**C0**	**C1**	**C2**	**C3**	**C4**	**C5**
Ilmat lämpötila	°C	190.0	190.0	190.0	190.0	**150.4**	**121.2**
Syöttövesi	°C	148.0	148.0	148.0	**120.0**	**120.0**	**120.0**
HP FW	°C	200	200	200	200	200	200
HP FW	°C	220	220	**200**	**200**	**200**	**200**
Savukaasut	°C	197	197	197	**155**	**155**	**155**
Nuohous	kg/s	6.0	**6.0**	**6.0**	**6.0**	**6.0**	**6.0**
Höyryvirta (SK)	kg/s	232.5	228.6	221.0	217.1	213.6	211.1
Muutos	%	0.0	-1.7	-5.0	-6.6	-8.1	-9.2
Selluntuotanto	MW	88.9	88.9	88.9	88.9	88.9	88.9
Tehdas	MW	92.4	92.4	92.4	92.4	92.4	92.4
Sähköä	MW	161.8	160.8	158.4	156.5	154.5	153.6
Myynti	MW	69.4	68.3	66.0	64.1	62.0	61.2

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Yhteenveto

- Tehdyt muutokset ovat edullisia
- Välitulistus ei kannata
- Höyryn arvojen nosto kannattaisi jos kattilat kestää
- Avustettu kierto kannattaisi, mutta korroosio = ?
- Läpivirtaus kannattaisi, mutta korroosio = ?

Liite VII

Esa Vakkilainen, LUT - report:
Once-through and reheater recovery boiler concepts

Lappeenrannan teknillinen yliopisto
Teknillinen tiedekunta, Energiatekniikka

Vakkilainen Esa, Kaikko, Juha, Hamaguchi, Marcelo

Once-through and reheater recovery boiler – concept studies

Final report 18.11.2009

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Summary

The starting point of this study was increasing kraft pulp mill electricity generation. It has already considerably improved though higher main steam pressure and temperature values.

This research focuses on a new pulp mill with a large recovery boiler at nominal capacity 5500 tds/24h (as fired liquor) which runs at about 200 kg/s steam flow. This study considers both the pulp mill with biomass boiler as well as pulp mill without biomass boiler.

In this study several recovery boiler concepts were compared with the whole pulp mill energy balance being considered. The studied concepts are

A. Natural circulation 82 %, 490 °C, 9.0 MPa (reference Joutseno)
B. Natural circulation 85 %, 505 °C, 10.2 MPa (reference Kymi)
C. Natural circulation 85 %, 515 °C, 12.0 MPa (reference Yonago)
D. Assisted circulation 85 %, 540 °C, 16.0 MPa (reference SoTu)
E. Natural circulation 85 %, 515/400 °C, 12.0/3.0 MPa (SkyRec)
F. Once-through 85 %, 540/460 °C, 26.0/5.4 MPa (SkyRec+)

Steam and electricity generation for each recovery boiler case is shown in Table 9-1. The steam production increases from Case A to Case B because of higher black liquor dry solids and more air preheating. The steam production increases from Case B to Case C because of high pressure preheating. The recovery boiler steam flow starts decreasing as further increases in main steam parameters require more heat.

As can be seen the modern recovery boiler Case C does produce about 20 % more electricity than roughly ten years ago, case A. reheating cases E and E160 seem to give only marginally better electricity production. The only alternative seems to be to increase the main steam temperature to 540 °C, Cases D and F. The pulping electricity usage is not constant. The main parameter that changes is the recovery boiler feedwater pump power requirement.

Electricity generation does not depend a lot on how the boiler steam side is configured. Reheating and once-through appear only marginally better when considering the recovery boiler electricity generation.

The increase in electricity generation seems very profitable up to case C. This confirms the rationality of design choices that have lead to the present recovery boiler. Case A costs more that it should were it built today. The reason is larger than required superheating surface and smaller than currently used superheater tube size. From cost of additional power, going to SoTu concept of 540 °C steam seems desirable. Currently the corrosion issues have not yet been solved so in this study we assume that superheaters do not corrode. Reheater boiler concept seems not at all profitable. The additional electricity generation was only marginal. Once-through recovery boiler did produce as much additional electricity than the SoTu concept of 540 °C steam. The corrosion issues still remain the same.

Yhteenveto

Tutkimuksen lähtökohtana on sellutehtaan sähköenergian kehityksen parantaminen. Sellutehtaan sähköenergiaa ovat parantaneet erilaiset jo käytetyt tavat kuten päähöyryn lämpötilan tai paineen nosto.

Tässä tutkimuksessa on otettu lähtökohdaksi kokonaan uusi sellutehdas, jossa nimelliskooltaan 5500 tka/24h (polttolipeänä) soodakattila ajaa noin 200 kg/s höyrykuormaa. Tarkasteluna on käsitelty sekä soodakattilan että voimakattilan muodostamaa kokonaisuutta samoin kuin pelkästään soodakattilan muodostamaa kokonaisuutta.

TABLE OF CONTENTS

ABBREVIATIONS

CHP	combined heat and power
CNCG	concentrated non condensable gases
DNB	departure from nucleate boiling.
DNCG	diluted non condensable gases
HP	high pressure steam (steam from recovery boiler)
LP	low pressure steam (3.5 - 6 bar)
MCR	maximum continuous rating
MP	medium pressure steam (9.5 – 14 bar)
NBSW	Northern bleached softwood pulp

1 INTRODUCTION

The Finnish Recovery Boiler Committee has undertaken to study the future recovery boiler concepts. The aim is to increase the electricity generating potential and energy efficiency of recovery boilers. This is in line with the Finnish Government's long-term climate and energy strategy and the aims of the European Union and its objectives. This work has been supported by TEKES.

The work consists of once-through recovery boiler concept and study how this might increase the electrical efficiency. Necessary automation and safety changes are to be listed. Final report is a summary of the main tasks.

1. Calculate mass and energy balances to a recovery boiler of about 200 kg_{steam}/s (~5000 tds/d).
2. Place heating surfaces at several typical pressures and temperatures along the flue gas flow
3. Show how water-steam circulation is done
4. Examine 100 % ja 80 % flows with concepts studied with APROS
5. Examine the effect of feedwater preheating
6. Examine the effect of air preheating
7. Look at how placing of reheater affects the recovery boiler

1.1 Comments to targets given 25.6.2009

SKYREC organized a meeting to get comments on different concepts studied. The following comments were received

- Maximum current superheating with long term experience is 515°C
- Calculate once-through boiler with reheater (without reheater does not make sense)
- The need is to calculate new concepts 515°C with reheating
- Choose main steam and reheated steam values so that for LP-steam desuperheating is maximum 30 °C or minimum 2 % of moisture.
- Study effect of feedwater preheating for Case C include the resizing of superheaters
- Study effect of air preheating for Case C include the resizing of superheaters
- Do mill steam consumption and electricity steam consumption separate to recovery boiler
- Reheater boiler needs more Sootblowing steam
- Sanicro price is ~300 €/m
- Examine low pressure or medium pressure steam production from flue gases

Case C represents the state-of-the-art with respect of electricity generation. It utilizes the maximum main steam temperature that can be considered currently economically 515°C. The mill is producing MP or LP steam from the recovery boiler flue gases 197°C -> 155°C.

To find from literature clear comparisons of current cases e.g. Swedish boilers and Finnish boilers.

The main steam pressure and temperature of concept D needs more thought.

When choosing the main steam values the low pressure steam the maximum moisture allowed for LP steam is 2 % and the maximum attemperating fro Lp steam is 30 ^{o}C.

There is no reason to consider just once-though boiler but to consider once-through reheater boiler.

2 DEVELOPMENT OF RECOVERY BOILER

The pulp and paper industry faces a new era. New environmental expectations have appeared. Cutting down air emissions is not enough. Pulp and paper mills need to maximize their bioenergy potential and minimize their electricity consumption to produce green electricity.

Recovery boilers, which produce bioenergy, are built all over the world. The recovery boiler has developed in the past 70 years. It has culminated with units that are among largest biofuel boilers in the world. For pulp mills the significance of electricity generation from the recovery boiler has been secondary. The most important design criterion for the recovery boiler has been the high availability.

2.1 Main steam temperature

Maximizing electricity generation is driving increases in the main steam pressures and temperatures. The maximum steam temperature can be limited by the ash properties. The first melting curve at the superheater front should be taken into account. Increasing mill closure with high chlorine and potassium decreases the melting temperatures. The overall mill heat balance should be used to optimize the feed water and flue gas temperatures.

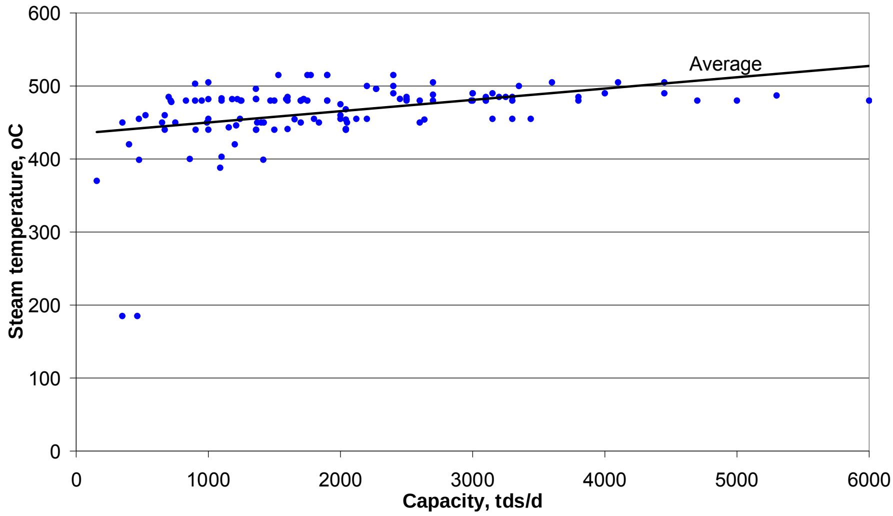

Figure 2-1, Main steam temperature as a function of recovery boiler capacity.

The main steam temperature of recent recovery boilers is shown in Figure 2-1 as a function of MCR capacity of that boiler. The average steam temperature increases with size. Small boilers tend to have lower pressures to reduce specific cost. There are many boilers with main steam parameters higher than 500 ^{o}C. Most of them are in Japan.

2.2 Relationship between main steam values

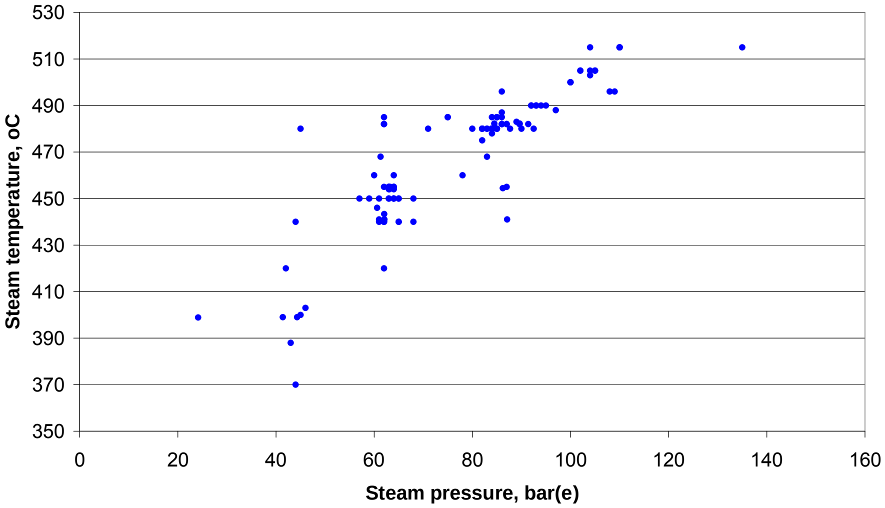

Figure 2-2, Main steam temperature as a function of recovery boiler main steam pressure.

The main steam temperature of recovery boilers is shown in Figure 2-2 with the corresponding main steam pressure. An increase in main steam temperature is usually accompanied with an increase in the main steam pressure. Increasing just either steam pressure or temperature alone has only a minor effect on back pressure electricity generation.

2.3 Black liquor dry solids

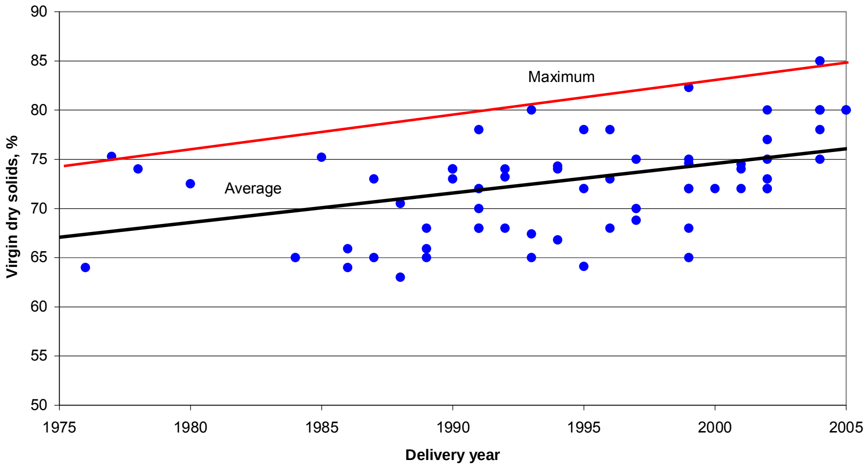

Figure 2-3, Virgin black liquor dry solids as a function of purchase year of the recovery boiler.

Black liquor dry solids has always been limited by the ability of available evaporation technology to handle highly viscous liquor. As technology has evolved so has the final black liquor dry solids. The virgin black liquor dry solids of recovery boilers is shown in Figure 2-3 as a function of purchase year of that boiler.

On average the virgin black liquor dry solids content has increased. This is especially true for latest very large recovery boilers. Design dry solids for the new green field mills and new recovery islands have been either 80 or 85 % dry solids. In Asia and South America 80 % (earlier 75 %) dry solids is in use. In Europe 85 % (earlier 80 %) dry solids is in use.

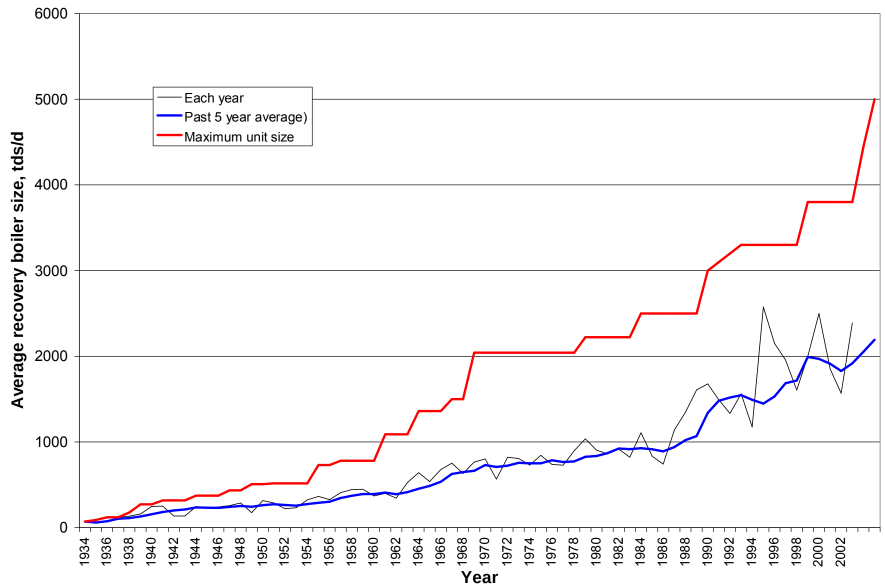

Figure 2-4, Size of the recovery boiler as a function of purchase year.

Recovery boiler size keeps increasing. The recovery boiler size doubles about every 20 years. Boilers with over 200 square meter bottom area are typical for the largest new greenfield mills. The largest recent proposals have been for a 6000 tds/d boiler. Average boiler size has typically been about half of the largest boiler bought.

The recovery boiler is now challenging circulating fluidized bed boilers for the title of largest bio-fuel fired boiler. Recovery boiler furnace size is about the size of the largest natural circulation coal fired boilers. This means that the existing mechanical and commercial limits of furnace size for natural circulation units have now been reached.

3 RECOVERY BOILER CONCEPTS

In the study some of the existing recovery boiler concepts are compared to future recovery boiler concepts. In the meeting 26.6.2009 it was agreed that the studied concepts are

A. Natural circulation 82 %, 490 ^{o}C, 9.0 MPa (reference Joutseno)
B. Natural circulation 85 %, 505 ^{o}C, 10.2 MPa (reference Kymi)
C. Natural circulation 85 %, 515 ^{o}C, 12.0 MPa (reference Yonago)
D. Assisted circulation 85 %, 540 ^{o}C, 16.0 MPa (reference SoTu)
E. Natural circulation 85 %, 515/400 ^{o}C, 12.0/3.0 MPa (SkyRec)
F. Once-through 85 %, 540/460 ^{o}C, 26.0/5.4 MPa (SkyRec+)

3.1 Case A - Modern high efficiency boiler

The modern recovery boiler is of a single drum design, with vertical steam generating bank and wide spaced superheaters. The most marked change was the adoption of single drum construction. The construction of the vertical steam generating bank is similar to the vertical economizer.

The effect of increasing dry solids concentration has had a significant effect on the main operating variables. The steam flow increases with increasing black liquor dry solids content. Increasing closure of the pulp mill means that less heat per unit of black liquor dry solids will be available in the furnace (Clement 1990).

The flue gas heat loss will decrease as the flue gas flow diminishes. Increasing black liquor dry solids is especially helpful since the recovery boiler capacity is often limited by the flue gas flow.

The most marked change in this case was that the mill (market NBSW pulp mill) was able to produce substantial amounts of electricity for sale even when selling all bark to neighbouring mills (Veitola, 2000).

In this concept the benefits of having a condensing tail were first realized. In addition this was one of the first boilers where biosludge with both DNCG and CNCG were burned with high dry solids black liquor (Vakkilainen, 2000)

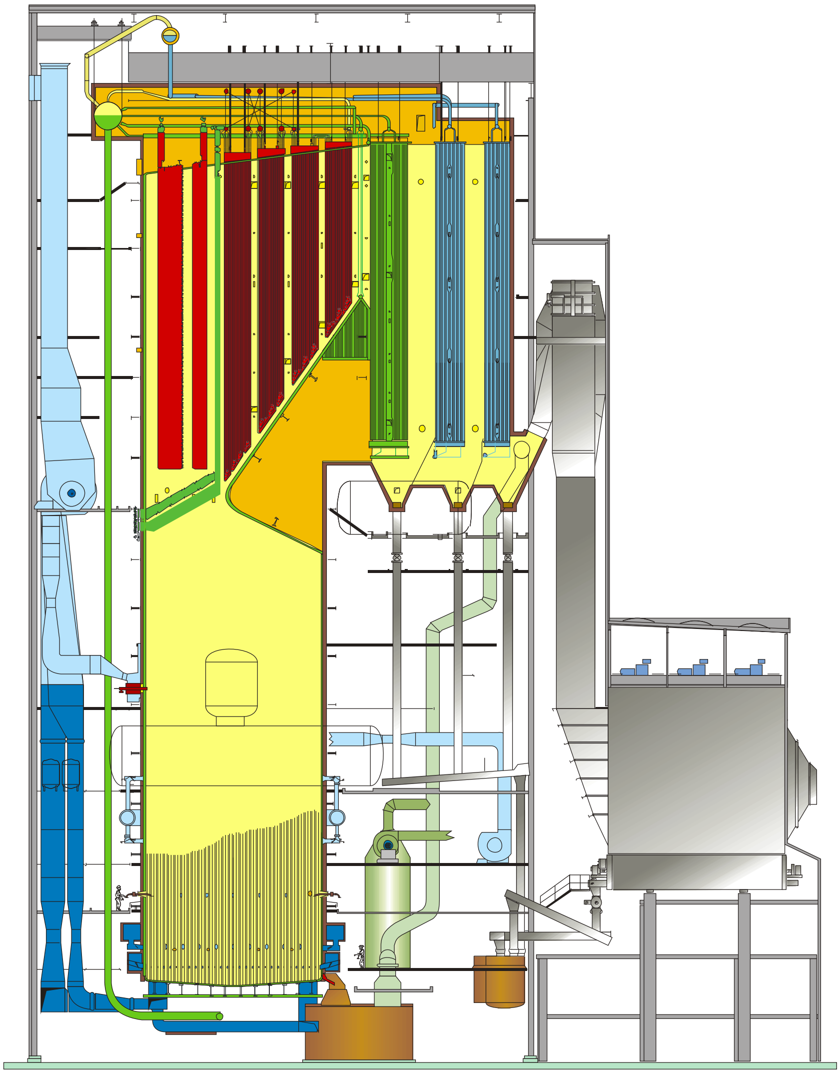

Figure 3-1, Modern recovery boiler, Vendor Andritz Oy, Capacity 3500 t ds/24h, Black liquor ds 82,3 % (80 %) Main steam 130 kg/s 93 bar(a) 490 °C.

3.2 Case B – High efficiency recovery boiler

During recent years the price of electricity has increased and especially the desirability of electricity produced from renewable fuels has risen. This has led to mills adopting strategies to increase the electrical generating efficiency (Raukola et al., 2002, Saviharju and Lehtinen 2005, Westberg 2007).

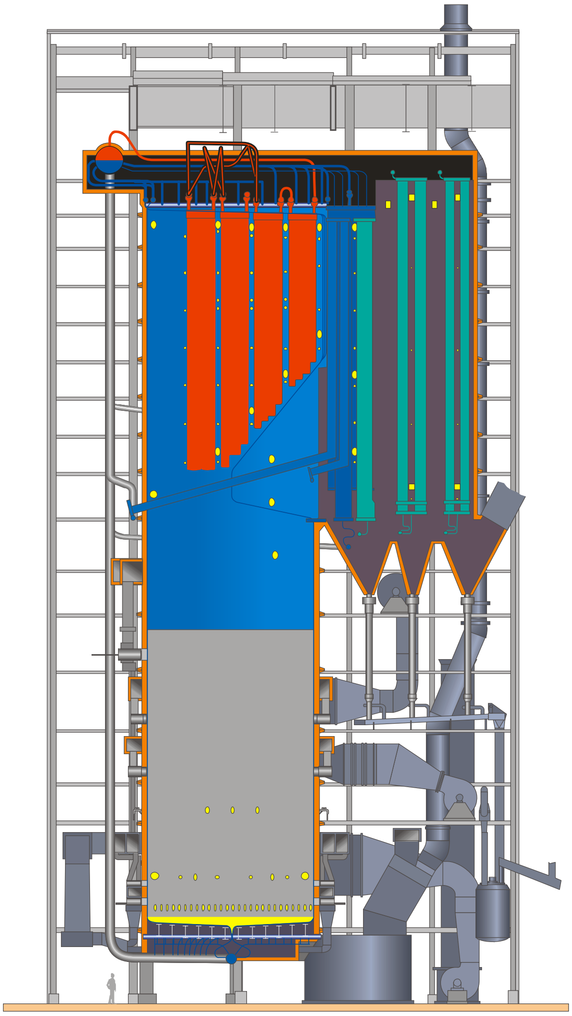

Figure 3-2, High efficiency recovery boiler, Vendor Metso Power Oy, Capacity 3600 t ds/24h, Black liquor ds 85 % (80 %) Main steam 170 kg/s 102 bar(a) 505 °C.

One of the aims of this project was to increase the share of electricity produced with biomass (Tikka, 2008). A special feature of this boiler is usage of 29 bar unregulated steam for sootblowing and high air preheating temperature to 190 °C. The feedwater inlet temperature has been raised ot 148 °C and there is an intermediate HP steam feedwater preheat stage between economizer I and Economizer II. Because of the high superheating temperature the last tubes of tertiary superhaters are of Sanicro 28 (Aikio, 2008)

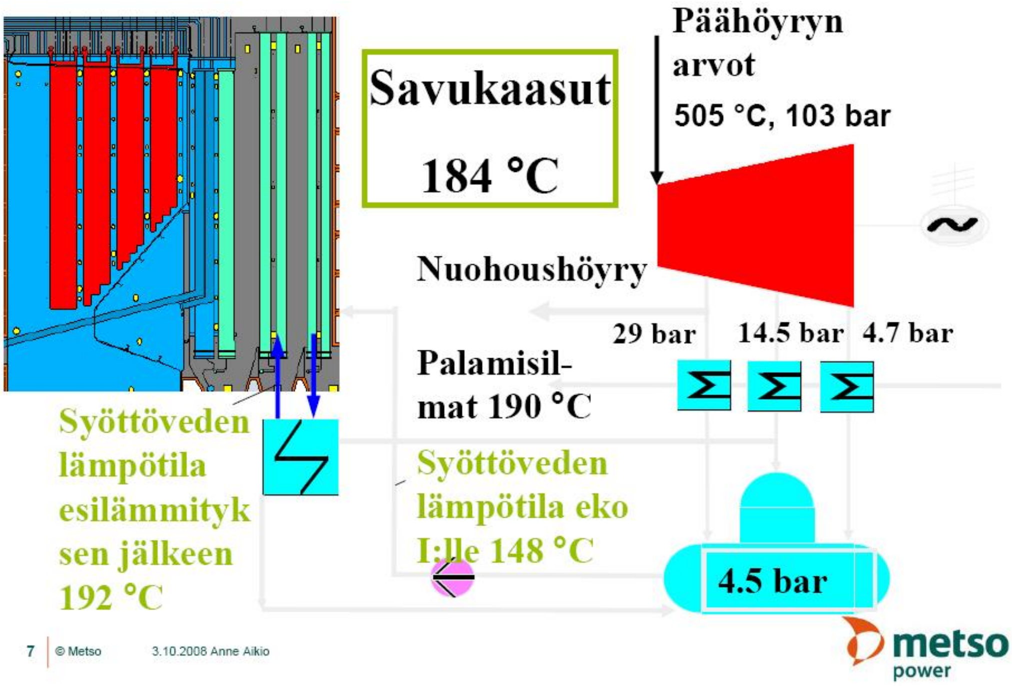

Figure 3-3, Some special features to increase electricity generating efficiency (Aikio, 2008).

3.3 Case C – High pressure and temperature recovery boiler

In 1998 the second generation high pressure and temperature recovery boiler started commercial operation in Japan (Arakawa et al., 2004). Figure 3-4 shows a second-generation high pressure and temperature recovery boilers. The second-generation recovery boiler is of single drum without evaporator design. Furnace outlet water or steam cooled screen tubes are not necessary with new 25%Cr special stainless steel for superheater.

Increasing superheating means that more heat transfer surface needs to be added. The higher main steam outlet temperature requires more heat to be added in the superheating section. Typically the furnace outlet gas temperature has increased. The alternative is to significantly increase superheating surface to decrease boiler bank inlet fluegas temperature. If boiler bank inlet gas temperature is reduced the average temperature difference between flue gas and steam is also decreased. This reduces heat transfer and substantially more superheating surface is needed. Low furnace outlet temperature design has been abandoned because of increased cost. With increasing dry solids content the furnace exit temperature can safely increase without fear of corrosion caused by carryover.

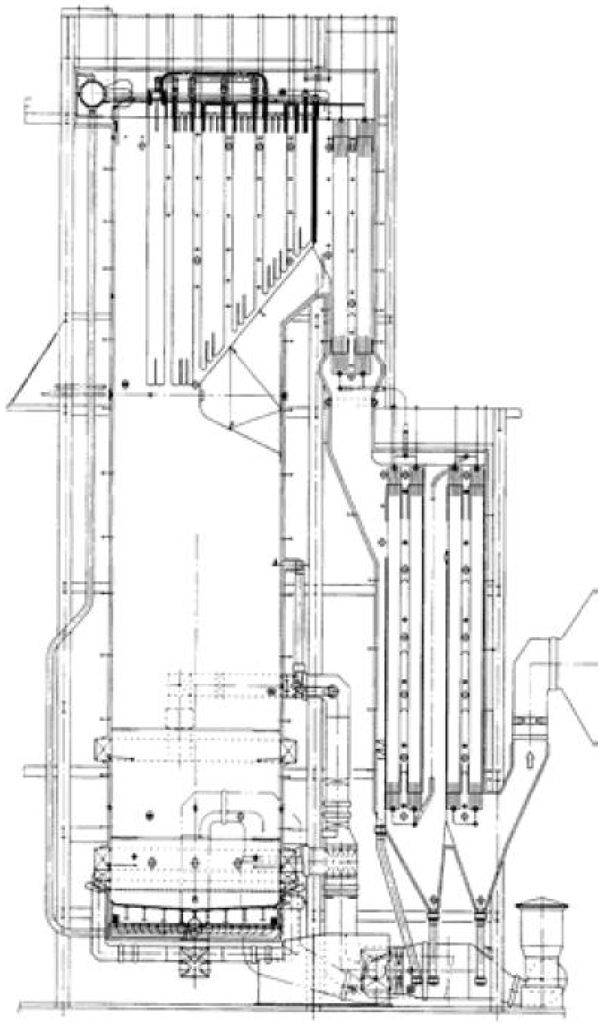

Figure 3-4, High pressure and temperature recovery boiler, Vendor Mitsubishi Heavy Industries, Ltd, Capacity 2500 t ds/24h, Black liquor ds 75 % Main steam 114 kg/s 109 bar(a) 515 °C**.**

3.4 Case D - Assisted circulation recovery boiler concept

Previously the target for higher electricity production has been to further increase temperature and pressure. previously the target concept has been maximum pressure with traditional design (Suomen Soodakattilayhdistys ry., 2007.)

The limit with natural circulation / assisted circulation design was chosen based on literature as 16 MPa (Steam 1992, Steam power engineering 1999). The target steam temperature was chosen as 540 ^{o}C. Concept was however never detailedly studied.

3.5 Case E - Reheater concepts

From steam boiler literature we know that one way to increase electrical generation is applying reheating (Steam, 1992). That is after the steam has expanded partly in a turbine we take it back to the boiler and through another set of heat transfer surfaces called reheating surfaces, where the steam temperature is again raised. Reheating has been practiced in steam boilers for about 100 years.

3.5.1 Case E – High pressure and temperature recovery boiler with reheater concept

Babcock and Wilcox has recently promoted reheating recovery boilers (Hicks et al., 2009). One of the key features is the ability to use old turbine and just add new high pressure set with the new recovery boiler. This typically means rather high reheating pressures.

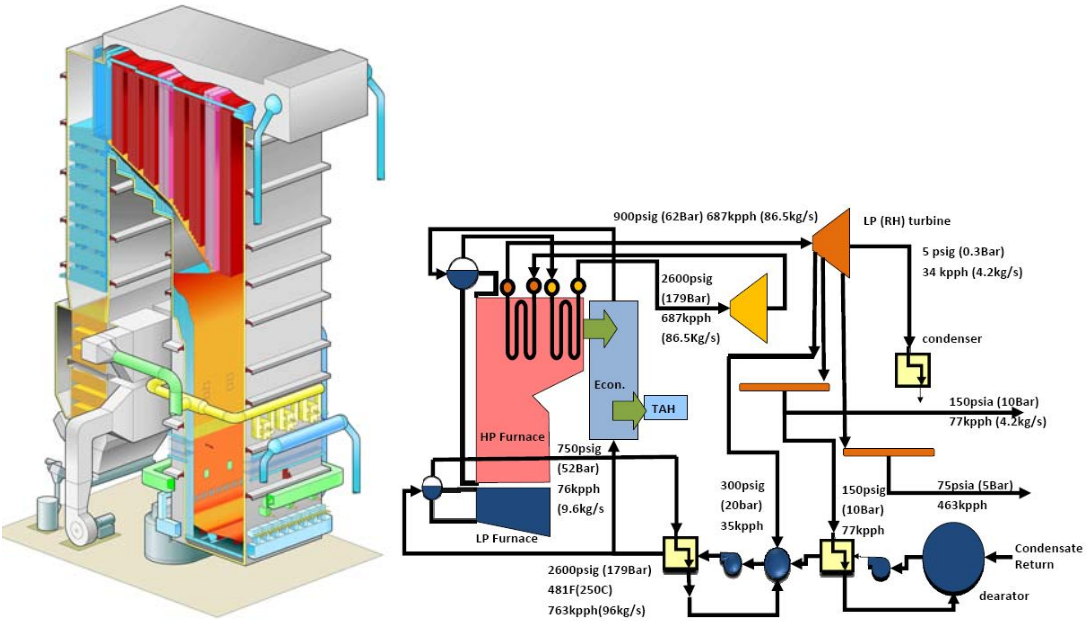

Figure 3-5, Reheater recovery boiler concept Vendor Babcock & Wilcox, Capacity 4500 t ds/24h, Black liquor ds 85 % Main steam 130 kg/s 179 bar(a) 510 °C reheated steam 62 bar(a) 443 °C**.**

One should also note the horizontal tube economizer. Running high dry solids i.e. practically no SO_2 creates non sticky conditions to economizer area.

3.5.2 First choice of reheat temperature

When choosing reheating pressure and temperature the requirement given (Chapter 1.1) was kept in mind. Choose main steam and reheated steam values so that for LP-steam desuperheating is maximum 30 ^{o}C or minimum 2 % of moisture. In table 3-1 several different steam values are examined. The starting condition was chosen based on given instructions as 515°C/12 MPa.

Table 3-1 4.5 bar(a) steam temperature and moisture with different reheats from 515 °C/12 MPa to different pressure and temperature combinations (bold values full fill condition <30 °C desuperheat and < 2 % moisture).

	480°C	460°C	440°C	420°C	400°C	380°C	360°C	340°C	320°C
5.4 MPa	182.7	***169.9***	***157.1***	***147.9***	147.9	147.9	147.9	147.9	147.9
	1.000	***1.000***	***1.000***	***0.994***	0.978	0.938	0.920	0.900	0.879
4.4 MPa	202.4	189.3	***176.1***	***162.8***	***147.9***	***147.9***	147.9	147.9	147.9
	1.000	1.000	***1.000***	***1.000***	***1.000***	***0.984***	0.967	0.934	0.914
3.4 MPa	228.2	214.5	200.8	187.0	***173.2***	***159.3***	***147.9***	147.9	147.9
	1.000	1.000	1.000	1.000	***1.000***	***1.000***	***0.995***	0.978	0.960
2.4 MPa	264.8	250.3	235.8	221.2	206.6	192.0	***177.3***	***162.6***	***147.9***
	1.000	1.000	1.000	1.000	1.000	1.000	***1.000***	***1.000***	***0.998***
1.4 MPa	326.8	310.8	294.8	278.7	262.6	246.5	230.4	214.3	198.1
	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

Of the choices the combination of 3.6 MPa out and 3.4 MP in with reheating to 400 °C was chosen. This means that steam to be reheated can be used as sootblowing steam.

3.5.3 Comparison of chosen reheat temperature and pressure

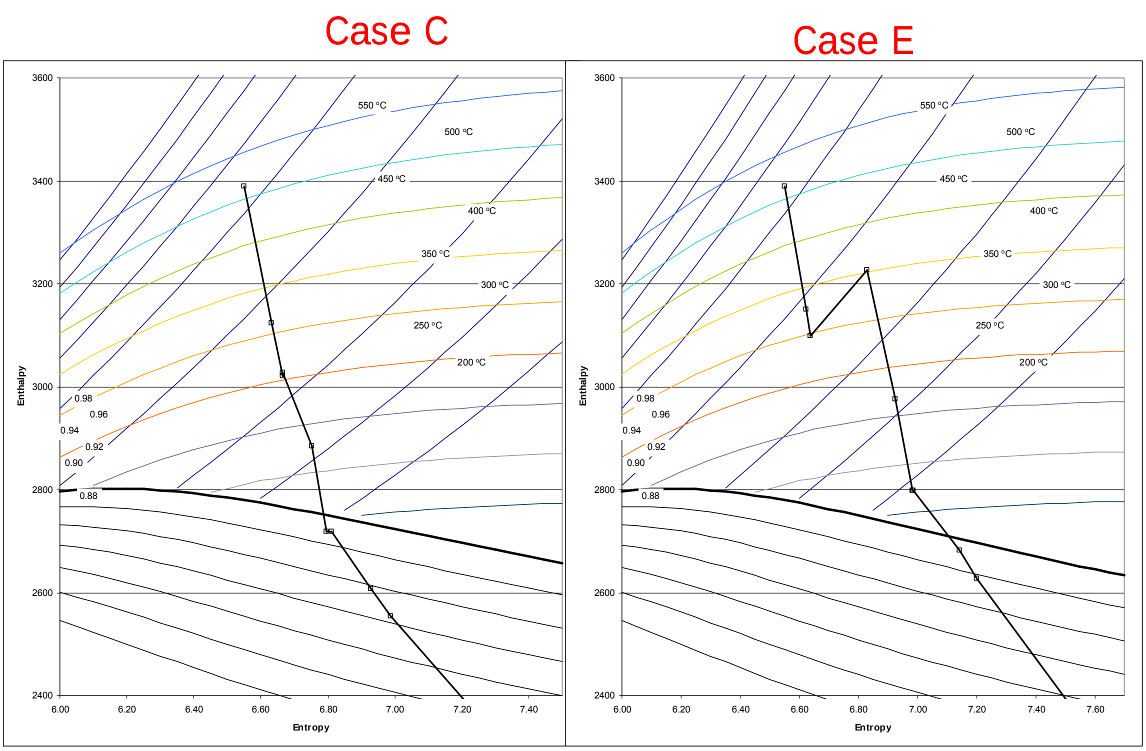

Figure 3-6, Comparison of case C and E

The chosen concept was calculated but the increase in electricity generation remained rather small. Therefore comparison with Case C was done.

Both start expansion at h=3389.2 kJ/kg at 514/118. After expansion to h=3098.9 kJ/kg at 348/34 reheater case E goes back for more heating and traditional case C continues expansion in the turbine. Case C expands to h=2726.1 kJ/kg at 149.5/4.5 while case E expands after reheat from h=3227.3 kJ/kg at 400/32 to h=2799.1 kJ/kg at 173/4.5.

Because 3389.2-2726.1= 663.1 kJ/kg and 3227.3-3098.9 + 3227.3-2799.1= 718.5 kJ/kg with difference of 55.4 kJ/kg the extra electricity from reheat seems large. However, the additional expansion is only 55.4/(3389.2 – 2799.1) if we assume that condensing tail expansion difference remains the same. This means that for each kg of steam expanding through turbine 8.4 % of more electricity is generated.

To generate reheated steam more heat is needed. In case C the heat addition is from 148 ^{o}C = 623.5 kJ/kg to main steam = 3340.4 kJ/kg (=2765.7 kJ/kg). In Case E more heat is added in reheat from 348 ^{o}C = 3098.9 kJ/kg to 400 ^{o}C = 3225.9 kJ/kg. So in Case C the heat addition is 3389.2 - 623.5 = 2765.7 kJ/kg and in Case E this is 2716.9 + (3227.3 - 3098.9) = 2894.1 kJ/kg. So in Case C the heat that produces 1 kg of steam produces only 0.956 kg steam with the same heat addition. The increase in electricity generation is therefore reduced to 0.956*718.5 = 686.6 kJ/kg or 3.4 %. If we take into account that the added sootblowing (+2 kg/s) reduces steam flow through the turbine and reheating causes poorer working of the condensing tail, the net benefit is reduced to almost zero.

3.5.4 Improving reheat from first premise

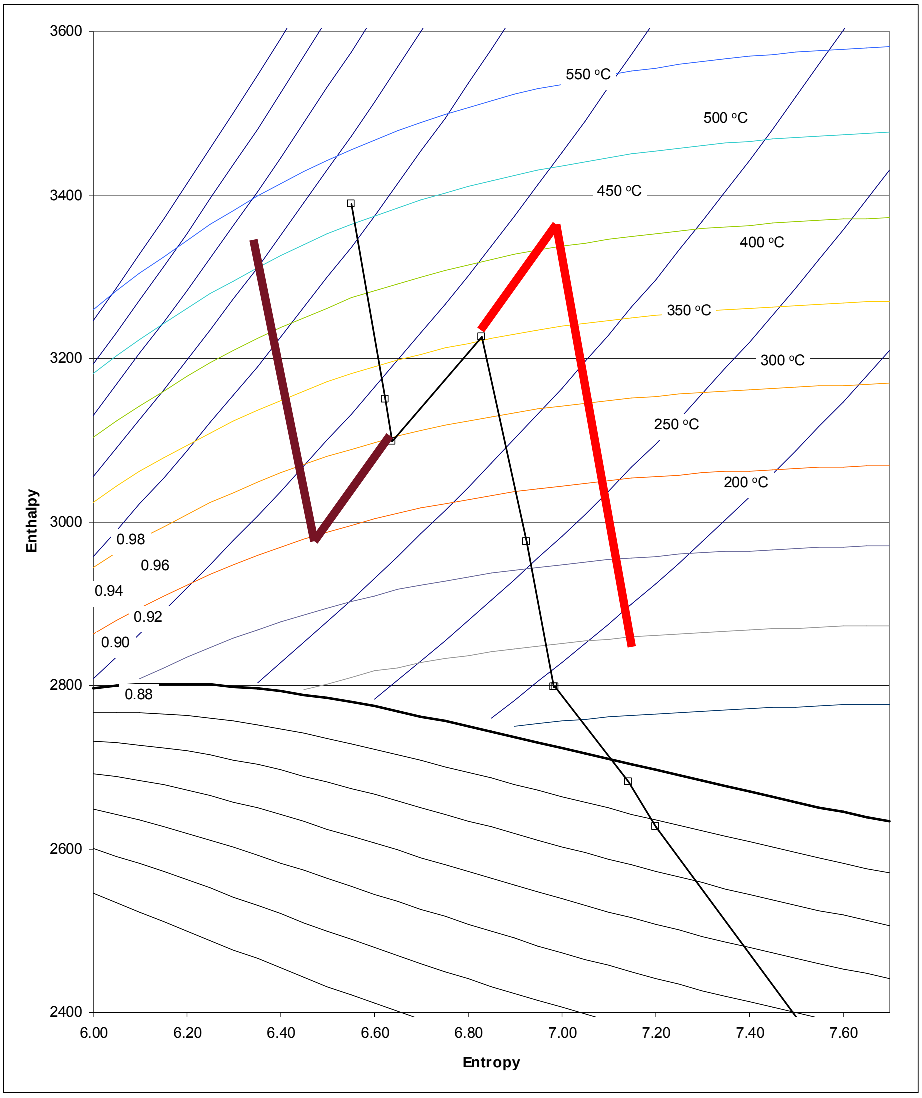

Figure 3-7, Options to improve reheat

One can increase reheating (the bright red line), but then the LP steam gets more and more superheated. A better alternative is to increase main steam pressure to e.g. 160 bar resulting in larger expansion, more heat addition and increased steam generation.

Therefore the alternative Case E with 160 bar furnace was calculated. The drawback is even more reheater surface.

3.6 Case F - Once-through recovery boiler with reheater concept

If we still want to increase the operating pressure we need to change to once-through boiler concept. Once-through boilers have been used since the 1930's and have been the main type for large utility boilers from the 1950's.

To improve cycle efficiency, utility boiler main steam pressures have increased to typically 248 bar. The steam temperatures have long remained conservative i.e. 540 ^oC, but have recently started to climb close to 600 ^oC.

Utility boilers use typically multiple feedwater heaters and have regenerative air heaters where flue gas heats air. These features add significantly to steam generation efficiency. To make comparison valid no additional heaters have been used for Case F. To choose main parameters again a comparison for end expansion conditions has been done, Table 3-2.

Table 3-2 4.5 bar(a) steam temperature and moisture with different reheats from 540 ^oC/26 MPa to different pressure and temperature combinations (bold values fullfill condition <30 ^oC desuperheat and < 2 % moisture).

	520°C	500°C	480°C	460°C	440°C	420°C	400°C	380°C	360°C
5.4 MPa	208.2	195.4	182.7	***169.9***	***157.1***	***147.9***	147.9	147.9	147.9
	1.000	1.000	1.000	***1.000***	***1.000***	***0.994***	0.978	0.938	0.920
4.4 MPa	228.7	215.6	202.4	189.3	***176.1***	***162.8***	***147.9***	***147.9***	147.9
	1.000	1.000	1.000	1.000	***1.000***	***1.000***	***1.000***	***0.984***	0.967
3.4 MPa	255.5	241.8	228.2	214.5	200.8	187.0	***173.2***	***159.3***	***147.9***
	1.000	1.000	1.000	1.000	1.000	1.000	***1.000***	***1.000***	***0.995***
2.4 MPa	293.8	279.3	264.8	250.3	235.8	221.2	206.6	192.0	***177.3***
	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	***1.000***
1.4 MPa	358.9	342.9	326.8	310.8	294.8	278.7	262.6	246.5	230.4
	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

Of the choices the combination of 5.6 MPa out and 5.4 MP in with reheating to 460 ^oC was chosen. This means that the reheat lines remain smaller than with lower pressures. If a higher temperature was chosen (e.g. 540 ^oC) then the expansion would be quite dry at around 5 bar.

4 WATER AND STEAM CIRCULATION

For a boiler to operate properly the steam water circulation must be designed for large variations of load, manageable temperature differences in parallel tubes and low possibility of tube inside erosion.

The main areas in steam-water side circulation design are choosing the right type of circulation, dimensioning downcomers and risers, dimensioning of superheater and dimensioning boiler banks.

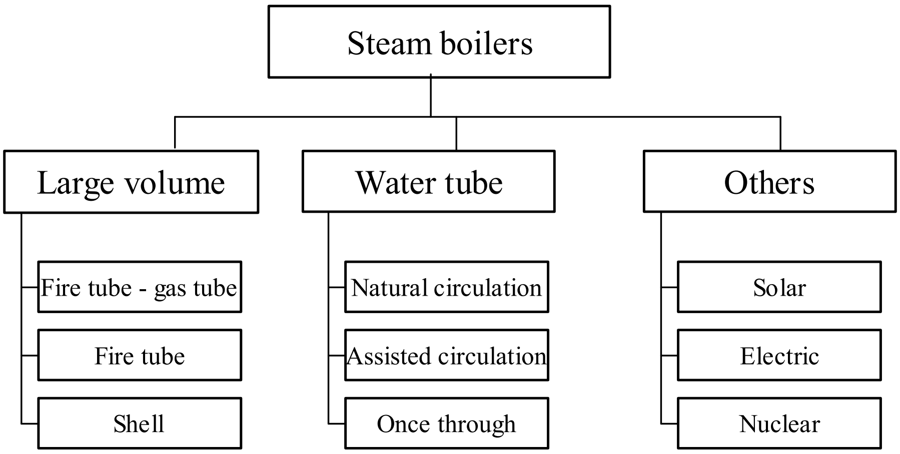

Figure 4-1, Classification of steam water side

There are two main groups of steam water circulation, Figure 4-1. The first group is the large volume boilers. In them the heating evaporates steam inside a large volume of water. For example a teakettle could be considered a large volume type.

Second group is the boilers where boiling occurs inside a tube filled initially with water. For example the coffee maker operates on this principle. Most of the large modern boilers belong to this group. In addition there is a group that could be called others of miscellaneous. They have features from both of these two groups. Many of the nuclear plant steam circuits as well as solar power circuits belong to this mixed group. All groups, in spite of the design are governed by the same laws.

4.1 Large volume boilers

Large volume boilers are usually fire tube boilers. Because of design they are limited by steam production (capacity) and operating pressure. The basic design has remained the same since the Scottish marine boilers of 1800.

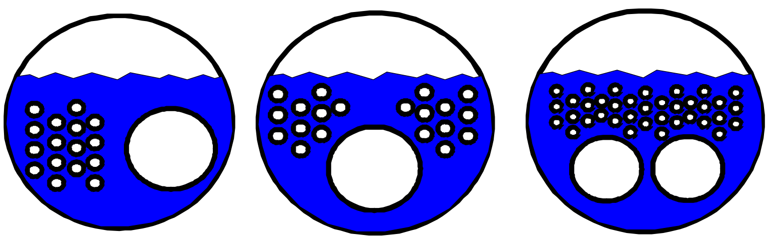

Figure 4-2, Firetube – gas tube boiler designs (Effenberger, 2000).

In large volume boilers water circulates downwards at the edges of the boilers, Figure 4-2. Steam bubbles rise, creating upward flow in the centerline of the boilers. Same mode of operation can be seen by watching a pot of water boiler on a stove.

4.2 Natural circulation boiler

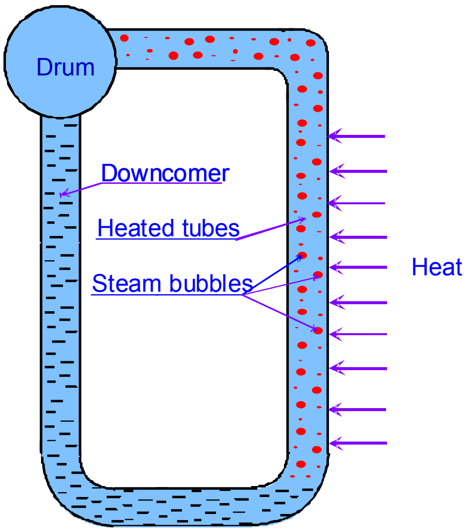

Figure 4-3, Principle of natural circulation.

Natural circulation is based on the density differences. The same principle can be seen in e.g. room in a cold winter day. Heated air rises on the wall where room is heated and subsequently cooled more dense air falls downwards on the opposite wall.

Natural circulation is caused by the density difference between saturated water and heated water partially filled with steam bubbles. In a natural circulation unit water tubes are connected to a loop, Figure 4-3. Heat is applied to one leg called raiser tubes, where water steam mixture flows upward. Denser saturated water flows downward in unheated leg called downcomer. Natural circulation means that the steam water movement in the evaporative tubes is achieved without use of external prime energy and mechanical means.

Driving force is static head difference between water in downcomers and steam/water mixture in furnace tubes.

$$\Delta P_{losses} = (\rho_{water} - \rho_{mixture})gh \qquad 4\text{-}1$$

where
ΔP_{losses} is the flow losses in the circulation
ρ_{water} is the density of the water in the downcomers
$\rho_{mixture}$ is the density of the water steam mixture in the heated section
h height of the circulation

Pressure increase decreases driving force. Natural circulation design is affected by several design factors. If we increase furnace height the driving head increases. We must try to avoid steam in downcomers. Efficient steam separators reduce the fraction of steam inside the drum. Inserting feedwater to drum at subsaturated state cools down and collapses remaining bubbles. Minimize axial flow inside drum helps creating equal flow in all parts of boilers. Natural circulation is also improved by higher heat flux in lower part of the tubes.

4.3 Assisted circulation

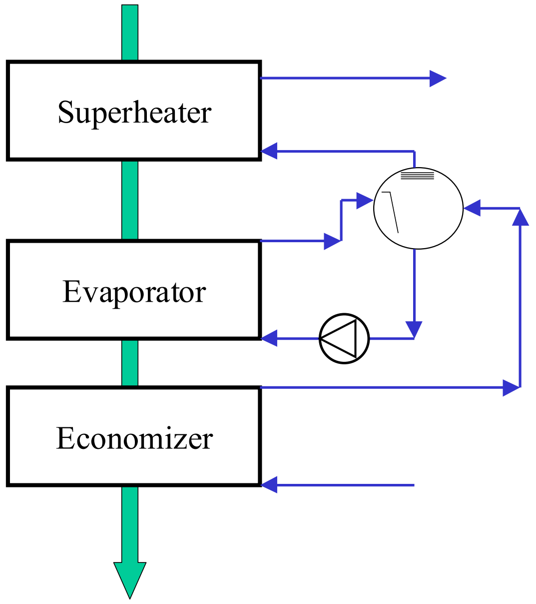

Figure 4-4, Assisted circulation in a HRSG.

Assisted circulation is typical in HRSG boilers and high pressure units. Water from the drum is pumped through evaporative surfaces. Synonyms for assisted circulation are forced circulation and controlled circulation.

4.3.1 Controlled circulation

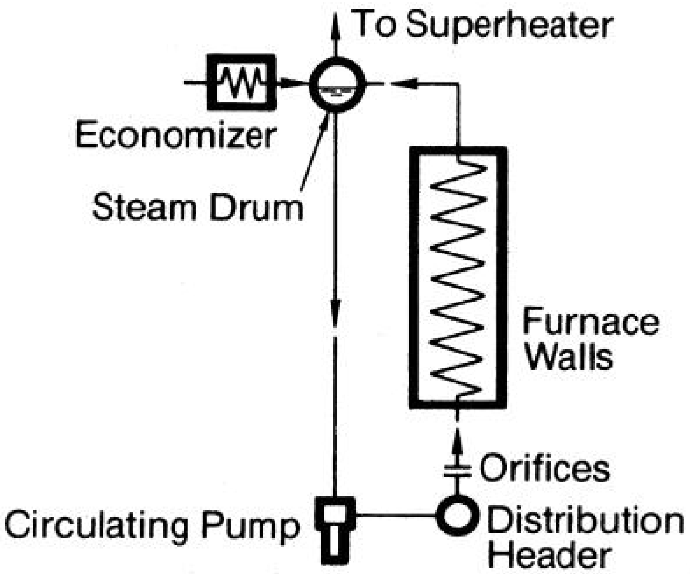

Figure 4-5, Controlled circulation (Combustion, 1991).

In controlled circulation a pump assists flow. Flow is regulated by orifices. This ensures even flow in all wall tubes. Controlled circulation is a trademark of ABB.

4.3.2 La Mont boiler

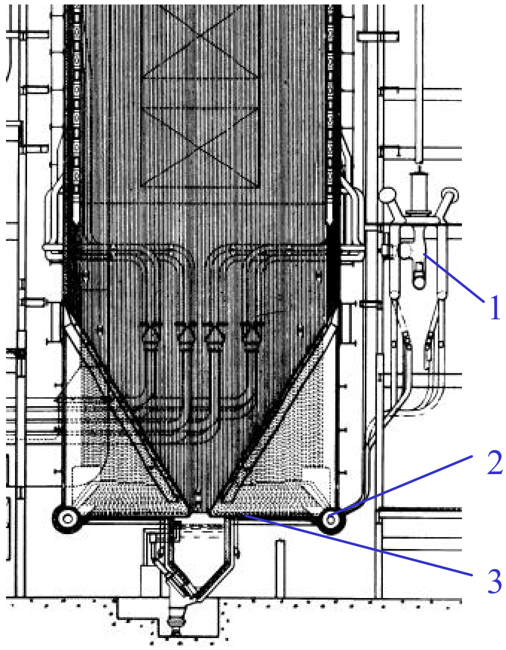

Figure 4-6, La Mont boiler, 1 - HP circulating pump, 2 - header with orifices, 3 - individual wall tubes (Ledinegg, 1966).

The most famous assisted circulation type is the La Mont boiler. The name comes from one manufacturer of these boilers. In La Mont boilers the drum pressure was usually below 19.0 MPa. The main advantage is that the designer can quite freely choose the tube pattern. Water flow through the tubes is controlled by appropriate sized orifices.

Circulation ratio in la Mont boilers is from 4 to 10. Pressure loss in a circuit was usually from 0.1 to 0.3 MPa.

4.4 Once-through boiler

In once-through boiler the water flows continuously through the boiler coming as 100 % steam at the main steam outlet. The circulation does not limit the pressure so boiler can be built at very high pressures. As positive circulation is kept up with the pressure difference the pressure loss through the boiler tends to be large. High pressure loss means high own power demand.

Feedwater purity must be very high as any contaminant tends to stay at the boiler walls. The feedwater must have about the same purity than the steam. The steam purity is dictated by the turbine requirements. Starting and shutting the boiler is problematic.

Because of pumps the mass flow densities in once through boilers are high, Table 4-1.

Table 4-1, Mass flow densities.

Surface	Mass flow density
	kg/m^{2}s
Convective superheater	1000
Furnace tubes	2000-3000
Economizer	600

The furnace tube arrangement is difficult. In natural and assisted circulation the furnace could be made of straight tubes of same temperature. Once-through boilers employ various tube patterns to cover the furnace walls. Based on the type of these circuits the once through boilers are divided into Sultzer Monotube boilers, Benson boilers and Ramzin boilers.

4.4.1 Sultzer Monotube boiler

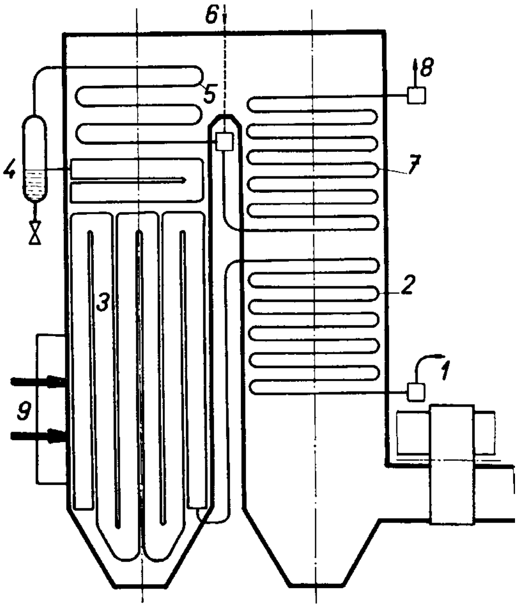

Figure 4-7, Sultzer Monotube circulation, 1 – feedwater inlet, 2-economizing surface, 3-furnace tubes, 4-bottle, 5-superheating surface, 6-desuperheating spray, 7-superheating, 8-main steam out (Doležal, 1967).

One of the first successful once through boilers was the Sultzer Monotube boiler. Its trademark is the use of a bottle, where remaining water droplets are separated from the steam. The flow in the furnace uses u-shaped tube bundles.

4.4.2 Benson-boiler

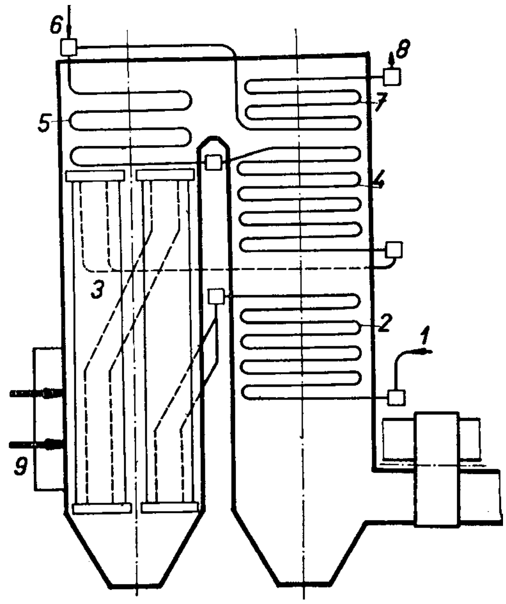

Figure 4-8, Benson boiler circulation, 1 – feedwater inlet, 2-economizing surface, 3-furnace tubes, 4-backpass surface, 5-superheating surface, 6-desuperheating spray, 7-superheating, 8-main steam out (Doležal, 1967).

A competitor to the Sultzer design the Benson boiler had a very similar tube pattern. Very rarely was the bottle or similar device used in a Benson boiler. To facilitate design Benson boiler uses straight heated up flowing parts and unheated down flow parts. In Benson boiler there is no definite point where the evaporation ends and the superheating begins, when operated under the critical pressure.

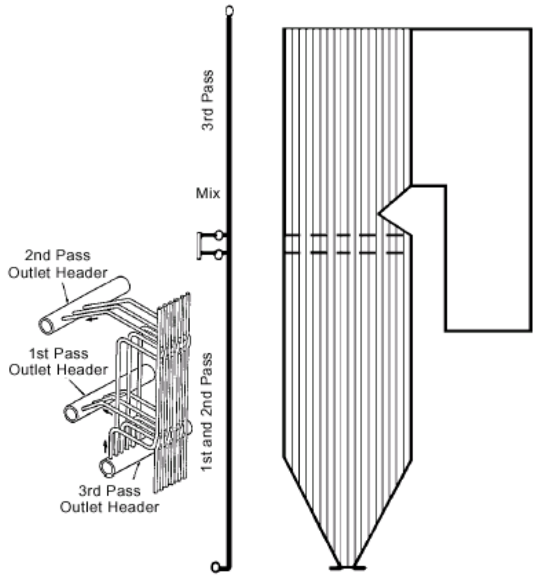

Figure 4-9, Dividing wall passes to segments (Smith, 1998).

Dividing each pass to several segments helps to maintain low temperature differences between adjacent tubes. Heat flux to tubes can vary because of localized fouling and tube placement.

4.4.3 Ramzin-boiler

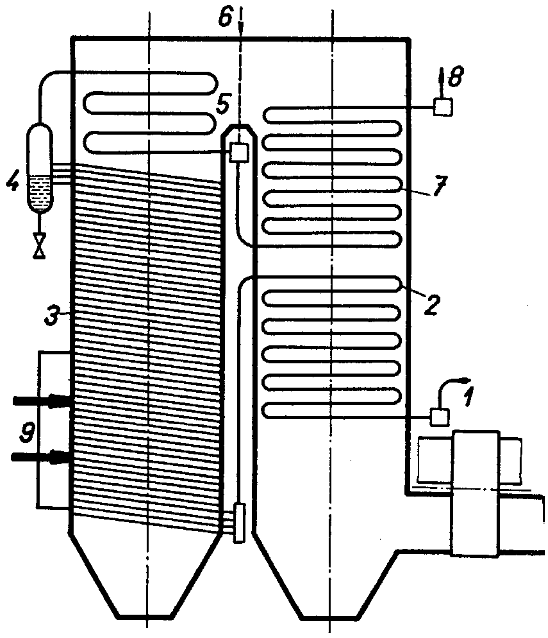

Figure 4-10, Ramzin circulation, 1 – feedwater inlet, 2-economizing surface, 3-furnace tubes, 4-bottle, 5-superheating surface, 6-desuperheating spray, 7-superheating, 8-main steam out (Doležal, 1967).

Ramzin boiler was developed in the Russia. It uses much the same operating principles that the Sultzer monotube boiler. The main distinctive feature of Ramzin boiler is that the tubes circle the furnace. It is expensive to manufacture. Separation (4) similar to Sultzer design, was added later. The main use of Ramzin boilers has been in former eastern block.

4.4.4 Tube selection for once through boiler

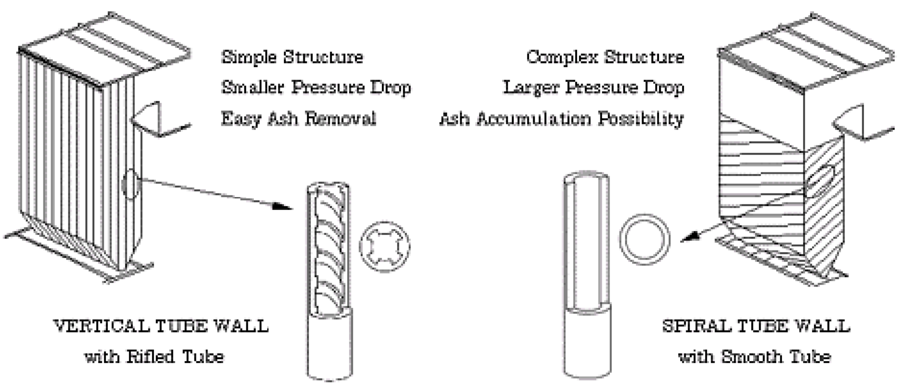

Figure 4-11, Selection of tubes for once through boilers (Mitsubishi Heavy Industries Ltd, 2001).

In once trough boilers the evaporation is brought to completion. Therefore parts of the tubes must be operated at very high vapor contents. This kind of operation stresses some tubes when water sometimes is separated from the tube walls and sometimes not. One helpful way is to make parts of the tubes from rifled or internally finned tubes. Water steam solution is brought into rotative motion and heavier water tends to stay longer at the tube walls.

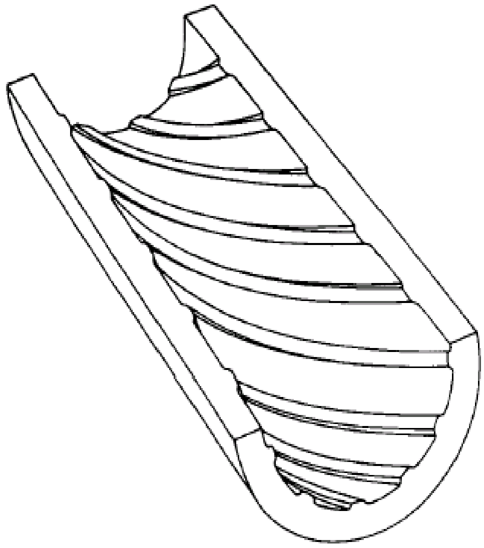

Figure 4-12, Typical internally spirally finned tube.

Spirally finned tube increases wall wetting, decreases the possibility of DNB and is more expensive than straight tube.

4.4.5 Combined circulation

Combined circulation is a trademark of former Combustion Engineering, now part of Ahlstom Power. Target in combined circulation is to improve ‘once-through’ in low loads. Includes pump for partial load operation. When low loads are run a part of the stam water solution can be recirculated to drum and pumped again through the boiler.

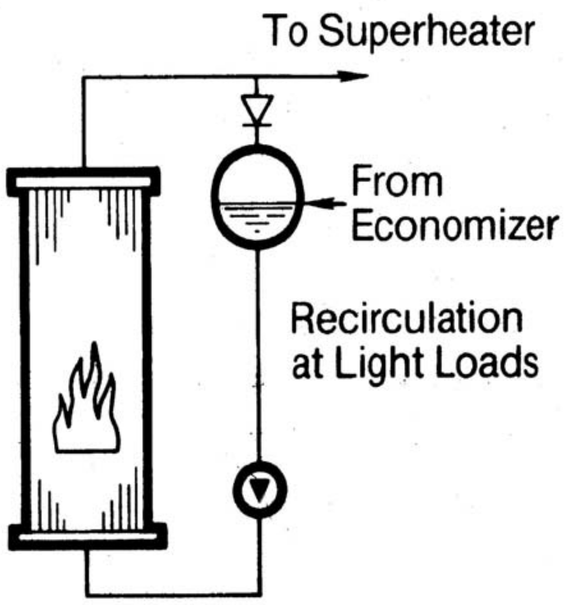

Figure 4-13, Combined circulation (Singer, 1981).

Headers were earlier of various shapes. Even square cross section was used. Nowadays only tubular headers are used.

4.4.6 Departure from nucleate boiling

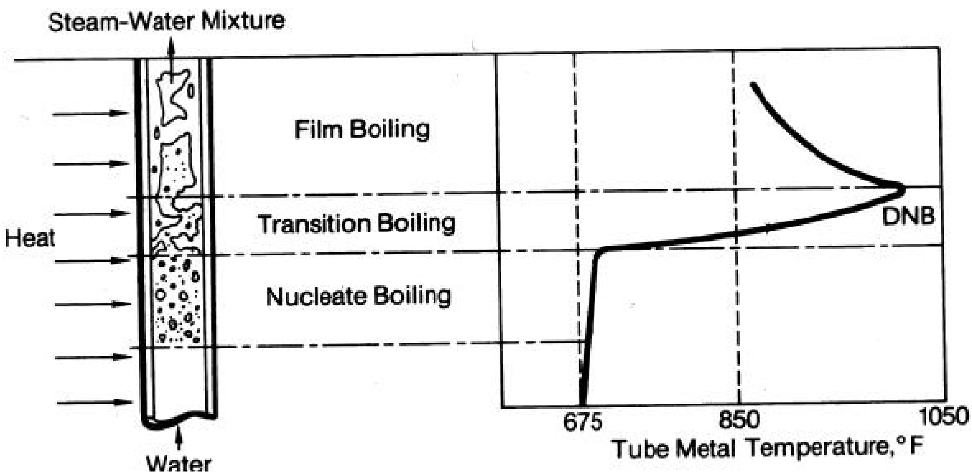

Figure 4-14, Departure from nucleate boiling.

The biggest design consern for once-through design is that DNB must be avoided. Furnace heat transfer must be arranged so that the furnace tube temperatures keep relatively constant even at partial load.

5 MILL BALANCES

Every recovery boiler case was considered in a mill setting. Two alternatives were used. The first is typical new mill with biomass boiler. The second was the same mill but with no additional boilers i.e. bark etc. are sold. This was done for not to confuse the electricity generating values with possible biomass boiler specific extra electricity generation.

5.1 Mill base dimensioning

Target annual production, t/a	1100000
Softwood, ADt/a	480000
Hardwood, ADt/a	620000
Target operating days, d	350
Required average production, ADt/24h	3143
Mill debarking	
Additional wood for combustion, m^3sub/a	500000

This mill corresponds to a new large mill at northern latitudes. The size was chosen large. The economical possibilities for extra electricity generation are better with large boilers.

5.2 Mill department sizing

Woodroom, m^3_{sub}/d	34300
Digester, ADt/d	3680
Oxygendel., ADt/d	3680
Screening, ADt/d	3680
Pulp washing, ADt/d	3680
Bleaching, ADt/d	3490
Pulpdryer, ADt/d	3490
Evaporation, t H_2O/h	1140
Recovery boiler, tDS/d	5300
Causticizing, m^3WL/d	20956
Lime kiln, t lime/d	1080
CNCG-handling, m^3/h	2300
DNCG-handling, m^3/s	40
Power boiler, kg/s	90
Turbogenerators	Case

The mill department sizing was done using LUT based mill balance program MILLFLOW.

5.3 Mill steam and electricity balances

Mill main balances were calculated to find out how changing the recovery boiler main steam parameters affect the kraft mill balances especially the recovery boiler electricity generation. The main balances were calculated using MILLFLOW excel spreadsheet as basis for balances.

When calculating the main balances the departmental steam usages correspond to needs for each case. So for each case the full mill steam and electricity balances are satisfied. The fiberline operation remains essentially unchanged as the mill production is kept constant. Recovery boiler preheating and pumping needs change from case to case. In addition in case A the evaporation is to lower solids. Main balance summary for recovery boiler is seen in Table 5-1.

Table 5-1 Recovery boiler operating values for each case.

		Joutseno	Kymi	Yonago	SoTu	SkyRec	SkyRec+	SkyRec
Case		**A**	**B**	**C**	**D**	**E**	**F**	**E160**
Capacity	tds/d	5500	5500	5500	5500	5500	5500	5500
capacity (virgin)	tds/d	5005	5005	5005	5005	5005	5005	5005
Dry solids	%	82.0	85.0	85.0	85.0	85.0	85.0	85.0
HHV	MJ/kgds	13.00	13.00	13.00	13.00	13.00	13.00	13.00
LHV	MJ/kgds	12.28	12.28	12.28	12.28	12.28	12.28	12.28
O2 in dry flue gas	%	2.8	2.8	2.8	2.8	2.8	2.8	2.8
Primary air percentage	%	23.0	22.0	22.0	22.0	22.0	22.0	22.0
Primary air temp.	°C	150.0	190.0	190.0	190.0	190.0	190.0	190.0
Secondary air percentage	%	50.0	54.0	54.0	54.0	54.0	54.0	54.0
Secondary air temp.	°C	120.0	190.0	190.0	190.0	190.0	190.0	190.0
Tertiary air percentage	%	27.0	12.0	12.0	12.0	12.0	12.0	12.0
Tertiary air temp.	°C	30.0	190.0	190.0	190.0	190.0	190.0	190.0
Quartenary air percent.	%	0.0	12.0	12.0	12.0	12.0	12.0	12.0
Quartenary air temp.	°C	30.0	190.0	190.0	190.0	190.0	190.0	190.0
Total air temperature	°C	102.6	190.0	190.0	190.0	190.0	190.0	190.0
Main steam pressure RB	bar(a)	94.0	104.0	124.0	164.0	124.0	264.0	164.0
Main steam temp. RB	°C	490.0	505.0	515.0	540.0	515.0	540.0	515.0
Main steam pressure PB	bar(a)	94.0	104.0	124.0	164.0	124.0	124.0	102.0
Main steam temp. PB	°C	490.0	505.0	515.0	540.0	515.0	515.0	505.0
Feedwater pressure	bar(a)	110.0	121.0	146.0	182.0	146.0	290.0	290.0
Feedwater temp.	°C	120.0	148.0	148.0	148.0	148.0	148.0	148.0
Reheater inlet pressure	bar(a)					36	56	36
Reheater inlet temp.	°C					348	337	310
Reheater outlet pressure	bar(a)					34	54	34
Reheater outlet temp.	°C					400	460	400
HP FW preheater inlet	°C	200	200	200	200	200	200	200
HP FWpreheater outlet	°C	200	200	220	220	220	220	220
Flue gas temp. (eco out)	°C	155	197	197	197	197	197	197
Flue gas temp. (to stack)	°C		155	155	155	155	155	155
Sootblowing	kg/s	6.0	6.0	6.0	6.0	8.0	8.0	8.0

The main balances were calculated using MILLFLOW excel spreadsheet as basis for balances. The mill condensing tail flow was set to balance the steam balance. The example pulp mill has condensing tail in its turbine. Most of the older pulp mills do not have a condensing tail, but run only backpressure operation. It should be noted that in the example mill there is no bark boiler. Recovery boiler is the sole steam producer in the mill. The bark is sold to outside of the mill.

In all cases the pulp mil produces more electricity than it consumes. This is because the mill is modern and thus energy efficient i.e. it has steam surplus. The second reason for high electricity generation is high steam parameters. The third reason is extra electricity generation done with condensing tail in the steam turbine.

Table 5-2 Main balance values for each case, power boiler in operation.

		Joutseno	Kymi	Yonago	SoTu	SkyRec	SkyRec+	SkyRec
Case		**A**	**B**	**C**	**D**	**E**	**F**	**E160**
Capacity	tds/d	5500	5500	5500	5500	5500	5500	5500
capacity (virgin)	tds/d	5005	5005	5005	5005	5005	5005	5005
Dry solids	%	82.0	85.0	85.0	85.0	85.0	85.0	85.0
Main steam pressure RB	bar(a)	94.0	104.0	124.0	164.0	124.0	264.0	164.0
Main steam temp. RB	°C	490.0	505.0	515.0	540.0	515.0	540.0	515.0
Main steam pressure PB	bar(a)	94.0	104.0	124.0	164.0	124.0	124.0	102.0
Main steam temp. PB	°C	490.0	505.0	515.0	540.0	515.0	515.0	505.0
Feedwater pressure	bar(a)	110.0	121.0	146.0	182.0	146.0	290.0	290.0
Feedwater temp.	°C	120.0	148.0	148.0	148.0	148.0	148.0	148.0
Reheater inlet pressure	bar(a)					36	56	36
Reheater inlet temp.	°C					348	337	310
Reheater outlet pressure	bar(a)					34	54	34
Reheater outlet temp.	°C					400	460	400
Sootblowing	kg/s	6.0	6.0	6.0	6.0	8.0	8.0	8.0
Steam flow RB	kg/s	215.0	226.4	232.5	232.0	224.0	218.5	220.8
Change in steam flow	%	0.0	5.3	8.1	7.9	4.1	1.6	2.7
Pulping usage total	MW	87.6	88.1	88.9	90.2	88.2	93.2	90.0
Mill total usage	MW	95.5	96.1	96.9	98.2	96.2	101.2	98.0
Electricity production	MW	234.4	239.5	249.8	262.9	250.1	263.4	251.1
Surplus electricity	MW	138.9	143.3	153.0	164.7	153.8	162.2	153.1
Efficiency to electricity	%	23.2	23.1	24.1	25.4	24.1	25.4	24.2
Change in electricty	MW	0.0	4.4	14.0	25.8	14.9	23.2	14.1
	%	0.0	3.2	10.1	18.5	10.7	16.7	10.2

We note that the steam production increases from Case A to Case B because of higher black liquor dry solids and more air preheating. The steam production increases from Case B to Case C because of high pressure preheating. The recovery boiler steam flow starts decreasing as further increases in main steam parameters require more heat.

The pulping electricity usage is not constant. The main parameter that changes is the recovery boiler feedwater pump power requirement, Table 5-3.

Table 5-3 Recovery boiler own power usage for each case.

		Joutseno	Kymi	Yonago	SoTu	SkyRec	SkyRec+	SkyRec
Case		**A**	**B**	**C**	**D**	**E**	**F**	**E160**
Air fan power	kW	2275	2296	2296	2296	2296	2296	2296
Flue gas fan power	kW	2570	2534	2534	2534	2534	2534	2534
Feedwater pumping power	kW	3055	3556	4347	5719	4187	8606	5443
Other power	kW	1500	1500	1500	1500	1500	1500	1500
Total power	kW	9401	9886	10677	12049	10518	14937	11773

Table 5-4 Main balance values for each case, no power boiler in operation.

		Joutseno	Kymi	Yonago	SoTu	SkyRec	SkyRec+	SkyRec
Case		**A**	**B**	**C**	**D**	**E**	**F**	**E160**
Capacity	tds/d	5500	5500	5500	5500	5500	5500	5500
capacity (virgin)	tds/d	5005	5005	5005	5005	5005	5005	5005
Dry solids	%	82.0	85.0	85.0	85.0	85.0	85.0	85.0
Main steam pressure RB	bar(a)	94.0	104.0	124.0	164.0	124.0	264.0	164.0
Main steam temp. RB	°C	490.0	505.0	515.0	540.0	515.0	540.0	515.0
Main steam pressure PB	bar(a)	91.0	104.0	124.0	164.0	124.0	124.0	102.0
Main steam temp. PB	°C	490.0	505.0	515.0	540.0	515.0	515.0	505.0
Feedwater pressure	bar(a)	110.0	121.0	146.0	182.0	146.0	290.0	290.0
Feedwater temp.	°C	120.0	148.0	148.0	148.0	148.0	148.0	148.0
Reheater inlet pressure	bar(a)					36	56	36
Reheater inlet temp.	°C					348	337	310
Reheater outlet pressure	bar(a)					34	54	34
Reheater outlet temp.	°C					400	460	400
Sootblowing	kg/s	6.00	6.00	6.00	6.00	8.00	8.00	8.00
Steam flow RB	kg/s	215.0	226.4	233.6	232.0	224.0	218.5	224.0
Change in steam flow	%	0.0	5.3	8.6	7.9	4.1	1.6	4.1
Pulping usage total	MW	87.6	88.1	88.9	90.2	88.2	93.2	90.0
Mill total usage	MW	91.1	91.7	92.4	93.8	91.8	96.8	93.6
Electricity production	MW	149.3	153.9	161.8	175.6	162.3	177.9	167.0
Surplus electricity	MW	58.2	62.2	69.4	81.7	70.5	81.1	73.4
Efficiency to electricity	%	20.4	20.4	21.4	23.2	21.5	23.5	22.7
Change in electricty	MW	0.0	4.0	11.2	23.6	12.3	22.9	15.2
	%	0.0	6.8	19.3	40.5	21.1	39.4	26.2

As can be seen the modern recovery boiler Case C does produce about 20 % more electricity than roughly ten years ago, case A. reheating cases E and E160 seem to give only marginally better electricity production. The only alternative seems to be to increase the main steam temperature to 540 ^{o}C, Cases D and F.

Electricity generation does not depend a lot on how the boiler steam side is configured. Reheating and once through appear only marginally better when considering the recovery boiler electricity generation.

6 BOILER DIMENSIONING

All described cases have been dimensioned. The dimensioning is based on typical recovery boiler dimensioning. The studied cases were

A. Natural circulation 82 %, 490 °C, 9.0 MPa (reference Joutseno)

B. Natural circulation 85 %, 505 °C, 10.2 MPa (reference Kymi)

C. Natural circulation 85 %, 515 °C, 12.0 MPa (reference Yonago)

D. Assisted circulation 85 %, 540 °C, 16.0 MPa (SoTu)

E. Natural circulation 85 %, 515/400 °C, 12.0/3.4 MPa (SkyRec) *Reheating*

F. Once-through 85 %, 540/460 °C, 26.0/5.4 MPa (Skyrec+) *Reheating*

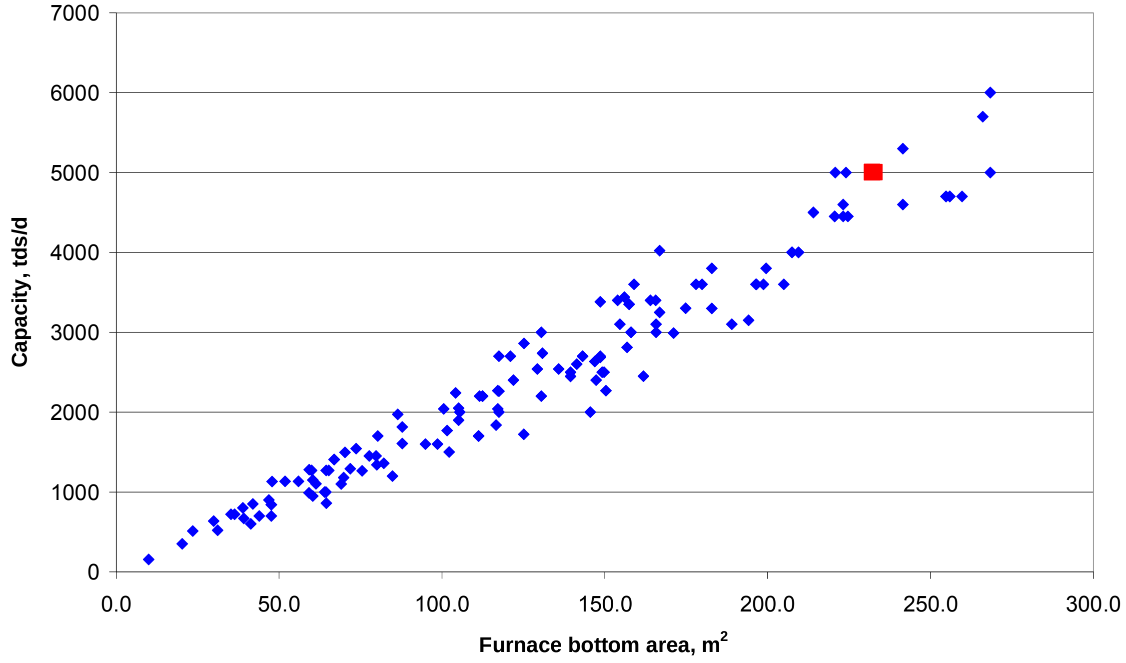

Figure 6-1, Boiler bottom area vs capacity, red squares indicate cases A-F.

Each boiler was dimensioned similar to commercial recovery boilers using recovery boiler specific dimensioning. The furnace bottom area size was kept constant, but furnace height varied, Figure 6-2. As can be seen the reheater cases E and F have rather low furnaces and thus high furnace nose temperatures. If we try to use traditional furnace nose temperatures the superheater surface area required quickly becomes much too large. Choise of variable furnace nose temperature meant that boiler bank entrance section temperature was kept reasonably unchanged.

Because of equal boiler bank entrance section temperature the boiler bank and economizer area comes up similar.

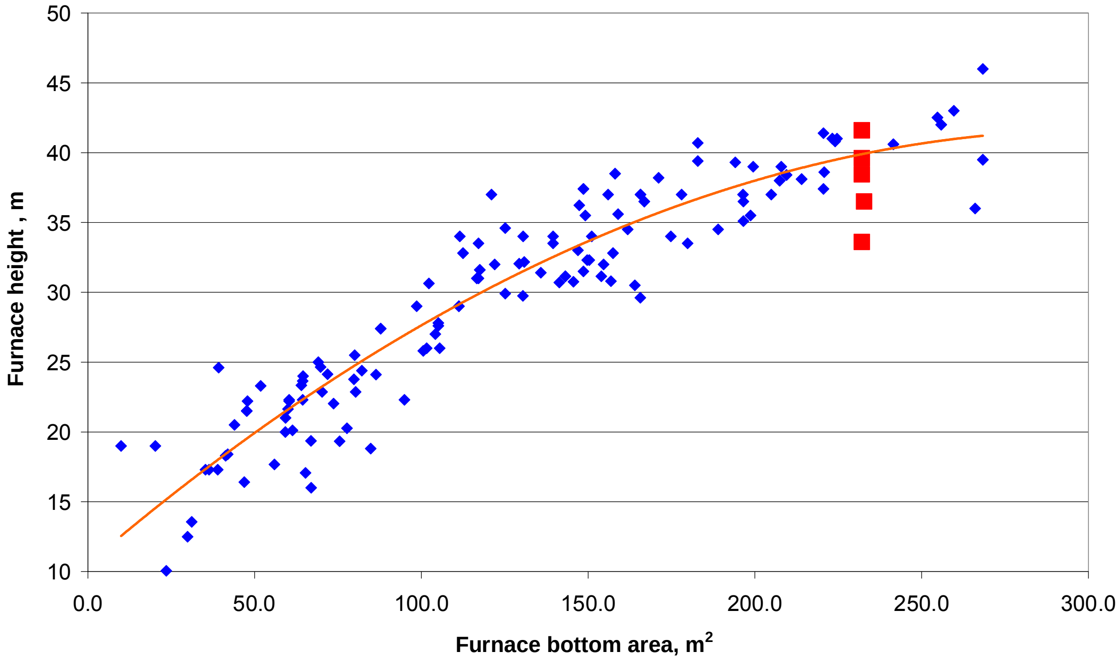

Figure 6-2, Boiler bottom area vs furnace height, red squares indicate cases A-F.

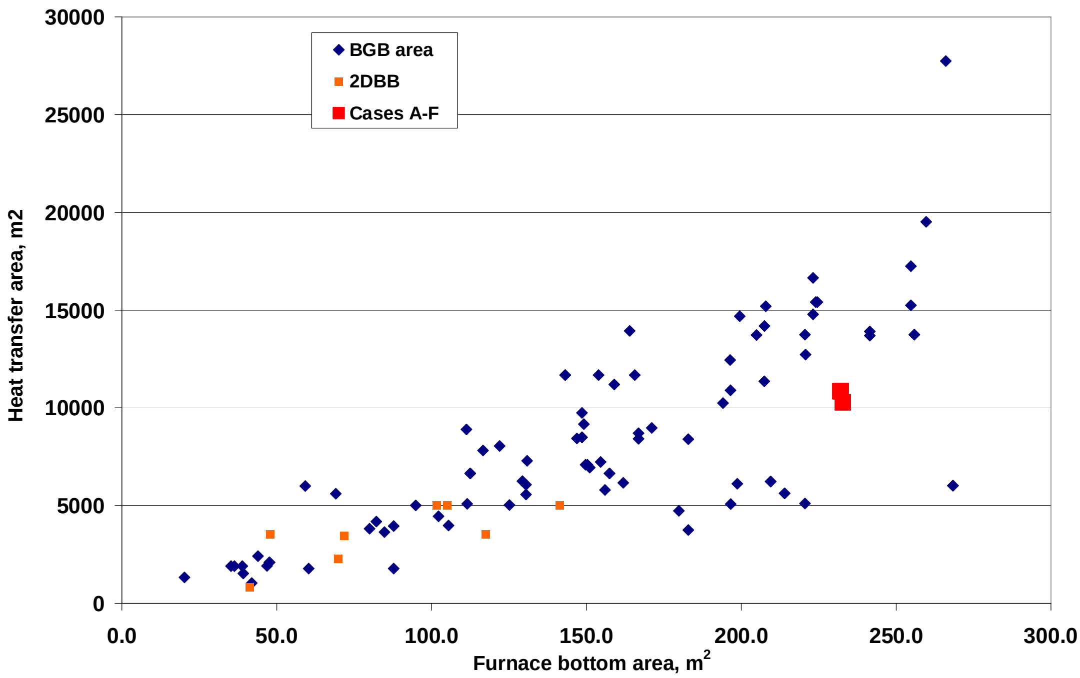

Figure 6-3, Boiler bottom area vs boiler bank area, red squares indicate cases A-F.

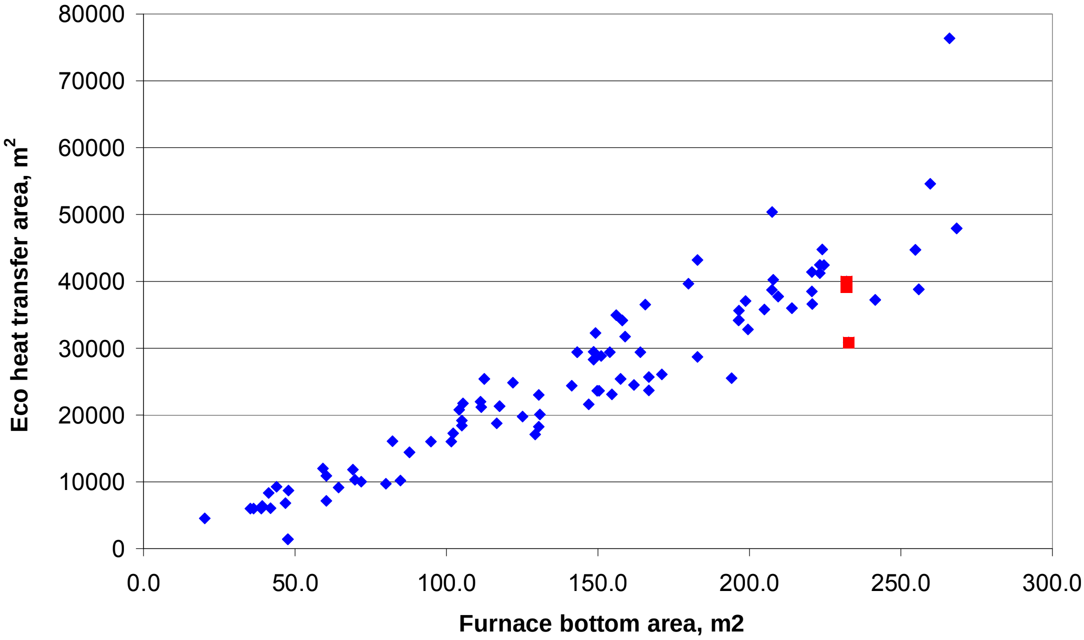

Figure 6-4, Boiler bottom area vs economizer area, red squares indicate cases A-F.

The superheater and reheater area between different cases varied quite much.

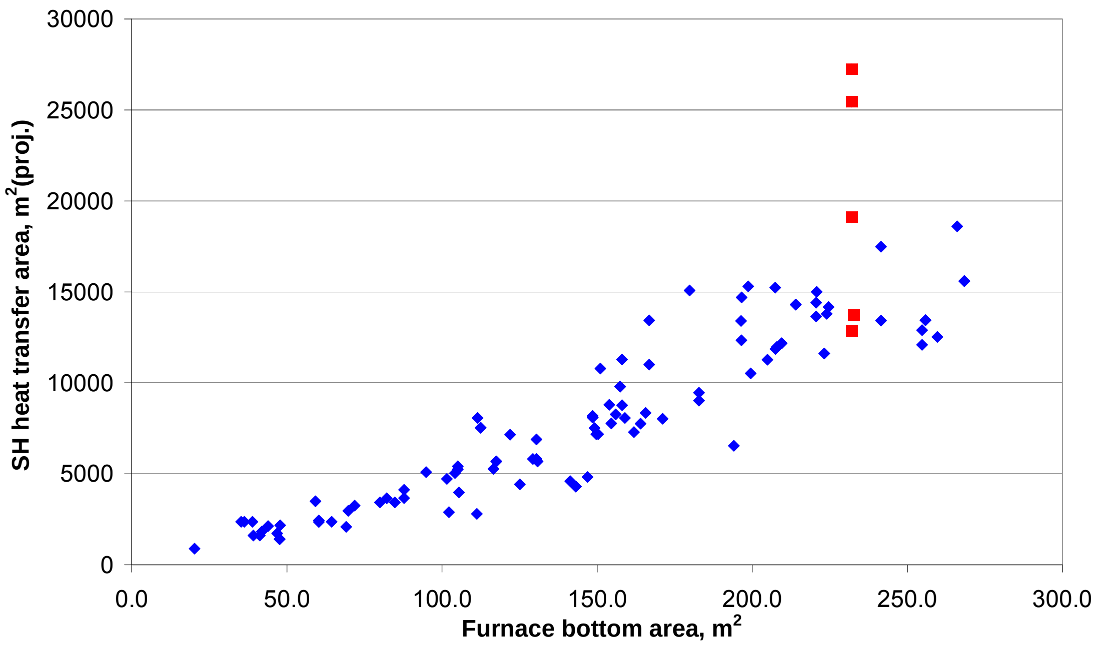

Figure 6-5, Boiler bottom area vs sum of superheater and reheater area, red squares indicate cases A-F.

Each case dimensioning is discussed in more detail.

6.1 Case A - Modern high efficiency boiler

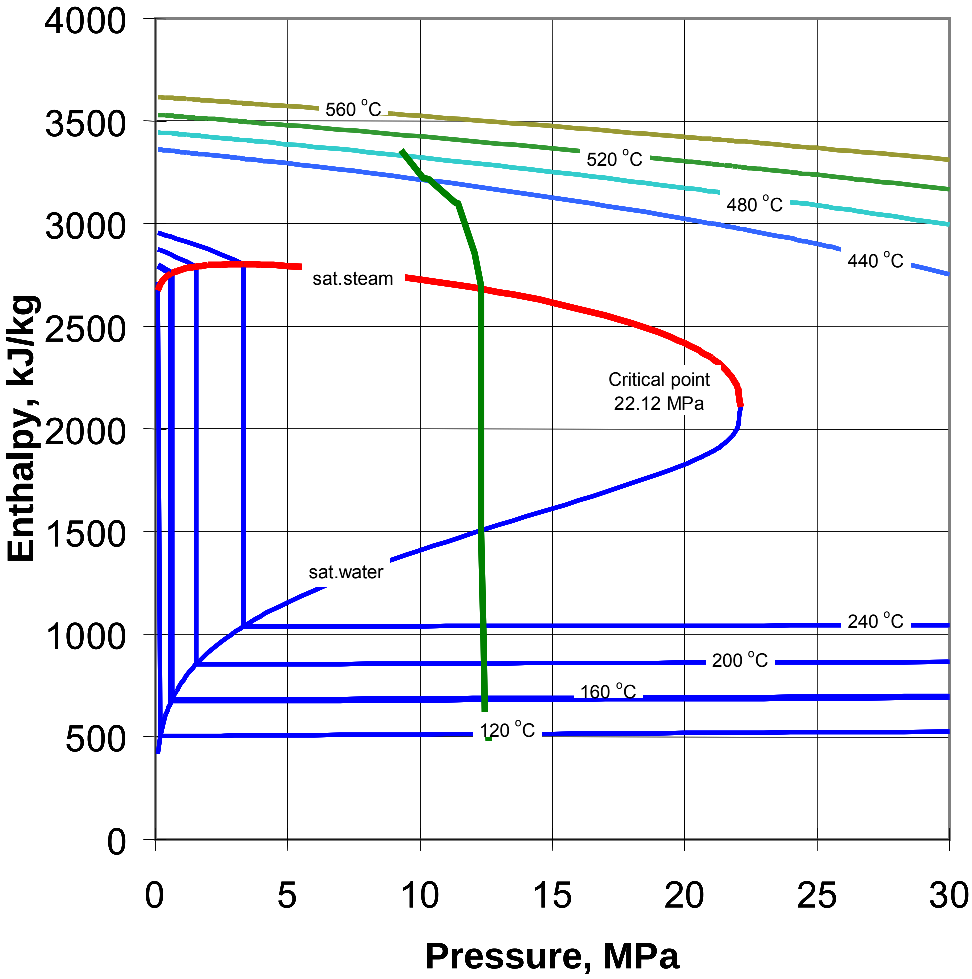

Figure 6-6, Modern recovery boiler in p-h-diagram, 215.0 kg/s, 9.0 MPa, 490 °C.

The heat addition diagram for Case A is presented as figure 6-1. As is typical the biggest pressure drop is in the superheaters.

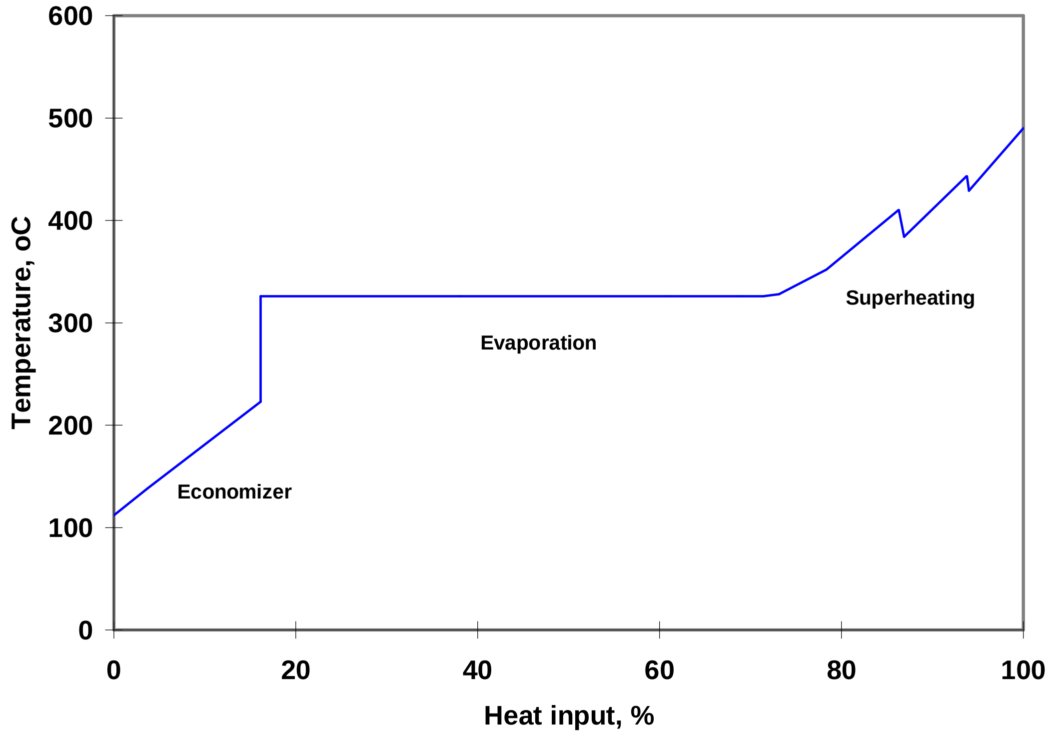

Figure 6-7, Modern recovery boiler in Φ-t-diagram, 215.0 kg/s, 9.0 MPa, 490 °C.

The heat-steam/waterside temperature diagram for Case A is presented as figure 6-2. The evaporation is overdimensioned as is typical and economizers are underdimensioned. This is because sizing boiler bank an economizers roughly of equal height gives savings in boiler house volume. The main dimensions for Case A are shown in Table 6-1.

Table 6-1 Main dimensions of modern recovery boiler, Case A.

Surface	**unit**	
Furnace area	m^2	232.8
Furnace height	m	36.5
Total boiler height	m	70.5
Furnace area	m^2	4417
Screen area	m^2	
Superheater area	m^2	16880
Superheater area (proj)	m^2	13731
Boiler bank area	m^2	10274
Economizer area	m^2	30855
Total area	m^2	

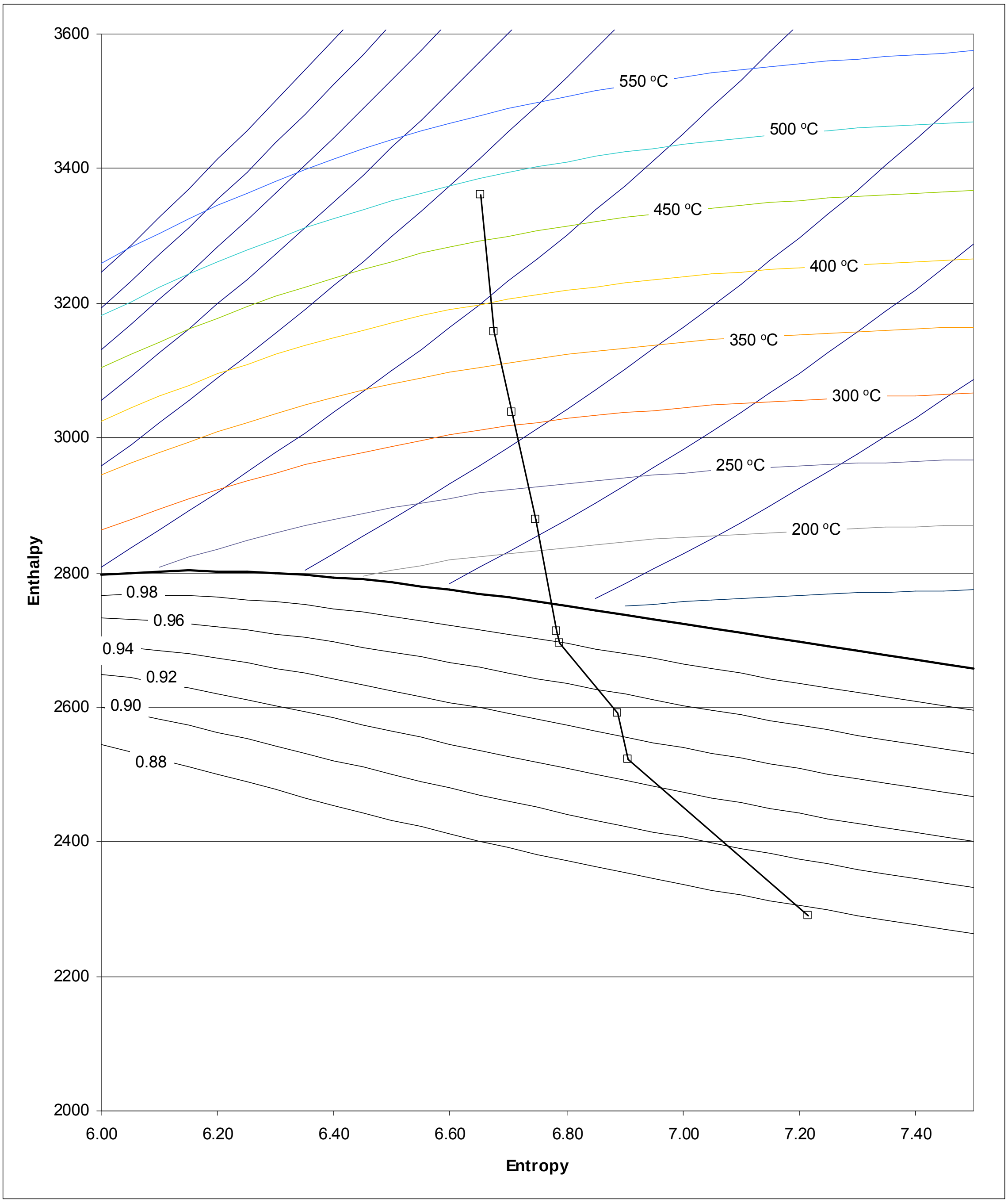

Figure 6-8, Modern recovery boiler turbine expansion in h-s-diagram, 215 kg/s, 9.0 MPa, 490 °C.

As seen in the figure 6-3 the turbine expansion tends to go to wet steam at about 5 bar(g) so this option requires higher low pressure steam values than others. In addition the turbine condenser end is at moisture which exceeds 12 %. Normally this would require special turbine design to be feasible.

If the turbine isentropic efficiency is lowered or turbine condenser end pressure is increased the turbine can be brought to more normal design conditions.

6.2 Case B – High efficiency recovery boiler

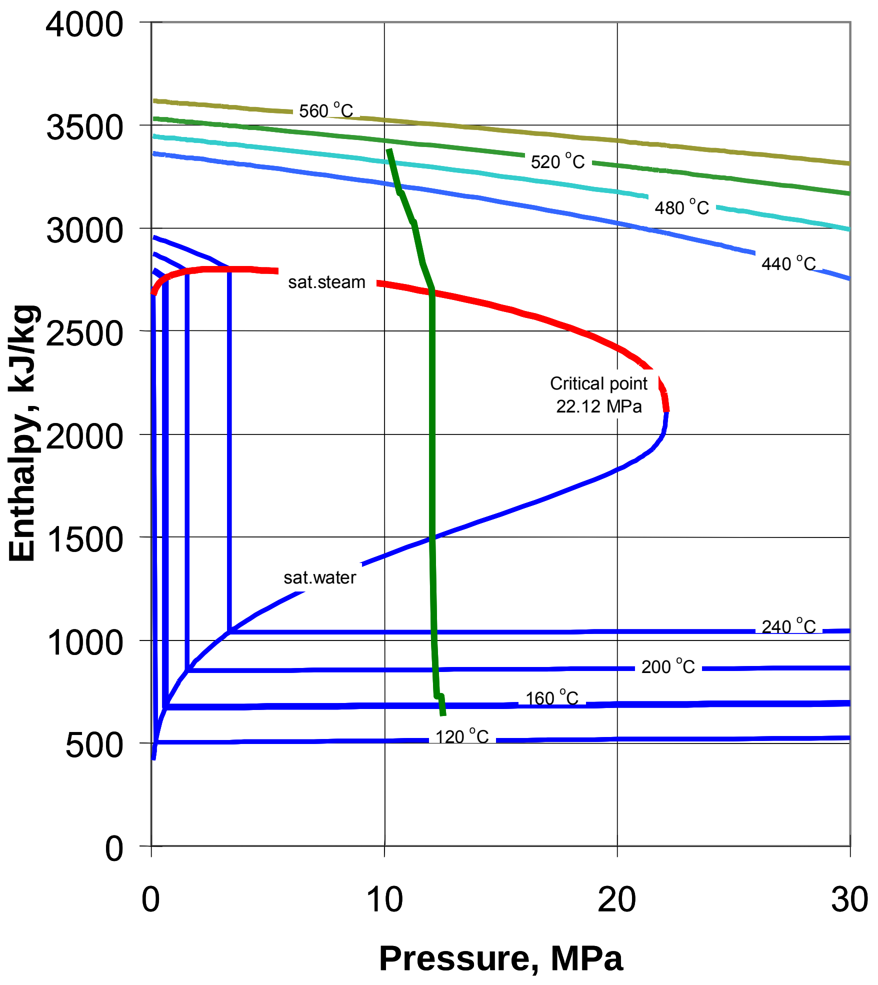

Figure 6-9, High efficiency recovery boiler in p-h-diagram, 226.4 kg/s, 10.2 MPa, 505 °C.

The heat addition diagram for Case B is presented as figure 6-4. This diagram does not markedly differ form the one for Case A. As can be seen the preheating of feedwater takes a fairly large portion of the heat flow.

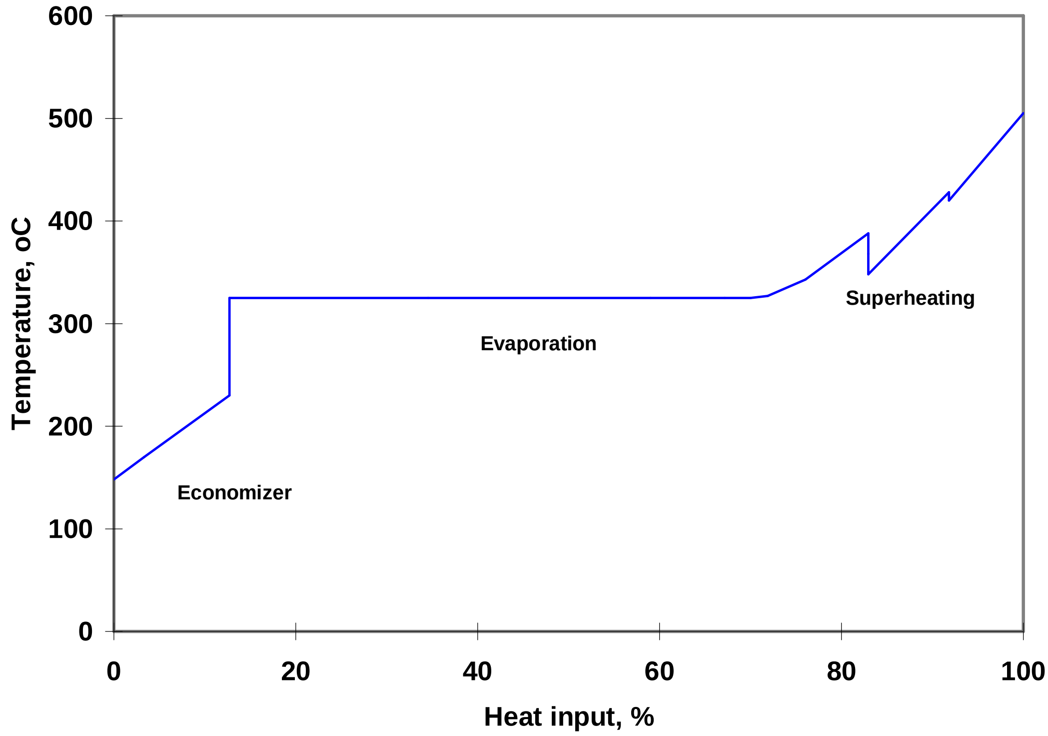

Figure 6-10, High efficiency recovery boiler in Φ-t-diagram, 226.4 kg/s, 10.2 MPa, 505 °C.

The heat-steam/waterside temperature diagram for Case B is presented as figure 6-5. The diagram is fairly similar to case A. The main dimensions for Case B are shown in Table 6-2.

Table 6-2 Main dimensions of high efficiency recovery boiler, Case B.

Surface	unit	
Furnace area	m^2	232.1
Furnace height	m	41.6
Total boiler height	m	75.1
Furnace area	m^2	5056
Screen area	m^2	
Superheater area	m^2	13536
Superheater area (proj)	m^2	12851
Boiler bank area	m^2	10852
Economizer area	m^2	39972
Total area	m^2	

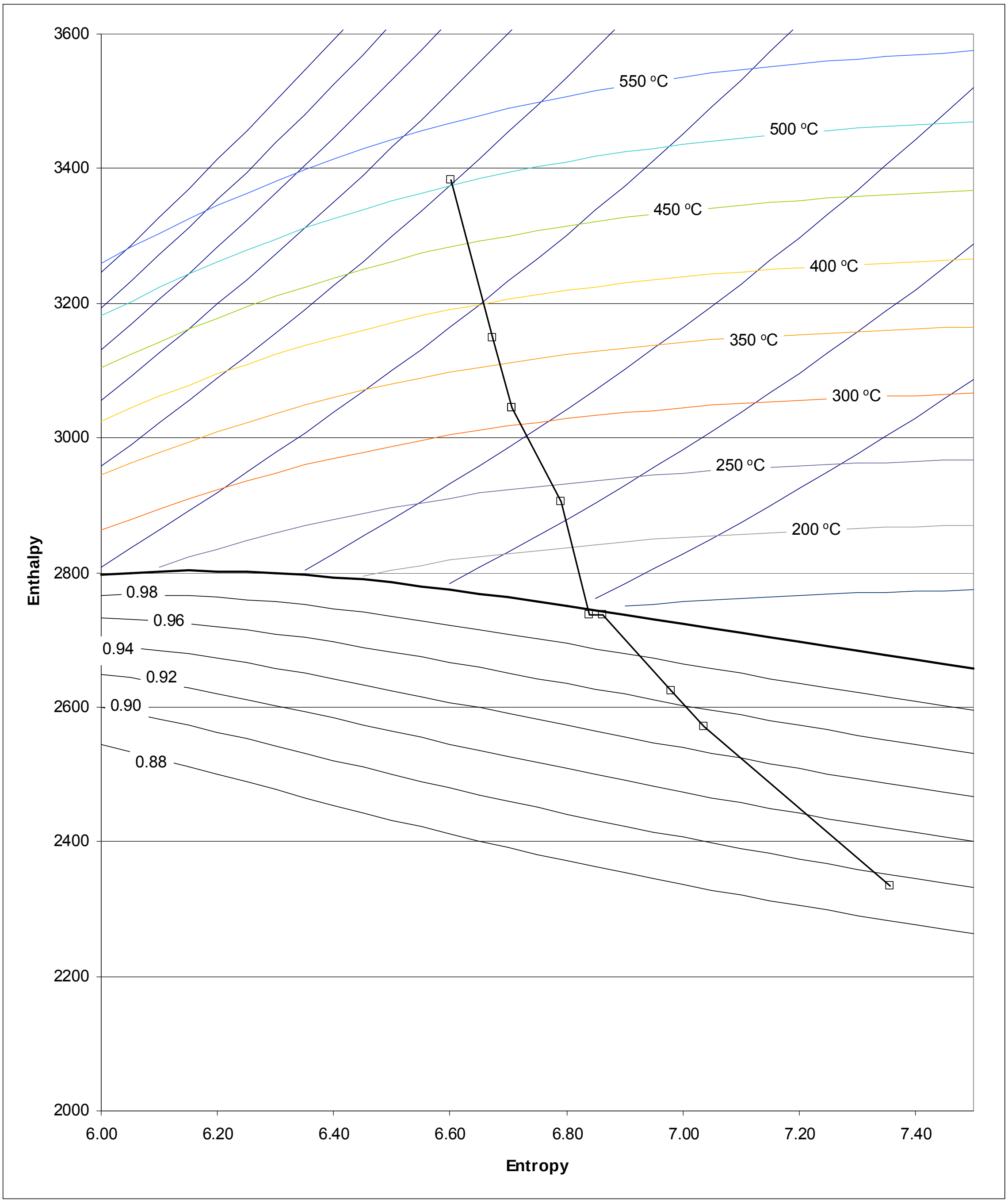

Figure 6-11, High efficiency recovery boiler turbine expansion in h-s-diagram, 226.4 kg/s, 10.2 MPa, 505 °C.

The high efficiency boiler turbine expansion seems to fit better the chosen LP pressure 3.5 bar(g). The end moisture is somewhat over 10 % which is still possible, but requires better materials for the last rows of turbine blades.

6.3 Case C – High pressure and temperature recovery boiler

The heat addition diagram for Case C is presented as figure 6-7. As is typical the biggest pressure drop is in the superheaters.

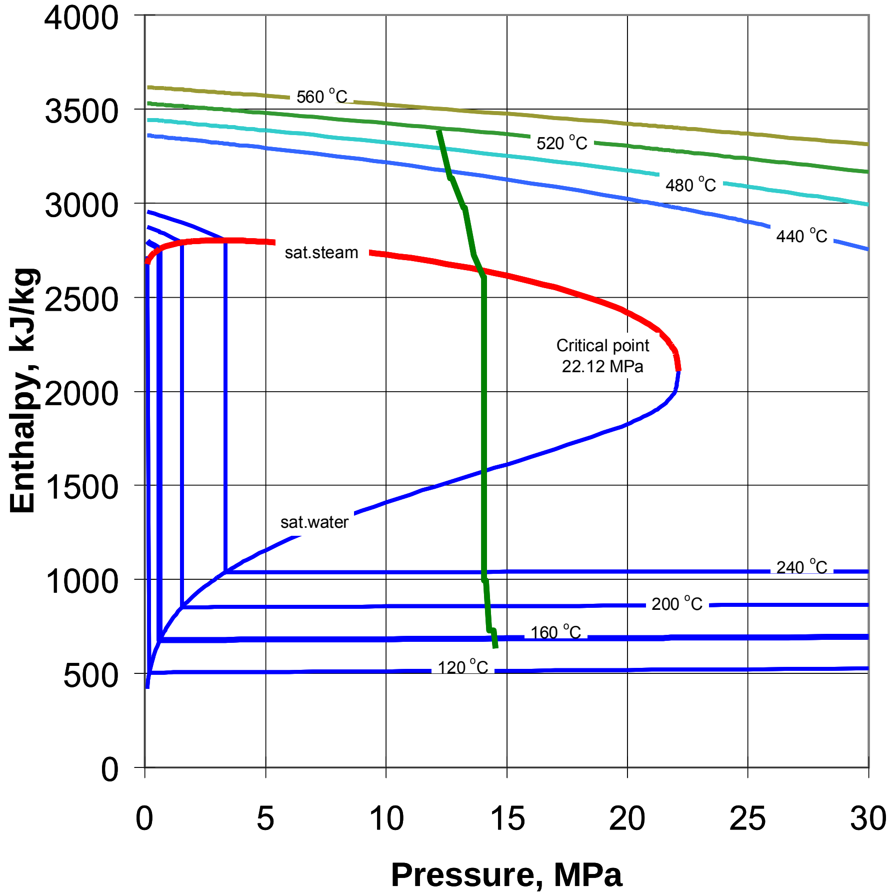

Figure 6-12, High pressure and temperature recovery boiler in p-h-diagram, 232.5 kg/s, 12.0 MPa, 520 °C.

There are not big changes in heat transfer surface placement nor in their sizing, therefore the p-h-diagram is fairly similar to cases A and B. As the pressure increases the portion of heat to evaporation decreases and the portion of heat to both superheating and preheating increases. This is the reason why different constructions from traditional are used in the boiler bank. Because the entrance to boiler bank has been kept fairly close to traditional values then the furnace inlet temperature has increases.

In the Φ-t-diagram one notices that the economizer outlet temperature starts to be fairly low compared to the evaporation temperature.

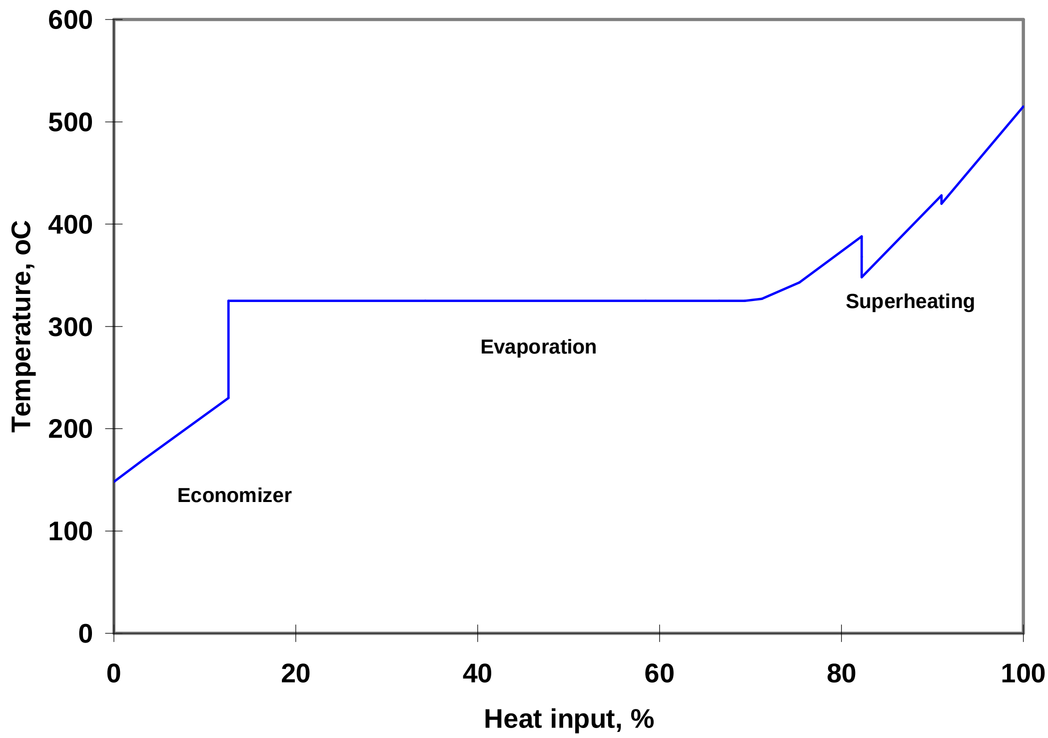

Figure 6-13, High pressure and temperature recovery boiler in Φ-t-diagram, 232.5 kg/s, 12.0 MPa, 520 °C.

Table 6-3 Main dimensions of high pressure and temperature recovery boiler, Case C.

Surface	**unit**	
Furnace area	m^2	232.8
Furnace height	m	41.6
Total boiler height	m	78
Furnace area	m^2	5056
Screen area	m^2	
Superheater area	m^2	13536
Superheater area (proj)	m^2	12851
Boiler bank area	m^2	10852
Economizer area	m^2	39849
Total area	m^2	

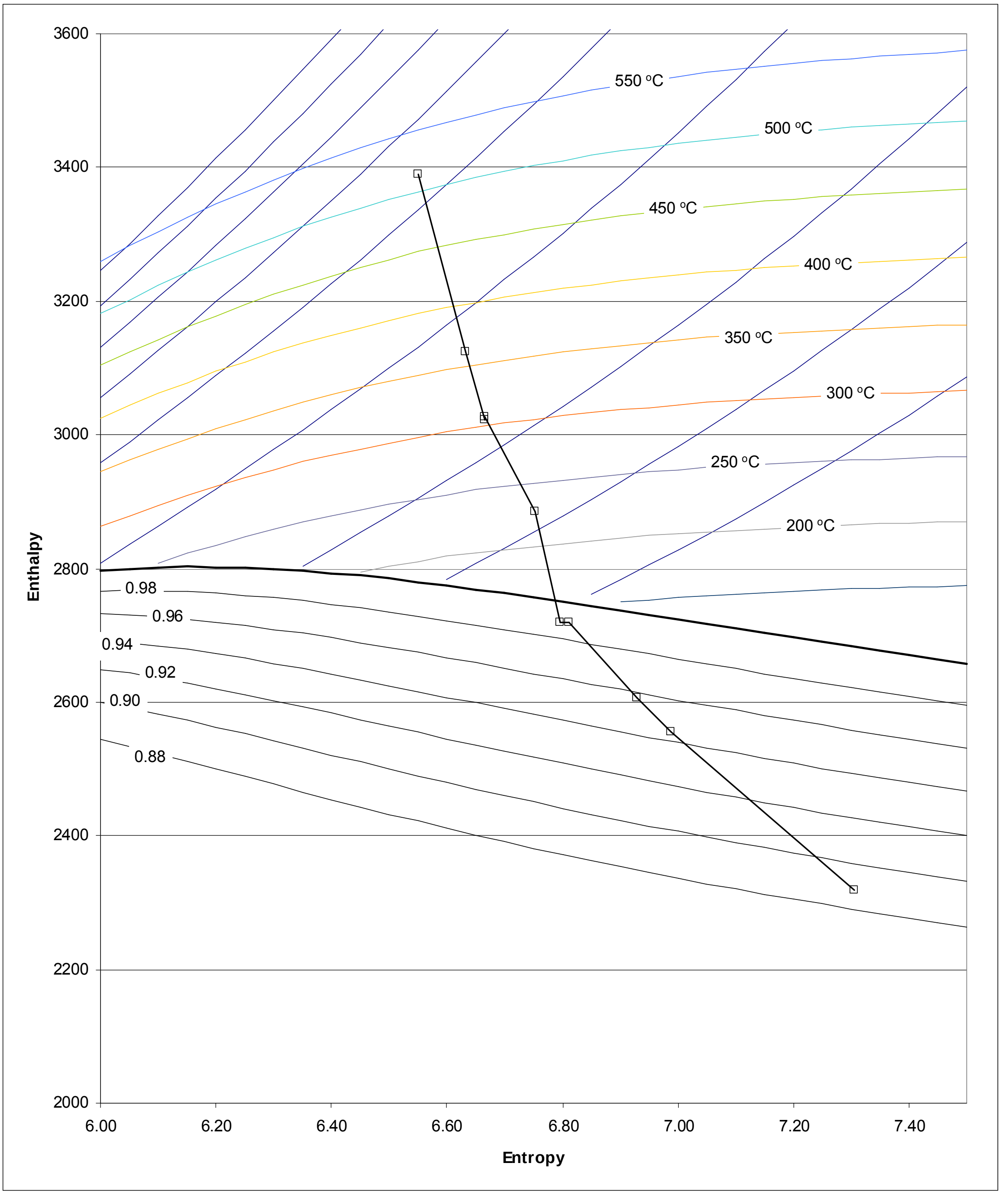

Figure 6-14, High pressure and temperature recovery boiler turbine expansion in h-s-diagram, 232.5 kg/s, 12.0 MPa, 520 °C.

6.4 Case D - Assisted circulation recovery boiler concept

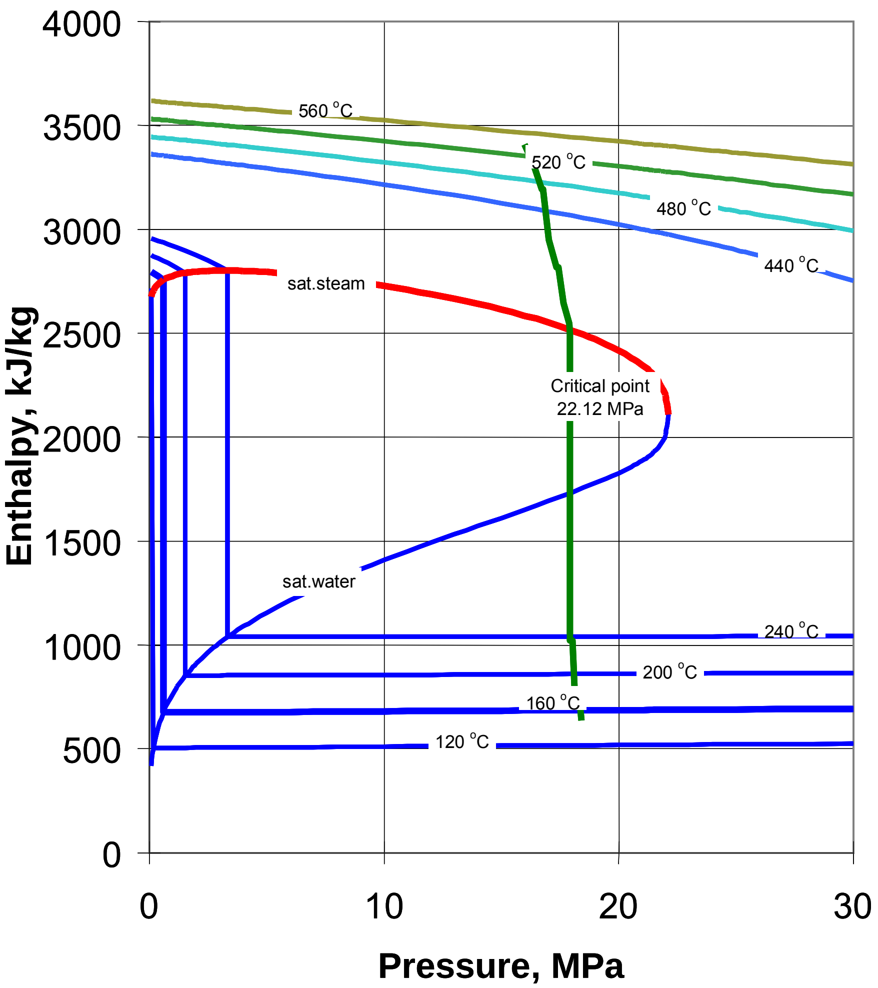

Figure 6-15, Assisted circulation recovery boiler in p-h-diagram, 232.0 kg/s, 16.0 MPa, 540 °C.

Table 6-4 Main dimensions of assisted circulation recovery boiler, case D.

Surface	**unit**	
Furnace area	m^2	232.1
Furnace height	m	39.6
Total boiler height	m	75
Furnace area	m^2	5082
Screen area	m^2	
Superheater area	m^2	20255
Superheater area (proj)	m^2	19014
Boiler bank area	m^2	10852
Economizer area	m^2	39765
Total area	m^2	

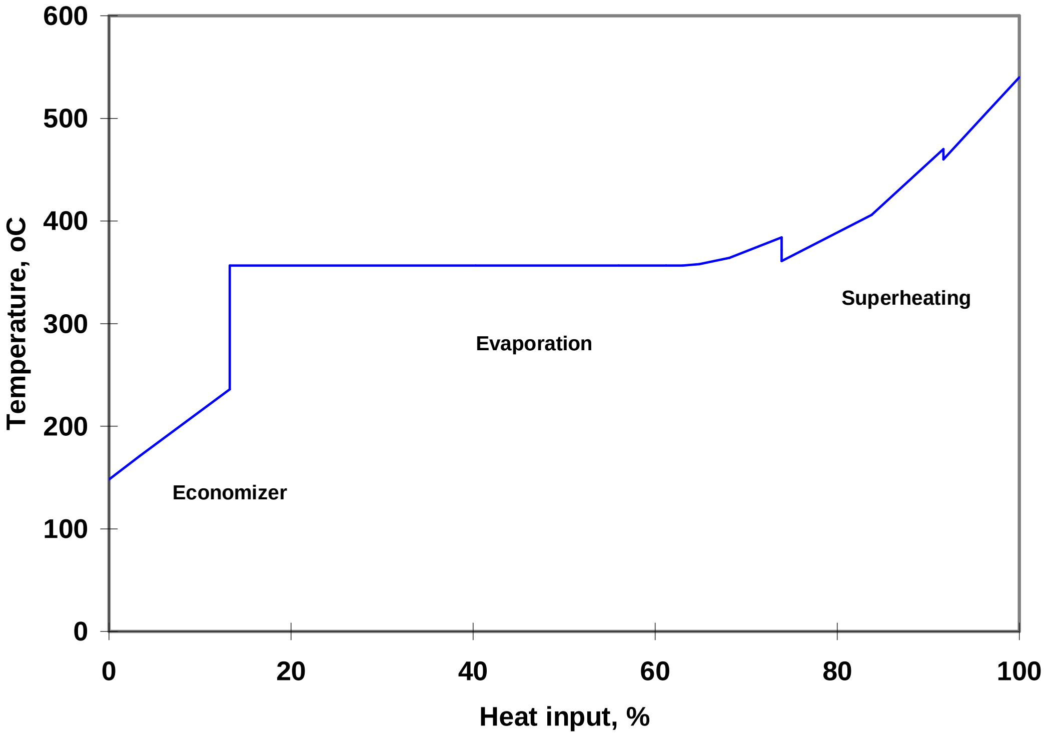

Figure 6-16, Assisted circulation recovery boiler in Φ-t-diagram, 232.0 kg/s, 16.0 MPa, 540 °C.

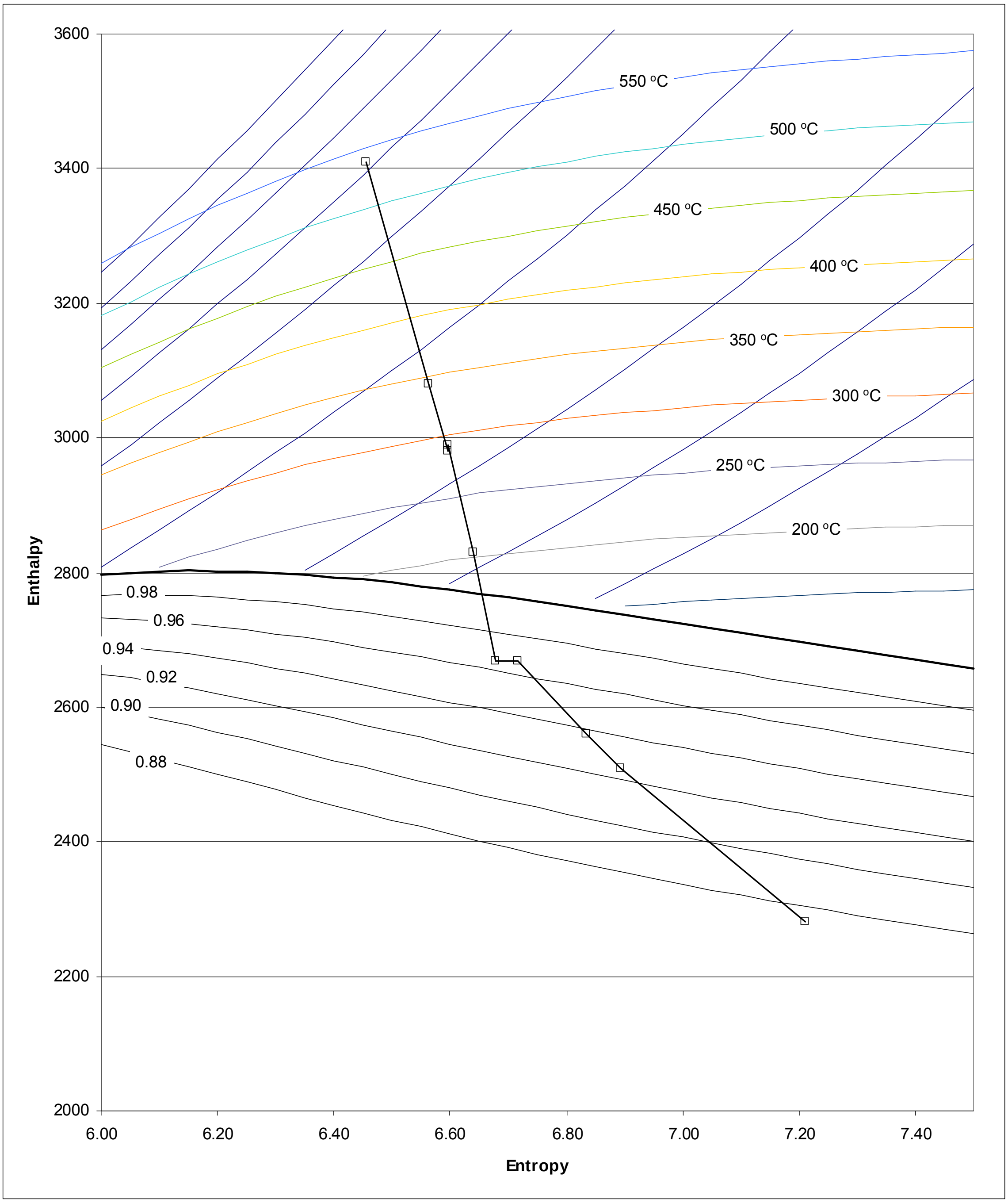

Figure 6-17, Assisted circulation recovery boiler turbine expansion in h-s-diagram, 232.0 kg/s, 16.0 MPa, 540 °C.

6.5 Case E – High pressure and temperature recovery boiler with reheat concept

This boiler equals the boiler of Case C but with reheating applied

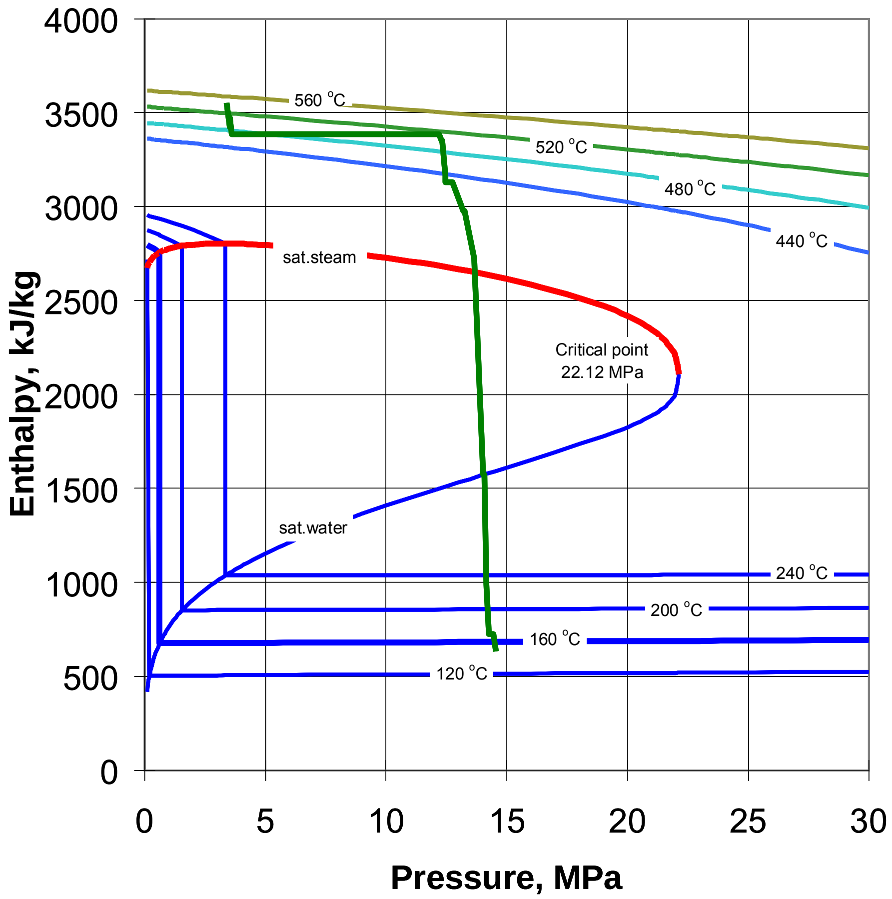

Figure 6-18, High pressure and temperature recovery boiler with reheat in p-h-diagram, 224.0 kg/s, 12.0/3.4 MPa, 515/400 °C.

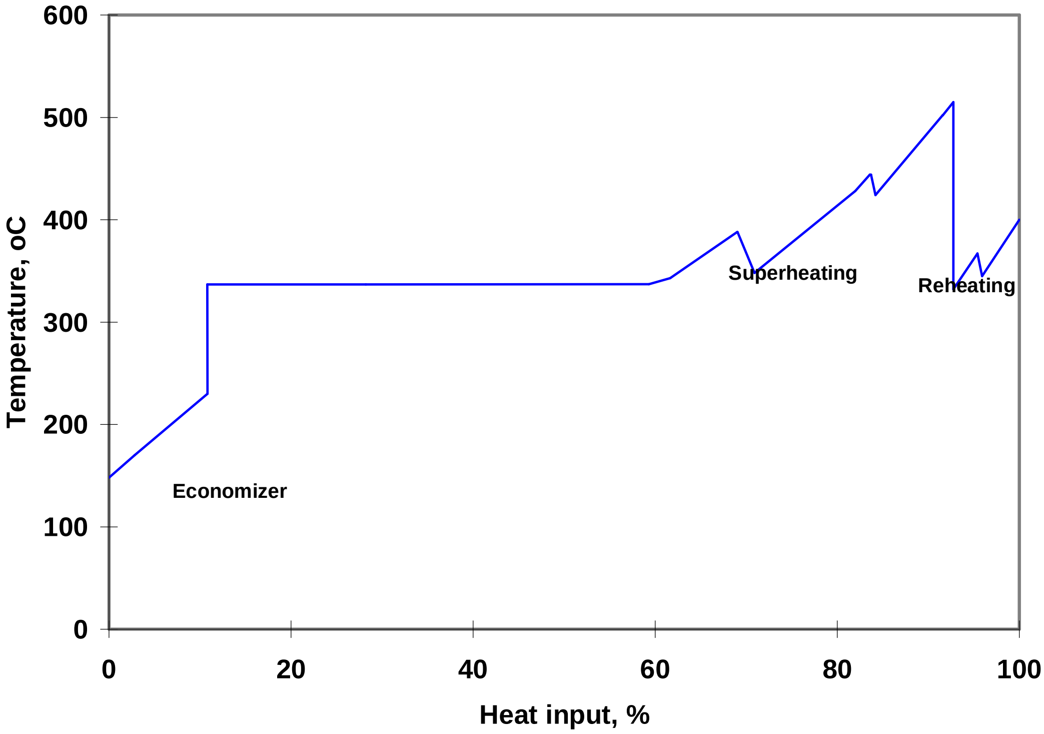

Figure 6-19, High pressure and temperature recovery boiler with reheat in Φ-t-diagram, 224.0 kg/s, 12.0/3.4 MPa, 515/400 °C.

Table 6-5 Main dimensions of high pressure and temperature recovery boiler with reheat, case E.

Surface	unit	
Furnace area	m^2	232.1
Furnace height	m	38.4
Total boiler height	m	75
Furnace area	m^2	4473
Screen area	m^2	
Superheater area	m^2	20255
Superheater area (proj)	m^2	25451
Boiler bank area	m^2	10852
Economizer area	m^2	39975
Total area	m^2	

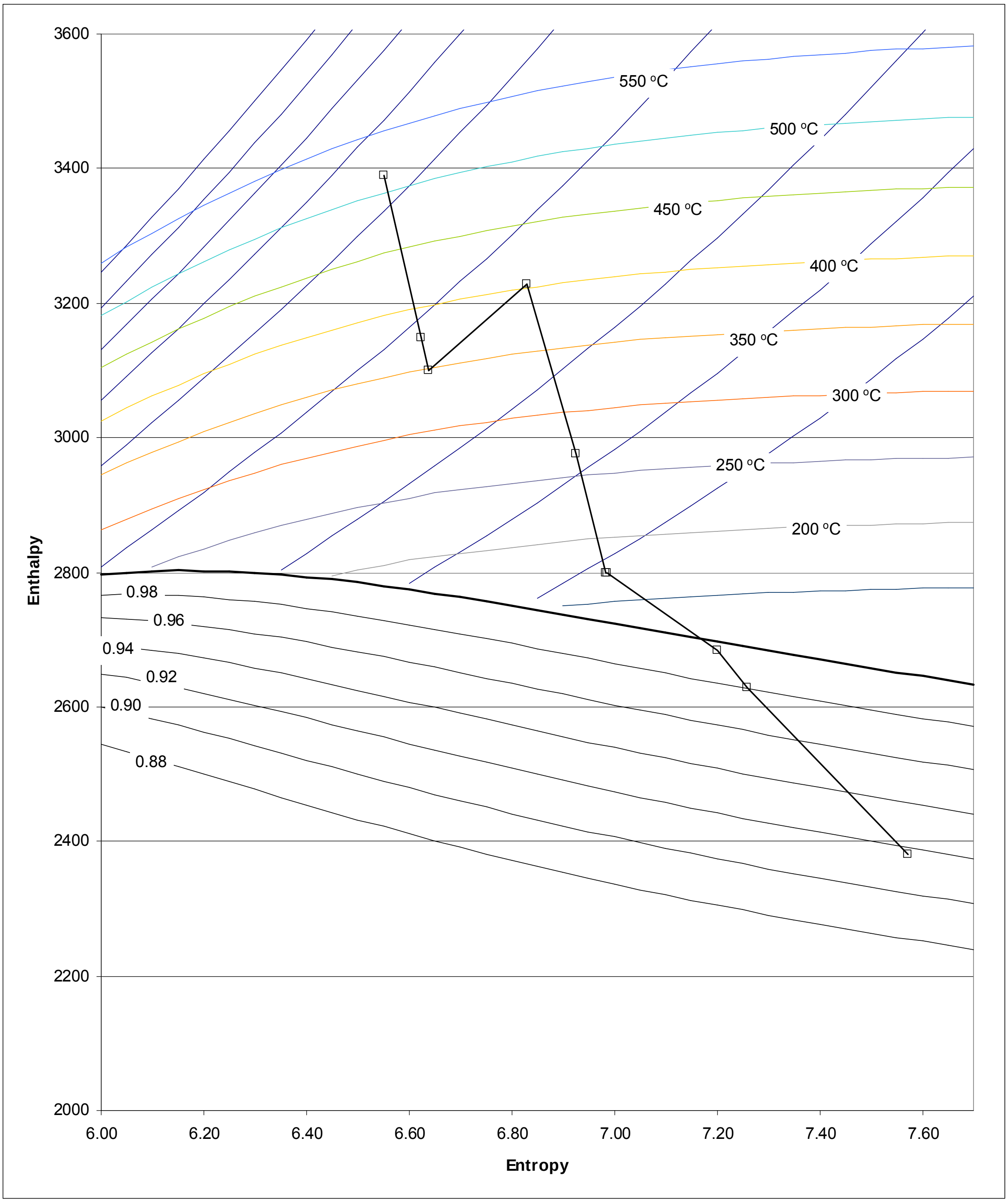

Figure 6-20, High pressure and temperature recovery boiler with reheat in h-s-diagram, 224.0 kg/s, 12.0/3.4 MPa, 515/400 °C.

6.6 Case F – Once-through recovery boiler with reheat concept

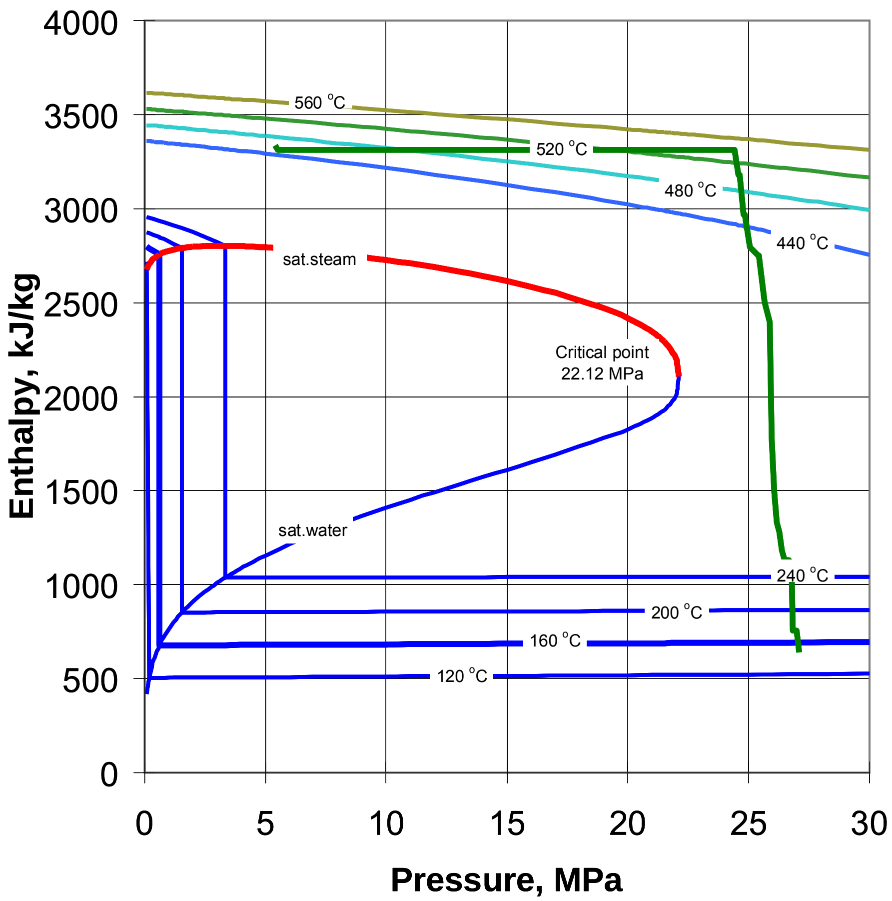

Figure 6-21, Once-through recovery boiler with reheat in p-h-diagram, 218.5 kg/s, 24.0/5.4 MPa, 540/460 °C.

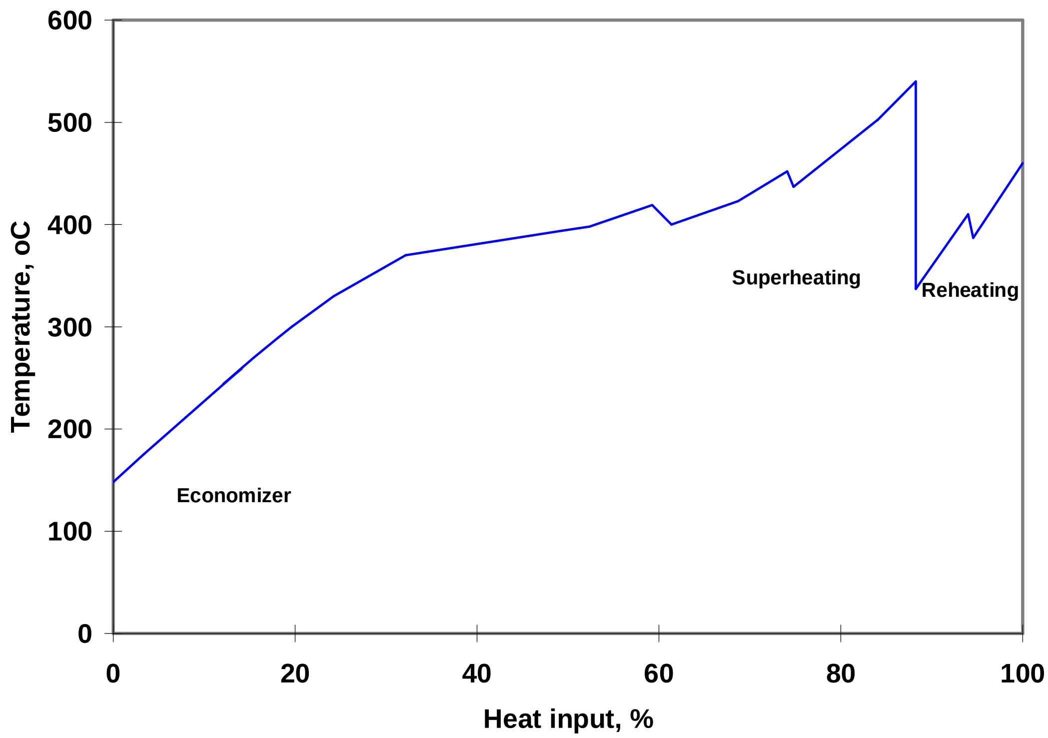

Figure 6-22, Once-through recovery boiler with reheat in Φ-t-diagram, 218.5 kg/s, 24.0/5.4 MPa, 540/460 °C.

Table 6-6 Main dimensions of once-through recovery boiler with reheat, Case F.

Surface	**unit**	
Furnace area	m^2	234.4
Furnace height	m	33.6
Total boiler height	m	72.0
Furnace area	m^2	4084
Screen area	m^2	796
Superheater area	m^2	24372
Superheater area (proj)	m^2	23803
Boiler bank area	m^2	12786
Economizer area	m^2	39235
Total area	m^2	105075

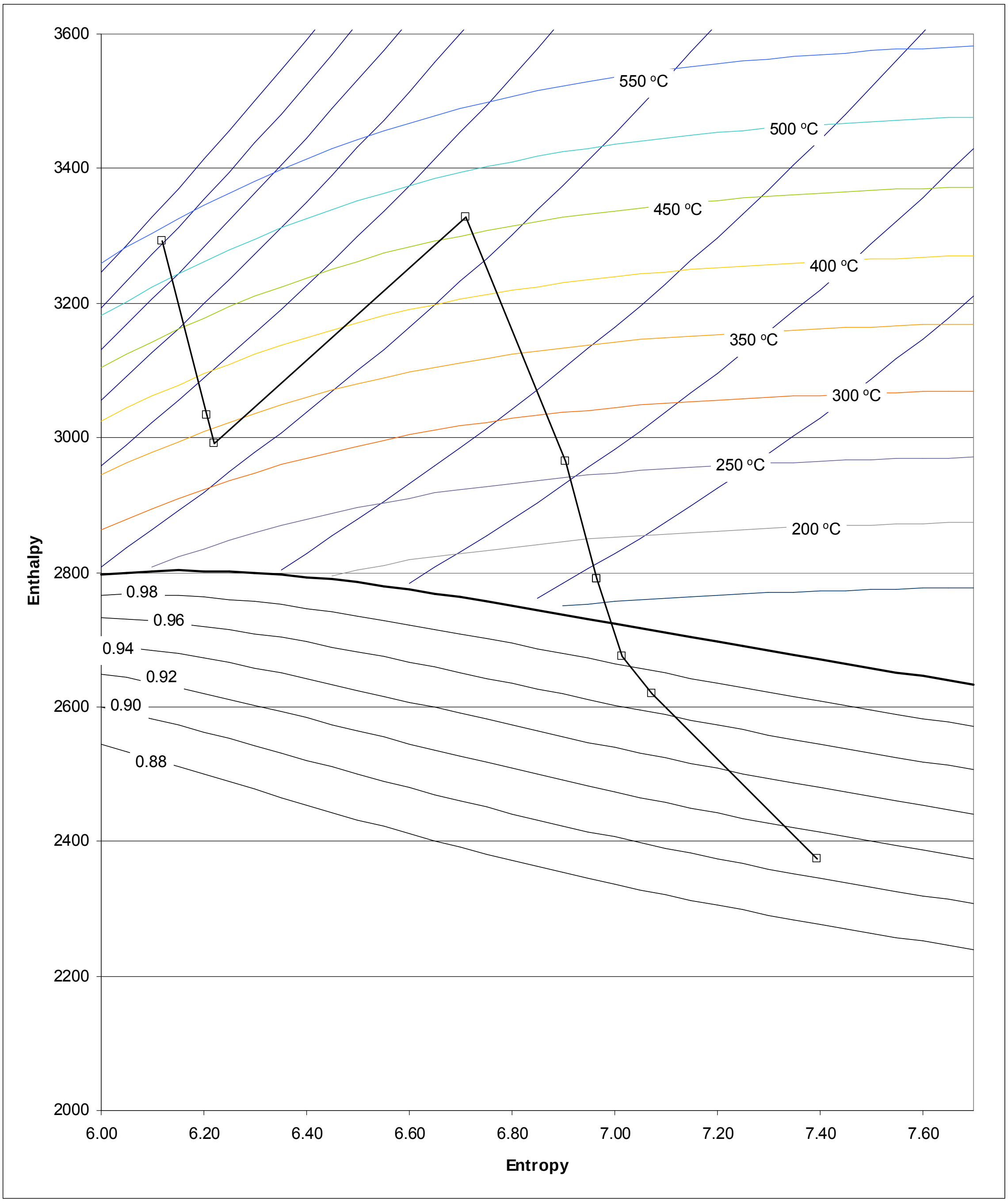

Figure 6-23, Once-through recovery boiler with reheat in h-s-diagram, 218.5 kg/s, 24.0/5.4 MPa, 540/460 °C.

6.7 Boiler size comparison

Recovery boiler pressure part weights for different options are shown in Table 6-7.

Table 6-7 Main size values for each case.

		Joutseno	Kymi	Yonago	SoTu	SkyRec	SkyRec+
Case		**A**	**B**	**C**	**D**	**E**	**F**
Capacity	tds/d	5500	5500	5500	5500	5500	5500
capacity (virgin)	tds/d	5005	5005	5005	5005	5005	5005
Dry solids	%	82.0	85.0	85.0	85.0	85.0	85.0
Main steam pressure RB	bar(a)	94.0	104.0	124.0	164.0	124.0	264.0
Main steam temp. RB	°C	490.0	505.0	515.0	540.0	515.0	540.0
General data							
Design pressure	bar(e)	130	129	148	186	148	289
Areas							
Furnace area	m2	233.6	232.1	232.1	232.1	232.1	234.4
Furnace height	m	36.5	41.6	41.6	39.6	38.4	33.6
Total boiler height	m	75.5	75.1	78.0	76.0	75.0	72.0
Furnace area	m2	4417	5056	5056	4813	4672	4084
Screen area	m2	0	796	0	796	796	796
Superheater area	m2	23712	13536	16102	20255	21306	24372
Superheater area (proj)	m2	16004	12984	15446	19429	20437	23803
Boiler bank area	m2	13600	10262	11982	11982	11982	12786
Economizer area	m2	40720	39676	39676	39529	39382	39235
Total area	m2	98454	82310	88262	96804	98575	105075
Pressure part weight							
Furnace panels weight	tons	1035	1085	1107	1157	1051	843
Screen weight	tons	0	465	0	588	503	543
Superheater weight	tons	2254	1463	1827	2490	2417	2569
Boiler bank weight	tons	813	740	1041	1041	1041	1080
Economizer weight	tons	1845	2080	2080	2072	2063	2057
Total weight	tons	5946	5832	6055	7348	7075	7091
Total hanging weight	tons	9250	8760	9270	10290	10170	10140
Cost							
Cost difference	M€	9.2	0.0	6.5	17.1	24.3	27.0
Electricity difference	MWe	-4.0	0.0	7.3	19.6	8.3	19.0
Cost for additional	k€/MWe	-2310	0	890	875	2921	1422
Price of extra power	€/MWh	-57.8	0.0	22.2	21.9	73.0	35.6

The increase in electricity generation seems very profitable up to case C. This confirms the rationality of design choices that have lead to the present recovery boiler. Case A costs more that it should were it built today. The reason is larger than required superheating surface and smaller than currently used superheater tube size. From cost of additional power, going to SoTu concept of 540 ^{o}C steam seems desirable. Currently the corrosion issues have not yet been solved so in this study we assume that superheaters do not corrode. Reheater boiler concept seems not at all profitable. The additional electricity generation was only marginal. Once-through recovery boiler did produce as much additional electricity than the SoTu concept of 540 ^{o}C steam. The corrosion issues still remain the same.

7 APROS-STUDIES

The Advanced Process Simulation Environment (APROS) provides tools, solution algorithms and mode libraries for fullscale modelling and simulation of dynamic processes, such as combustion power plants. The model libraries have been comprehensively validated against real physical process experiments. The modular and hierarchical approach of APROS allows unique flexibility of process analysis at various conceptual levels.

APROS allows the inclusion of the user's own models in the calculation as well as easy connection to external models, automation systems or control room equipment. A large process model can be divided into several flowsheet diagrams. This can be done both in a hierarchical and a horizontal way. At any time, the complete model information can be saved into a model snapshot file containing the full model configuration and its momentary state data at the time instant. Similarly, at any time, the user can backtrack to a snapshot once saved in the past.

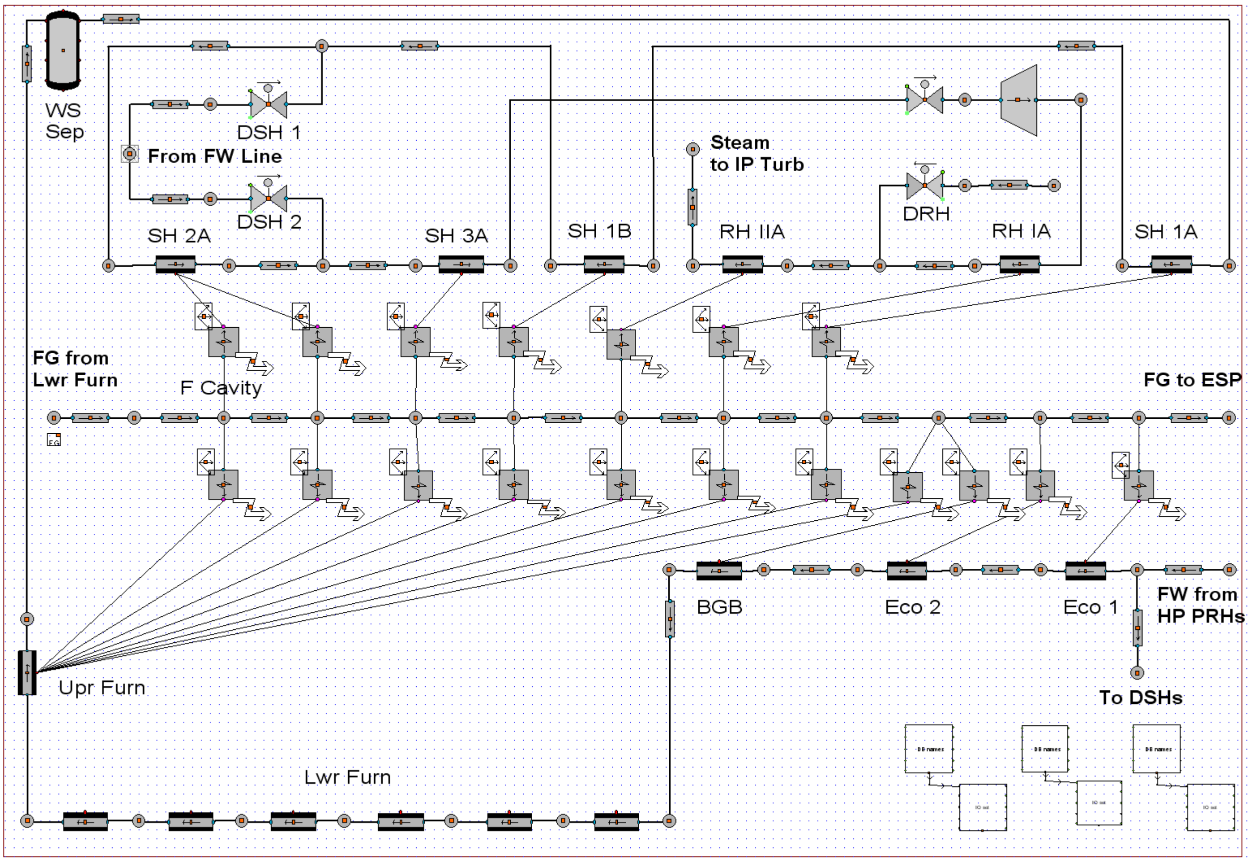

Figure 7-1, Once-through recovery boiler with reheat APROS model, 218.5 kg/s, 24.0/5.4 MPa, 540/460 °C.

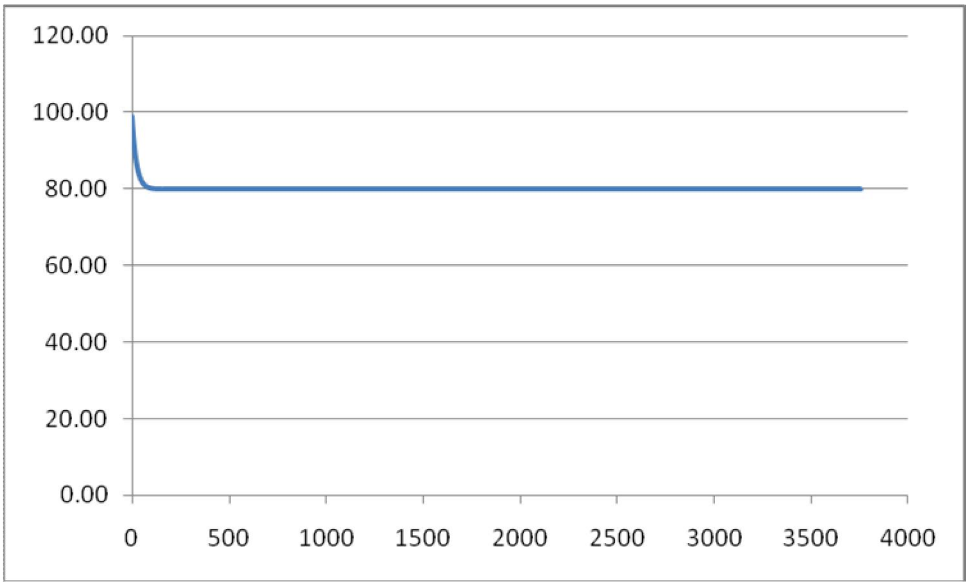

Figure 7-2, Change in firing rate in once-through recovery boiler with reheat.

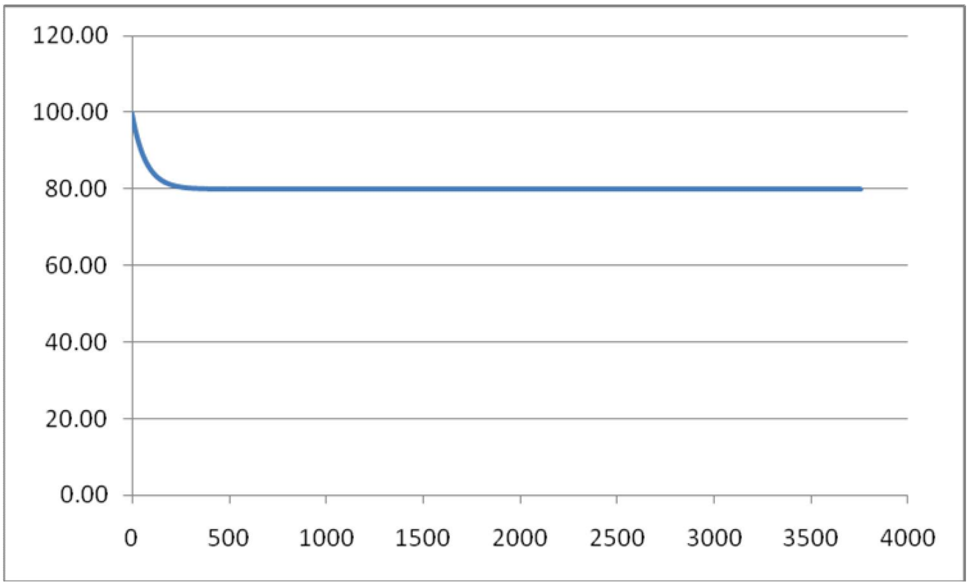

Figure 7-3, Desired change in steam flow in once-through recovery boiler with reheat.

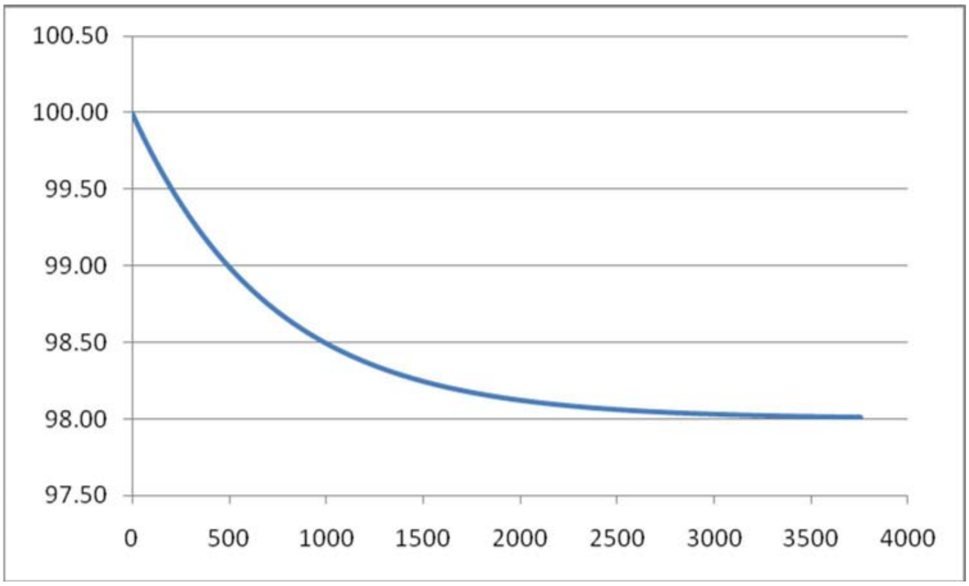

Figure 7-4, Desired change in steam temperature in once-through recovery boiler with reheat.

8 PREHEATER CONCEPTS

One of the most successful ways to increase electricity generation form recovery boilers hah been the implementation of different preheating schemes (Raukola et al., 2002).

The preheating schemes have been selected based on typical practice.

8.1 Air preheater concepts

It is important to heat air. In Case C5 the air on average is preheated only to 121.2 ^{o}C. This was typical to so called cold tertiary air systems. Cold tertiary was used to increase the mixing of air to flue gases in the furnace.

In Case C4 the air on average is preheated already to 150.4 ^{o}C. This was typical after newer air systems became wider spread. In Case C3 the air on average preheated to 190 ^{o}C. This is the case for modern high electricity boilers (Aikio, 2009).

8.2 Water preheater concepts

In cases C5 – C3 the feedwater was preheated to 120 ^{o}C. Flue gas temperature is then 155 ^{o}C. In Case C2 the feedwater is preheated to 148 ^{o}C before the economizers. This means that flue gas exit temperature increases to 198 ^{o}C. The flue gas is cooled down in air heater so the temperature to stack remains constant.

In case C1 the feedwater is additionally preheated between economizers from 200 to 220 ^{o}C. This high pressure preheater concept is patented.

8.3 Sootblowing concepts

In cases C5 – C1 the sootblowing was taken from inside the recovery boiler. In Case C0 the Sootblowing is taken from turbine so some expansion in turbine occurs which increases the electricity generation.

8.4 Electricty generation changes

Electricity generation in cases C5 – C0 is shown in the Table 8-1.

Table 8-1 Main values and electricity generation for additional cases.

Case		As case C **C0**	inside SB **C1**	No FW prh **C2**	Low FW **C3**	Air 150 **C4**	Air 120 **C5**
Capacity	tds/d	5500	5500	5500	5500	5500	5500
capacity (virgin)	tds/d	5005	5005	5005	5005	5005	5005
Dry solids	%	85.0	85.0	85.0	85.0	85.0	85.0
ds (virgin)	%	83.8	83.8	83.8	83.8	83.8	83.8
recycle ash	%	9.0	9.0	9.0	9.0	9.0	9.0
HHV	MJ/kgds	13.00	13.00	13.00	13.00	13.00	13.00
HHV (virgin)	MJ/kgds	14.29	14.29	14.29	14.29	14.29	14.29
LHV	MJ/kgds	12.28	12.28	12.28	12.28	12.28	12.28
LHV (virgin)	MJ/kgds	13.49	13.49	13.49	13.49	13.49	13.49
O2 in dry flue gas	%	2.8	2.8	2.8	2.8	2.8	2.8
Primary air	%	22.0	22.0	22.0	22.0	22.0	22.0
Primary air temp	°C	190.0	190.0	190.0	190.0	**160.0**	**150.0**
Secondary air	%	54.0	54.0	54.0	54.0	54.0	54.0
Secondary air temp	°C	190.0	190.0	190.0	190.0	**160.0**	**150.0**
Tertiary air percentage	%	12.0	12.0	12.0	12.0	12.0	12.0
Tertiary air temp	°C	190.0	190.0	190.0	190.0	**120.0**	**30.0**
Quartenary air	%	12.0	12.0	12.0	12.0	12.0	12.0
Quartenary air temp	°C	190.0	190.0	190.0	190.0	**120.0**	**30.0**
Total air percentage	%	100.0	100.0	100.0	100.0	100.0	100.0
Total air temperature	°C	190.0	190.0	190.0	190.0	150.4	121.2
Reduction	%	96.00	96.00	96.00	96.00	96.00	96.00
Main steam pressure RB	bar(a)	124.0	124.0	124.0	124.0	124.0	124.0
Main steam temp RB	°C	515.0	505.0	515.0	515.0	515.0	515.0
Feedwater pressure	bar(a)	146.0	146.0	146.0	146.0	146.0	146.0
Feedwater temperature	°C	148.0	148.0	148.0	**120.0**	**120.0**	**120.0**
HP FWpreh inlet temp	°C	200	200	200	200	200	200
HP FWpreh outlet temp	°C	220	220	**200**	**200**	**200**	**200**
Flue gas temp (eco out)	°C	197	197	197	**155**	**155**	**155**
Flue gas temp (to stack)	°C	155	155	155	155	155	155
Sootblowing	kg/s	6.0	**6.0**	**6.0**	**6.0**	**6.0**	**6.0**
Steam flow	kg/s	232.5	228.6	221.0	217.1	213.6	211.1
Change in steam flow	%	0.0	-1.7	-5.0	-6.6	-8.1	-9.2
Pulping usage total	MW	88.9	88.9	88.9	88.9	88.9	88.9
Mill total usage	MW	92.4	92.4	92.4	92.4	92.4	92.4
Electricity production	MW	161.8	160.8	158.4	156.5	154.5	153.6
Surplus electricity	MW	69.4	68.3	66.0	64.1	62.0	61.2

9 CONCLUSIONS

In this study several recovery boiler concepts were compared with the whole pulp mill energy balance being considered. The studied concepts are

G. Natural circulation 82 %, 490 °C, 9.0 MPa (reference Joutseno)
H. Natural circulation 85 %, 505 °C, 10.2 MPa (reference Kymi)
I. Natural circulation 85 %, 515 °C, 12.0 MPa (reference Yonago)
J. Assisted circulation 85 %, 540 °C, 16.0 MPa (reference SoTu)
K. Natural circulation 85 %, 515/400 °C, 12.0/3.0 MPa (SkyRec)
L. Once-through 85 %, 540/460 °C, 26.0/5.4 MPa (SkyRec+)

Steam and electricity generation for each recovery boiler case is shown in Table 9-1. The steam production increases from Case A to Case B because of higher black liquor dry solids and more air preheating. The steam production increases from Case B to Case C because of high pressure preheating. The recovery boiler steam flow starts decreasing as further increases in main steam parameters require more heat.

Table 9-1 Steam and electricity generation for each case.

		Joutseno	Kymi	Yonago	SoTu	SkyRec	SkyRec+	SkyRec
Case		**A**	**B**	**C**	**D**	**E**	**F**	**E160**
Capacity	tds/d	5500	5500	5500	5500	5500	5500	5500
capacity (virgin)	tds/d	5005	5005	5005	5005	5005	5005	5005
Dry solids	%	82.0	85.0	85.0	85.0	85.0	85.0	85.0
Main steam pressure RB	bar(a)	94.0	104.0	124.0	164.0	124.0	264.0	164.0
Main steam temp. RB	°C	490.0	505.0	515.0	540.0	515.0	540.0	515.0
Steam generation								
Steam flow RB	kg/s	215.0	226.4	233.6	232.0	224.0	218.5	224.0
Change in steam flow	%	0.0	5.3	8.6	7.9	4.1	1.6	4.1
Electricity								
Pulping usage total	MW	87.6	88.1	88.9	90.2	88.2	93.2	90.0
Mill total usage	MW	91.1	91.7	92.4	93.8	91.8	96.8	93.6
Electricity production	MW	149.3	153.9	161.8	175.6	162.3	177.9	167.0
Surplus electricity	MW	58.2	62.2	69.4	81.7	70.5	81.1	73.4
Efficiency to electricity	%	20.4	20.4	21.4	23.2	21.5	23.5	22.7
Change in electricty	MW	0.0	4.0	11.2	23.6	12.3	22.9	15.2
	%	0.0	6.8	19.3	40.5	21.1	39.4	26.2

As can be seen the modern recovery boiler Case C does produce about 20 % more electricity than roughly ten years ago, case A. reheating cases E and E160 seem to give only marginally better electricity production. The only alternative seems to be to increase the main steam temperature to 540 °C, Cases D and F. The pulping electricity usage is not constant. The main parameter that changes is the recovery boiler feedwater pump power requirement.

Electricity generation does not depend a lot on how the boiler steam side is configured. Reheating and once-through appear only marginally better when considering the recovery boiler electricity generation.

Table 9-2 Cost difference and price of extra power for each case.

		Joutseno	Kymi	Yonago	SoTu	SkyRec	SkyRec+
Case		**A**	**B**	**C**	**D**	**E**	**F**
Capacity	tds/d	5500	5500	5500	5500	5500	5500
capacity (virgin)	tds/d	5005	5005	5005	5005	5005	5005
Dry solids	%	82.0	85.0	85.0	85.0	85.0	85.0
Main steam pressure RB	bar(a)	94.0	104.0	124.0	164.0	124.0	264.0
Main steam temp. RB	°C	490.0	505.0	515.0	540.0	515.0	540.0
Cost							
Cost difference	M€	9.2	0.0	6.5	17.1	24.3	27.0
Electricity difference	MWe	-4.0	0.0	7.3	19.6	8.3	19.0
Cost for additional	k€/MWe	-2310	0	890	875	2921	1422
Price of extra power	€/MWh	-57.8	0.0	22.2	21.9	73.0	35.6

The increase in electricity generation seems very profitable up to case C. This confirms the rationality of design choices that have lead to the present recovery boiler. Case A costs more that it should were it built today. The reason is larger than required superheating surface and smaller than currently used superheater tube size. From cost of additional power, going to SoTu concept of 540 ^{o}C steam seems desirable. Currently the corrosion issues have not yet been solved so in this study we assume that superheaters do not corrode. Reheater boiler concept seems not at all profitable. The additional electricity generation was only marginal. Once-through recovery boiler did produce as much additional electricity than the SoTu concept of 540 ^{o}C steam. The corrosion issues still remain the same.

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APPENDICES

Appendix I: Recovery boiler balances for each case
Appendix II: Mill electricity generation for each case

APPENDIX I

APPENDIX II

Liite VIII

Patrik Yrjas, Åbo Akademi - tilanneraportti
Tulistinmateriaalien laboratoriokokeet

SKYREC CORROSION TEST MATRIX, 2009 1(2)

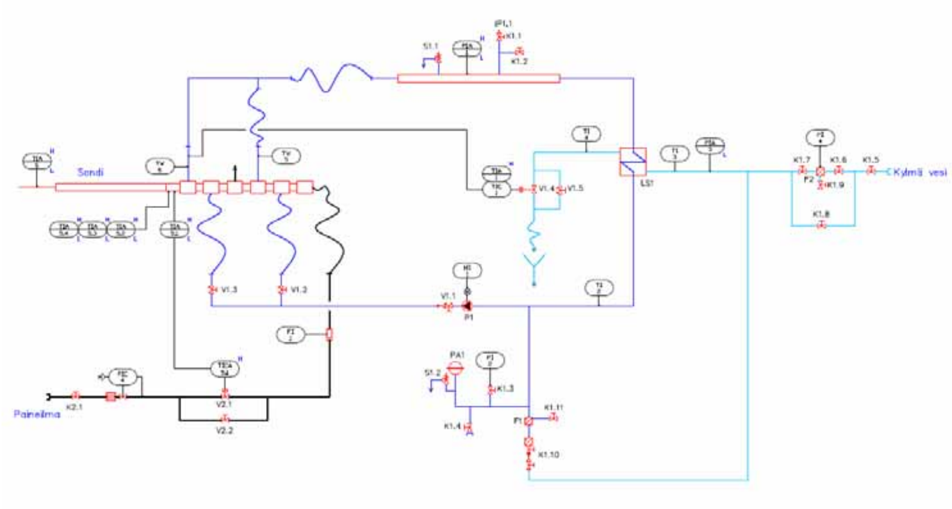
Test no.	Oven no.	Material	Salt	Temp.	Gas atmosphere	Comments		
1	1	10CrMo	**ash 5 + BL-char**	450	5% CO, 95% N2		SEM	no corr.
2		T91	Na2SO4				SEM	no corr.
3		Sanicro 28	To = 884				SEM	no corr.
4		HR11N					SEM	no corr.
5		10CrMo				repetition	SEM	no corr.
6	2	10CrMo	ash 5 + BL-char	500	5% CO, 95% N2		SEM	no corr.
7		T91					SEM	no corr.
8		Sanicro 28					SEM	no corr.
9		HR11N					SEM	no corr.
10		T91				repetition	SEM	no corr.
11	3	10CrMo	ash 5 + BL-char	550	5% CO, 95% N2		SEM	no corr.
12		T91					SEM	no corr.
13		Sanicro 28					SEM	no corr.
14		HR11N					SEM	no corr.
15		Sanicro 28				repetition	SEM	no corr.
16	4	10CrMo	ash 5 + BL-char	600	5% CO, 95% N2		SEM	corrosion
17		T91					SEM	corrosion
18		Sanicro 28					SEM	no corr.
19		HR11N					SEM	corrosion
20		HR11N				repetition	SEM	no corr.
21	5	10CrMo	**ash 8 + BL-char**	450	5% CO, 95% N2		SEM	corrosion
22		T91	NaCl, KCl	(0.3 % Cl)			SEM	corrosion
23		Sanicro 28	Na2SO4, K2SO4				SEM	no.corr.
24		HR11N	To = 526				SEM	no corr.
25		10CrMo				repetition	SEM	corrosion
26	6	10CrMo	ash 8 + BL-char	500	5% CO, 95% N2		SEM	corrosion
27		T91					SEM	no corr.
28		Sanicro 28					SEM	no corr.
29		HR11N					SEM	no corr.
30		T91				repetition	SEM	no corr.
31	7	10CrMo	ash 8 + BL-char	550	5% CO, 95% N2		SEM	coloring
32		T91					SEM	no corr.
33		Sanicro 28					SEM	no corr.
34		HR11N					SEM	no corr.
35		Sanicro 28				repetition	SEM	no corr.
36	8	10CrMo	ash 8 + BL-char	600	5% CO, 95% N2		SEM	corrosion
37		T91					SEM	coloring
38		Sanicro 28					SEM	coloring
39		HR11N					SEM	coloring

SKYREC CORROSION TEST MATRIX, 2009

Test no.	Oven no.	Material	Salt	Temp.	Gas atmosphere	Comments		
40		HR11N				repetition	SEM	coloring
41	9	10CrMo	**ash 9 + BL-char**	450	5% CO, 95% N2		SEM	no.corr.
42		T91	NaCl	(1.3 mol% Cl)			SEM	corrosion
43		Sanicro 28	Na2SO4				SEM	no.corr.
44		HR11N	To = 621				SEM	no.corr.
45		10CrMo				repetition	SEM	corrosion
46	10	10CrMo	ash 9 + BL-char	500	5% CO, 95% N2		SEM	corrosion
47		T91					SEM	no.corr.
48		Sanicro 28					SEM	no.corr.
49		HR11N					SEM	no.corr.
50		T91				repetition	SEM	no.corr.
51	11	10CrMo	ash 9 + BL-char	550	5% CO, 95% N2		SEM	corrosion
52		T91					SEM	no.corr.
53		Sanicro 28					SEM	no.corr.
54		HR11N					SEM	no.corr.
55		Sanicro 28				repetition	SEM	no.corr.
56	12	10CrMo	ash 9 + BL-char	600	5% CO, 95% N2		SEM	no.corr.
57		T91					SEM	no.corr.
58		Sanicro 28					SEM	no.corr.
59		HR11N					SEM	corrosion
60		HR11N				repetition	SEM	no.corr.
61	13	10CrMo	**ash 10 + BL-char**	450	5% CO, 95% N2		SEM	no corr.
62		T91	KCl	(1.3 mol% Cl)			SEM	no corr.
63		Sanicro 28	Na2SO4, K2SO4				SEM	no corr.
64		HR11N	To = 522				SEM	no corr.
65		10CrMo				repetition	SEM	no.corr.
66	14	10CrMo	ash 10 + BL-char	500	5% CO, 95% N2		SEM	no.corr.
67		T91					SEM	no corr.
68		Sanicro 28					SEM	no corr.
69		HR11N					SEM	no corr.
70		T91				repetition	SEM	no corr.
71	15	10CrMo	ash 10 + BL-char	550	5% CO, 95% N2		SEM	corrosion
72		T91					SEM	corrosion
73		Sanicro 28					SEM	corrosion
74		HR11N					SEM	corrosion
75		Sanicro 28				repetition	SEM	corrosion
76	16	10CrMo	ash 10 + BL-char	600	5% CO, 95% N2		SEM	corrosion
77		T91					SEM	corrosion
78		Sanicro 28					SEM	corrosion
79		HR11N					SEM	corrosion
80		HR11N				repetition	SEM	corrosion

Liite IX

Markku Orjala, VTT - tilanneraportti
Tulistinputkimateriaalien korroosiotutkimus soodakattilalla



Tulistinputkimateriaalien korroosiotutkimus soodakattilalla

Tilaaja: Suomen Soodakattilayhdistys ry

Tilaaja

Suomen Soodakattilayhdistys ry

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Työn sisältö

Tutkimuksessa kartoitetaan kuuden materiaalin kuumakorroosioriskit soodakattilan tulistinalueella kahdella eri kattilalla tai kahdessa eri lämpötilassa tilaajan osoittamissa paikoissa. Tutkimuksessa selvitetään tulistinalueelle kertyvien kerrostumien koostumusta, tutkitaan eri tulistinmateriaalien kestävyyttä. Materiaalien altistusaika on n. 1000 tuntia. Kerrostumien muodostumisen monitorointiin ja tulistinmateriaalien kestävyyden arviointiin käytetään VTT:llä kehitettyjä sondeja.

Tilannekatsaus 25.11.09

- Joutsenon laitoksella huoltoseisokki viikolla 48
- Laitokselle on toimitettu tiedot sondien vaatimuksista (yhteet, vesi, ilma, sähkö yms.)
- Sondien kunnostustoimenpiteet loppusuoralla
- Sondin jäähdytysratkaisun suunniteltu (kts. tämän raportin kannen kuva) ja komponenttien hankinta ovat käynnissä. Kokoaminen/rakentaminen käynnistyy täysimääräisesti komponenttien saavuttua. Tavoiteaikataulu joulukuu.
- Kaikki testattavat holkkimateriaalit on hankittu ja näytekappaleiden valmistus menossa
- Mittausten aloittaminen ensi vuoden alussa (tavoiteaikataulu tammikuu)

JAKELU

Tilaaja
VTT / projektiryhmä

Liite X

Hannu Makkonen, Riku Mattila, Oulun yliopisto - tarjous Tulenkestävien massojen kokeellisesta tutkimuksesta

TARJOUS TUTKIMUKSEN SUORITTAMISESTA

Tarjoamme __tulenkestävien soodakattimateriaalien__ tutkimuksen suorittamista alla mainituin ehdoin.

1 Tarjouksen tekijä

Oulun yliopisto, prosessimetallurgian laboratorio.

2 Tarjouksen kohde ja suoritusaika

On liitteellä 1.

3 Maksuehdot

Tutkimus laskutetaan sopimushintaan 14 000 € ALV 0 %
Maksu suoritetaan kertasuorituksena loppuraportoinnin jälkeen.

4 Muut ehdot

Tarjous on voimassa 2 kuukautta tarjouskirjeen päiväyksestä.

Mikäli tarjous tulee hyväksytyksi, sopimukseen sovelletaan Oulun yliopiston tilaajarahoitteisen tutkimuksen yleisiä sopimusehtoja (Liite 2).

5 Tutkimuksen tekijää koskevat tiedot

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Allekirjoitus
Oulun yliopisto 25/11 2009

Jouko Härkki
____
Tutkimuksen vastuullinen johtaja

KOKEELLINEN VERTAILEVA TUTKIMUS TULENKESTÄVISTÄ MASSOISTA SOODAKATTILASSA

1 TAUSTAA

Oulun yliopiston prosessi- ja ympäristötekniikan osaston prosessimetallurgian laboratoriossa tutkittiin syksyllä 2005 soodakattilan tulenkestäviä materiaaleja. Tutkimuksen tilaajana oli Suomen Soodakattilayhdistys ry. [1]

Kokeellisessa osassa testattiin osittain spinelliin pohjautuvaa materiaalia altistamalla se soodakattilan sulalle Stora Enson Oulun tehtaalla. Vertailukohteena käytettiin nykyisin käytössä olevaa samottista materiaalia. Spinelliä sisältäneet koekappaleet kestivät soodakattilan olosuhteita paremmin kuin nykyisin käytetystä materiaalista valmistettu kappale. Spinelliä sisältävän materiaalin lisäksi jatkotutkimuksiin suositeltiin myös ZrO_2-pohjaista materiaalia sekä forsteriitin ja ceriumoksidin soveltuvuuden arviointia.

2 TUTKIMUSSUUNNITELMA

Testit on tarkoitus suorittaa Stora Enson Oulun tehtaiden soodakattilassa ajon aikana. Suoritusajaksi on kaavailtu vuoden 2009 loppua ja 2010 alkua.

2.1 Materiaalit

Tutkittaviksi materiaaleiksi on valittu seuraavat:

- Vertailu materiaali (Hassle ja MagnesiaRautatiili tehtaalta)
- Spinelliä muodostavaa massaa (Betker tai vastaava)
- Valmista spinelliä sisältävää massaa
- ZrO2 kaupallista massaa (Zircoa-Cast™ Castable Refractory, 0872-8D)
- CeO2 pohjainen massa tai pinnoite
- Forsteriitti pohjainen massa
- Tiivis aloksimassa (tehtaalla bloki).

2.2 Koekappeleiden valmistus

Koekappaleet valmistetaan massanvalmistajien ohjeiden mukaisesti.

Tulenkestävistä massoista valmistetaan noin 100-150mm pitkä neliöprofiilinen tanko jonka sivu on noin 50mm. Koekappale kiinnitetään teräs tankoon ”tikkariksi”.

Massat kuivataan 110°C valun ja sidoksen muodostuksen jälkeen. Sen jälkeen poltetaan tiilen valmistus lämpötilaa vastaavaksi.

Tikkarit ladotaan asennuspaketiksi, jossa on pahvin mentävä rako tikkareiden välillä. Pakettia ylläpitää teräksinen kehikko, jonka toiseen aukkoon tikkarien teräsvahvikkeet kiinnittyvät ja jossa on ulosvetoa ja asennusta varten tanko kehikossa. Raot tilkitään tulenkestävällä villalla.

Kehikon tekee Oulun yliopisto yhteistyössä tehtaan kanssa.

2.3 Kokeiden suorittaminen

Tikkareita mahtuu 250mm x 100mm ruiskutusaukkoon noin kolmesta viiteen kappaletta kerrallaan, jotka asetetaan kehikossa sisään. Vähintään yksi ”tikkareista” on vertailumateriaalia. Mitataan upotussyvyys ja erillisellä termoelementillä lämpötila.

Toimitaan samoin seuraavien materiaalien kanssa.

Koekappaleita pidetään kattilassa kunnes on seuraava ajotauko.

Testin läpikäyneet koekappaleet merkitään, kuvataan ja säilötään jatkotutkimusta varten.

2.4 Koekappaleiden analysointi

Koekappaleet mitataan sekä kuvataan ennen ja jälkeen kokeen. Tästä saa jo käsityksen mikä vertailtavista materiaaleista on paras. Jos halutaan edetä tutkimuksessa ja vastata kysymykseen miksi kyseinen materiaali kesti kokeessa täytyy koekappaleen mikrorakenne tutkia.

Mikrorakenteen tutkiminen on oma projektinsa.

2.5 Aikataulu

Koekappaleen muottien 6-10 kpl valmisteluaika vähintään 2 päivää.
Kehikoiden 2kpl valmisteluaika 2 päivää.
Koekappaleen teko 1 kpl/päivä joten muotteja tarvitaan useita 6 kpl muotteja homma hoituu nopeammin noin 1 päivässä.
Koekappaleiden poltto 1 päivä 6 kpl kerralla.
Kappaleiden kuvaus ja kasaaminen kehikkoon 1 päivä.
Yhteensä minimi valmisteluaika kahdelle testikehikolle koekappaleineen on noin 2+2+1+1+1= 7 päivää

Kappaleiden purku, kulumien mittaus ja valokuvaus 1 vko.
Raportointi havainnoista ja suositukset jatkosta 1 vko.

Yhteensä tehollista työaikaa arvoidaan kuluvan noin 3 vko.

2.6 Lähteet

Hannu Makkonen ja Riku Mattila. Soodakattilan keraamiset rakenteet. 2005. Luottamuksellinen.

3 KUSTANNUKSET

Tehokasta työaikaa kuluu arviolta noin 3 viikkoa. Tähän sisältyy kuitenkin jonkin verran päällekkäistä työaikaa yliopiston pajan, laboratorioinsinöörin ja tutkijan välillä. Laskutus on siis noin henkilökuukauden verran. Koemateriaalien hankinta ja valmistukseen kuluu jonkin verran rahaa samoin matkoihin jne. Arvio muihin kuluihin on noin 1500 euroa. Kokonaiskustannus on 14000 euroa alv0%.