DESIGN AND OPERATION OF A PILOT SCALE S-CO2 SYSTEM BY CONCENTRATED SOLAR POWER

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EU s-CO2 Seminar, 29th September 2016

,
ENERGY TRANSFORMED FLAGSHIP
www.csiro.au

Commonwealth Scientific and Industrial Research Organization
National Solar Energy Centre, Newcastle NSW Australia

Advanced Solar Technologies

Introduction

- Concentrated Solar Power (CSP) using supercritical CO_2 recompression Brayton cycles have been shown to achieve higher overall thermal efficiencies when compared to power cycles using superheated or supercritical steam.
- The high efficiency and compactness of sCO_2, as compared with steam Rankine cycles operating at the same high temperature, make this cycle attractive for central receiver solar plants.
- Much less power is required to recompress the CO_2 in the supercritical CO_2 Brayton Cycle compared with using air in typical gas turbines, thereby increasing the overall amount of electricity produced by about 30 per cent.
- This higher efficiency also means that the capital cost is much less because fewer mirrors are required and the receivers and towers are smaller.
- This presentation investigates the structural design of a direct sCO2 solar receiver absorber tube with an operating pressure of 20 MPa, an inlet temperature of 500° C and an outlet temperature of 700° C.
- This however presented design issues that required attention as explained on the following slides:

CSIRO s-CO_2 activities

IN-FIELD PILOT

- Completed fabrication of s-CO_2 test loop and solar receiver, bop rated for up to 720°C and 30MPa output though most receiver testing will be at ≈20MPa.
- System operated at supercritical conditions (on gas heater) for commissioning
- Plumbing allowance made for a future small turbine.

MATERIALS EXPERIMENTS

- High temperature materials “lifing” experiments and creep calculations for s-CO_2 >700°C, >25MPa

SYSTEM & PROCESS MODELLING

- The material, component and system knowledge gained will be used for development of a solar s-CO_2 demonstration project.

30MPa

CSIRO Supercritical Brayton Cycle project

THE UNIVERSITY OF SYDNEY

ARENA

Australian Government

Australian Renewable Energy Agency

Sandia National Laboratories

NREL

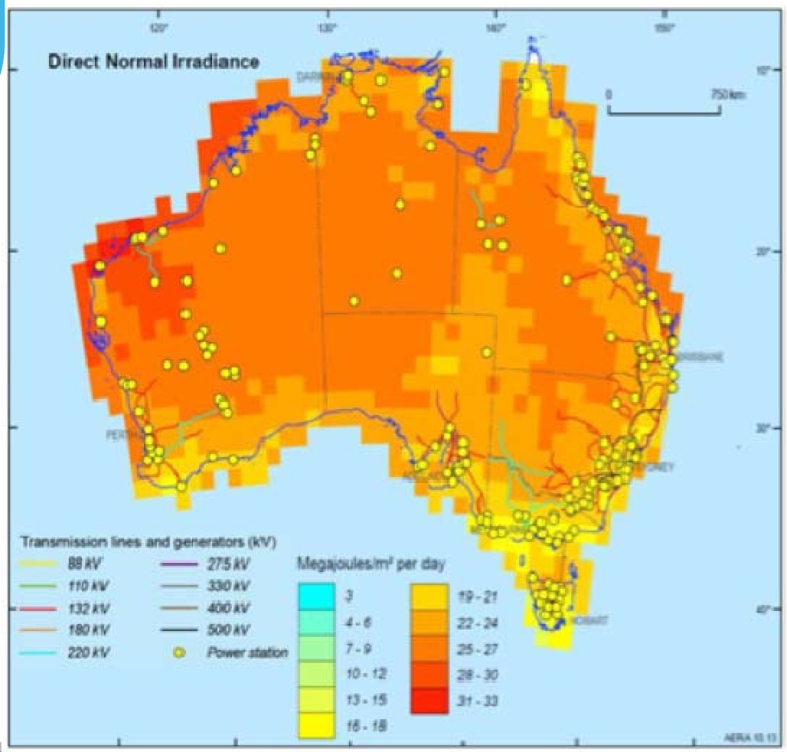
NATIONAL RENEWABLE ENERGY LABORATORY

<u>System Demonstration</u>

- Turbo machinery
- SCO_2 receiver
  - Decoupled with storage
  - Direct illuminated
- Heat Exchange

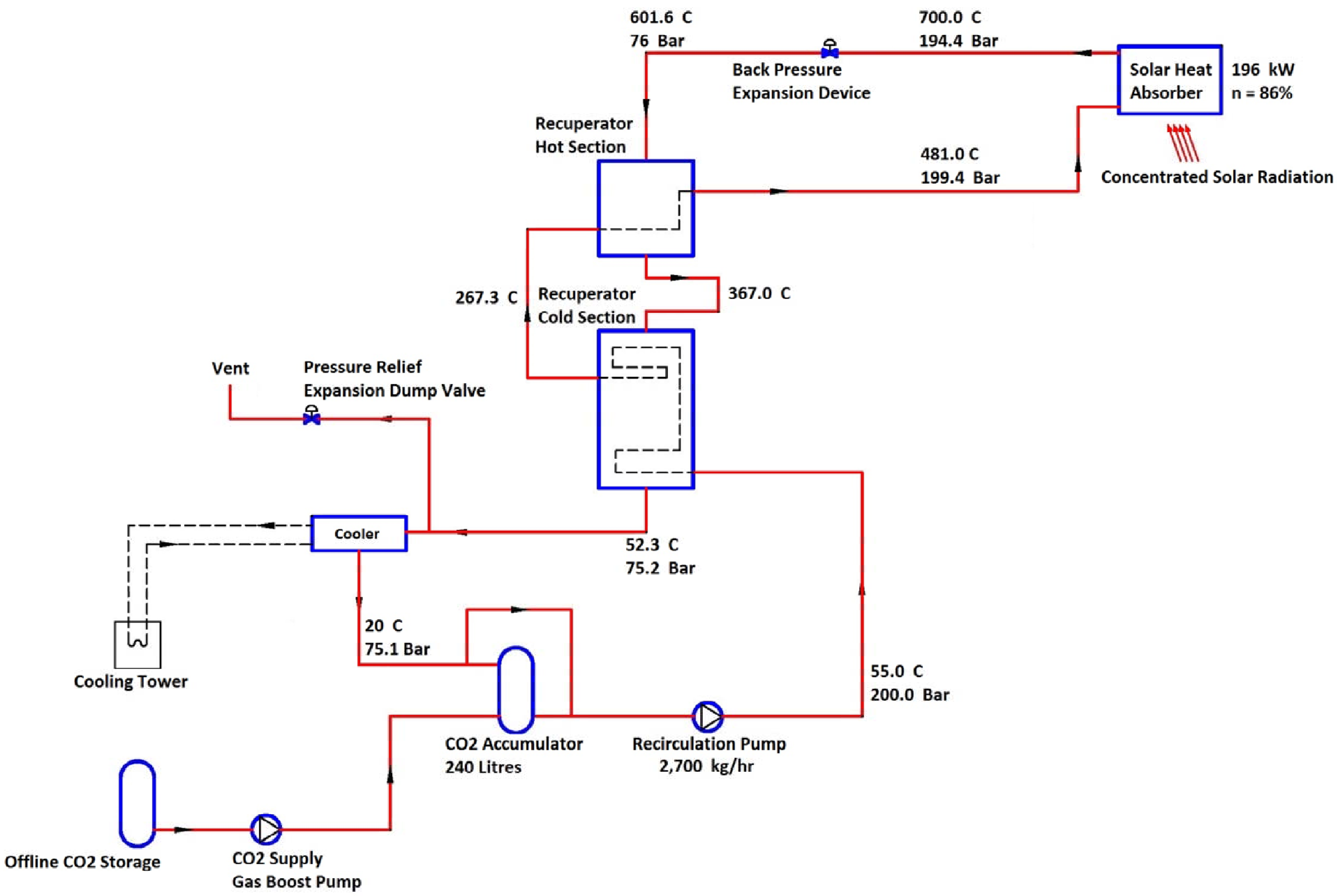
Overall System Model

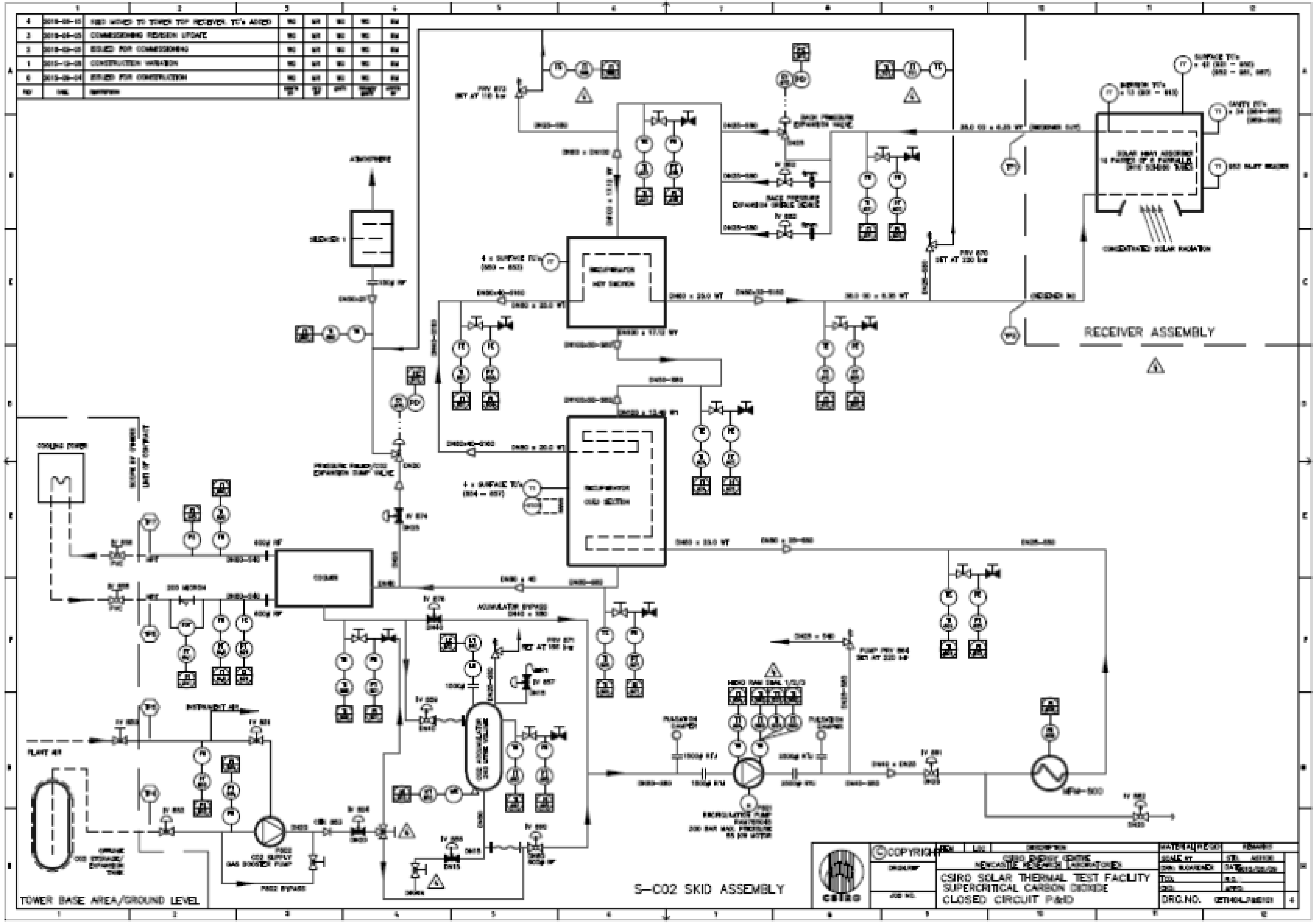
Commercial application and deployment strategy



CSIRO

s-CO_2 solar pilot loop




RECEIVER ASSEMBLY
S-CO2 SKID ASSEMBLY
TOWER BASE AREA/GROUND LEVEL
COOLING TOWER
COOLER
RECUPERATOR HOT SECTION
RECUPERATOR COLD SECTION
ATMOSPHERE
CO2 ACCUMULATOR
PLANT AIR
INSTRUMENT AIR
CONCENTRATED SOLAR RADIATION
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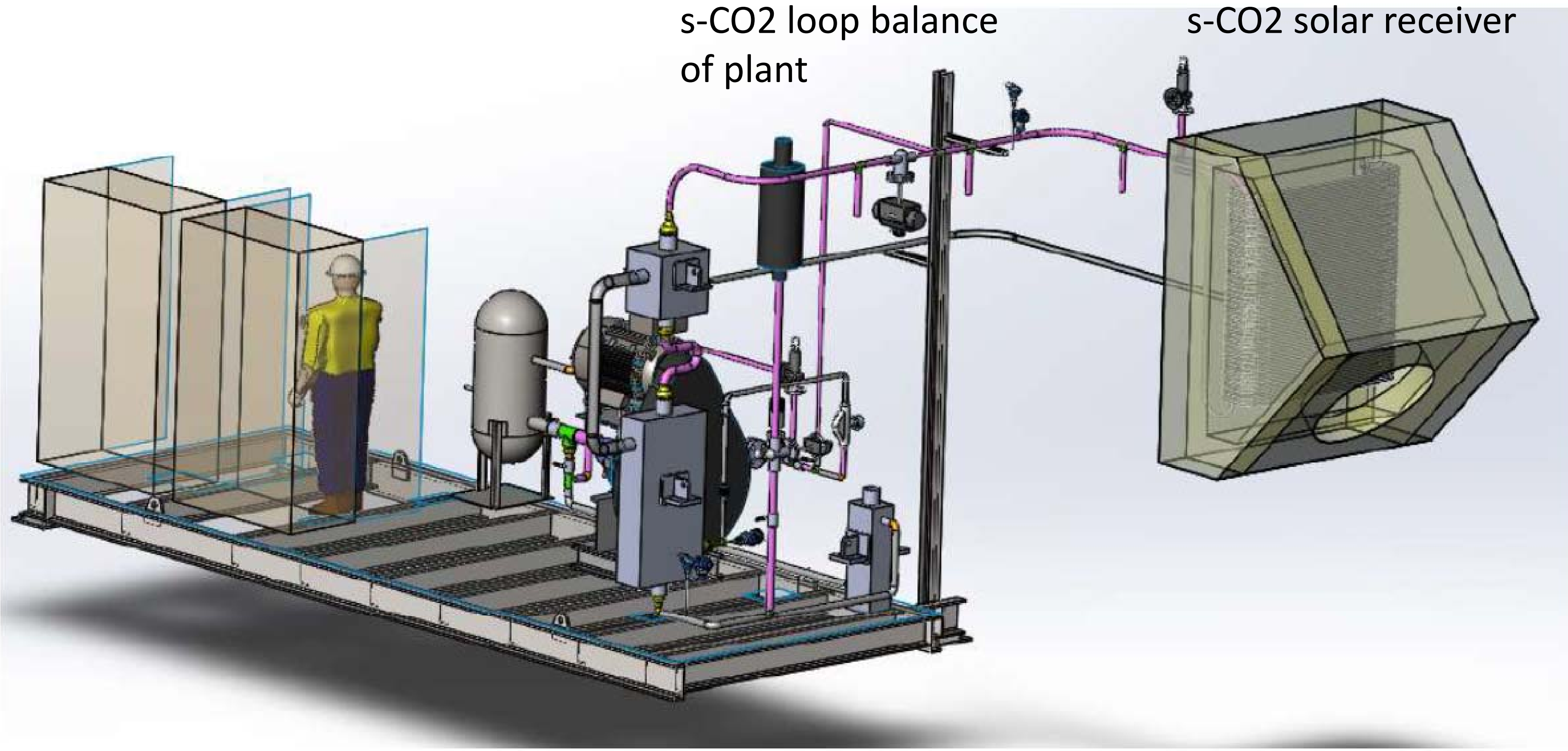
CSIRO SOLAR THERMAL TEST FACILITY
SUPERCRITICAL CARBON DIOXIDE
CLOSED CIRCUIT P&ID
DRG.NO.

Illustrated layout of pilot s-CO_2 test loop and solar receiver as installed on top of solar tower



s-CO_2 Solar thermal Receiver

s-CO_2 solar receiver

SCO_2 System Demonstration

s-CO_2 receiver on sun

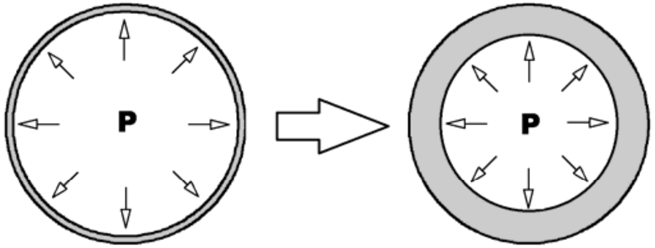
Outline – design of s-CO2 receiver according to thermo-mechanical properties

1. Introduction
2. Specific Design Constraints for an sCO2 Receiver
3. Stress in the Tube Wall
4. Tube Size Options
5. Tube Material Stress Limits
6. Tube Size Compare with Finite Element Analysis
7. Results and Tube Size Selection
8. Final Receiver Design and Construction
9. Summary

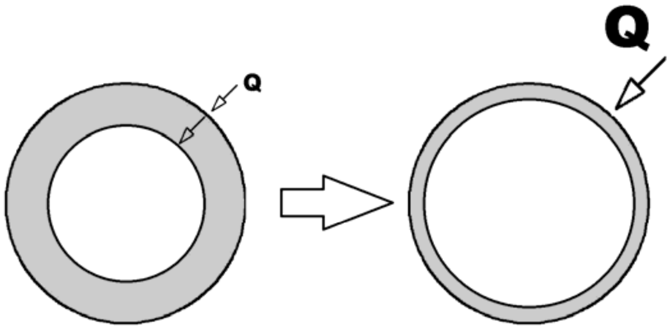
Specific Design Constraints for an sCO2 Receiver

More Specifically:

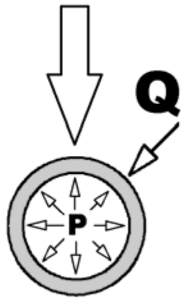
- The high internal pressure drives the absorber tube toward needing a greater wall to diameter ratio, but…



- The need for high heat transfer and reduced thermal stress drives the design toward needing a thin pipe wall.



- They oppose. The contradictory nature of these two drivers results in shrinkage of tube size to both withstand pressure and allow higher heat transfer through the wall whilst minimising wall stress.

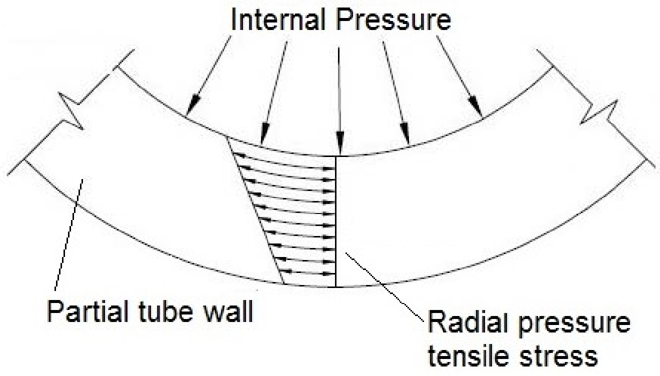


- Smaller tubes means more parallel tubes to keep dP to an acceptable minimum.

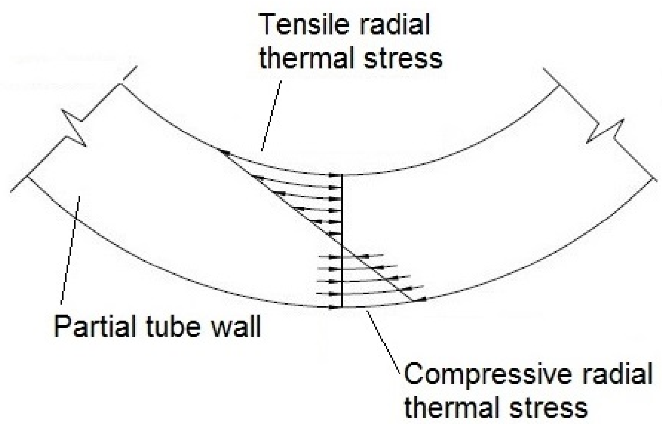
Stress in the Tube Wall

- For thick walled tubes the hoop stress is not uniform but is always tensile for a positive internal stress.
- The tangential stress is the dominant pressure stress. The radial stress equals the applied internal stress and this reduces to zero at the outside wall.
- For thermal gradient stress through the wall the tangential stress is also dominant. The tangential stress between the inside wall and the outside wall oppose each other.
- The outside wall stress goes negative because the outside wall is hotter which results in a higher amount of thermal expansion.
- The inside wall opposes this and the outside wall goes into compression. Conversely the inside wall receives a tensile stress as a result.

Note that this work only considers tangential and radial stresses. The axial stress due delta T around the tube circumference is just as significant but has been ignored in this study as axial stress is dealt with through pipe thermal expansion and flexibility design.



Pressure Hoop Stress



Thermal Gradient Tangential Stress

Tube Size Options

Market survey was done of commercial materials:

- Haynes 230 Nickel alloy
- 253MA Austenitic Stainless Steels
- 316 Stainless Steel

Preliminary calculations on tube sizes greater than 1 inch meant that the thermal gradient stresses were too high due to thick wall. So sizes 1” or less were evaluated.

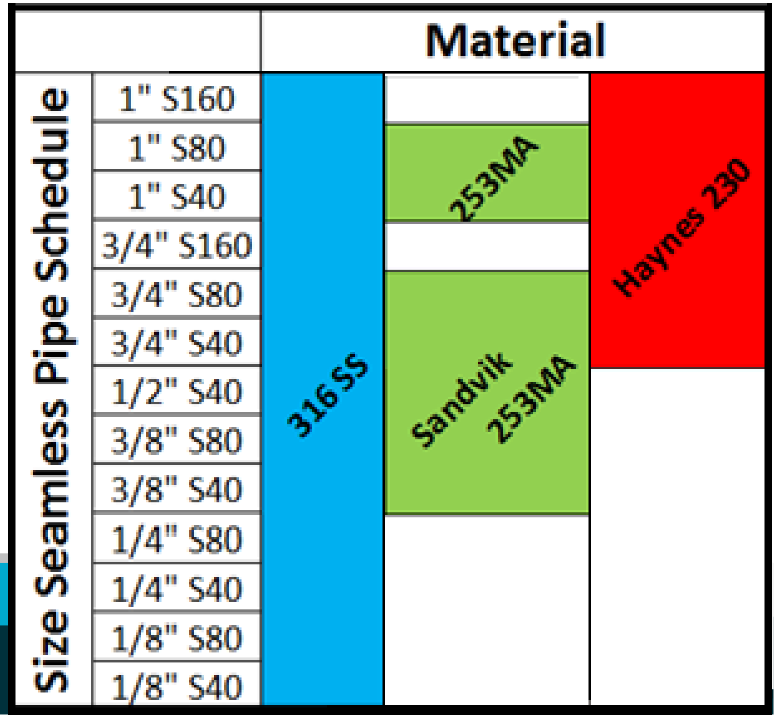
There are also limitations in available sizes for each of these materials.

- Haynes said they do not mill pipe sizes smaller than ¾ inch
- Sandvik said they do not mill 253MA in pipe sizes smaller than 3/8 inch.
- 316 Stainless Steel available in all sizes including ¼ and 1/8 inch. But not as strong.

The small pipe sizes (1/8 or ¼ inch) require multiple parallel flow paths, high dP and complex manufacture

Small tube sizes create difficulty in attaching instrumentation such as thermocouples.

The outcome resulted in 9 size options >>

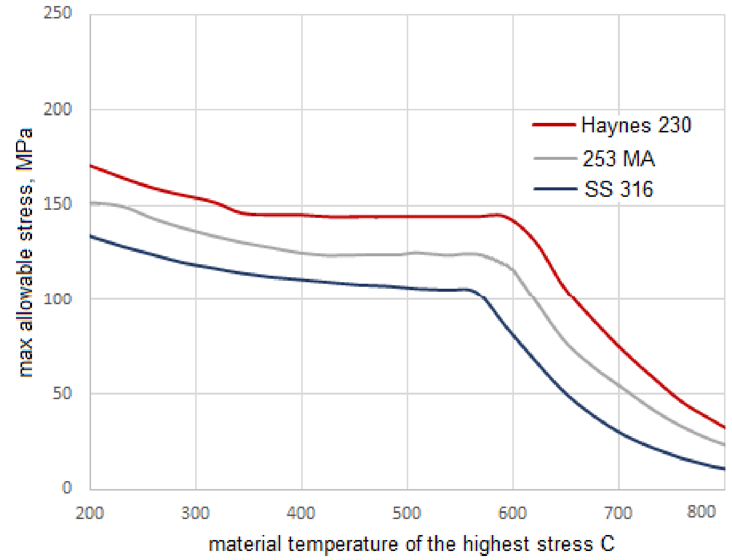


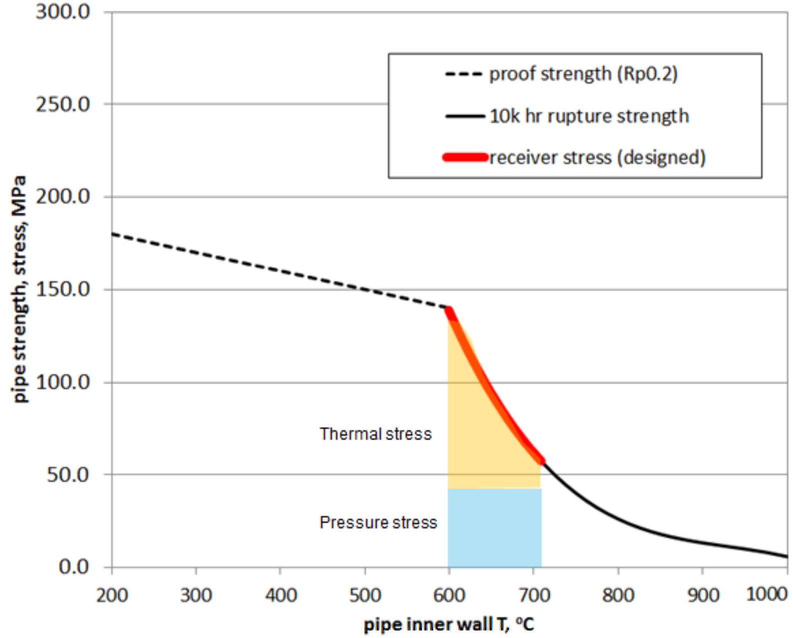
Tube Material Stress Limits

The major design constraint is the allowable stress limit.

The three materials are compared >

For each material, the time dependence stress limit begins at ~600 C.
The sCO2 receiver is operating well into this region and the stress limit is well into the time dependent range.





Tube Sizes Compared with FEA

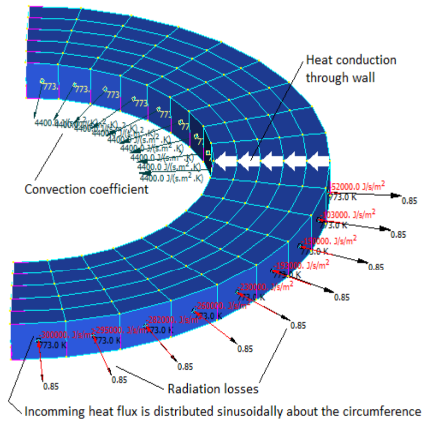
The approach was to compare the 9 sizes together.

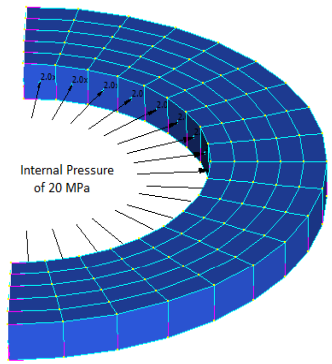
The same model was used for HT analysis as well as mechanical.

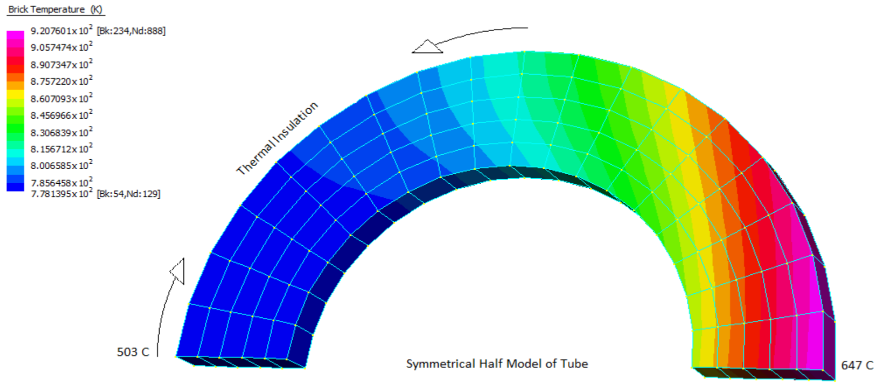
2D flow for heat and stress.
(Note previous comment about axial stress)

Half pipe symmetry adopted.

Input fluid convection coefficient were determined by other methods within CSIRO.



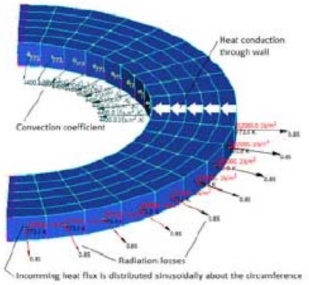


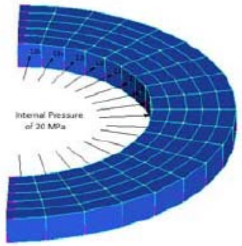


Location	Inlet
Fluid temperature	773 K
Solar Flux	300 kW/sq.m peak front edge 0 kW/sq.m side edge
Convection fluid	4400 W/sq.m K
Receiver cavity Ambient temp	Ave 773 K
Emissivity	0.85

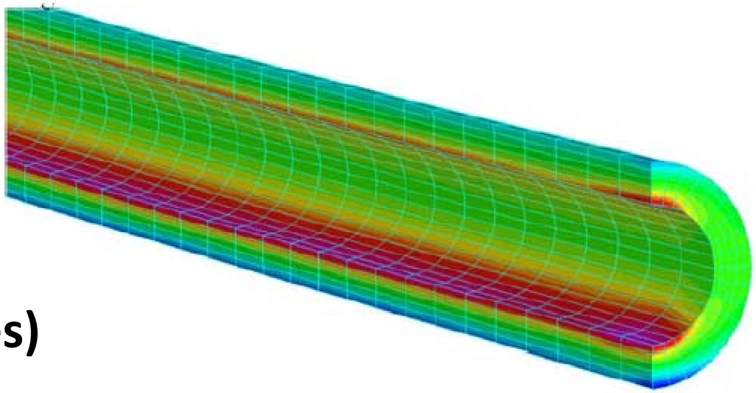
FEA

Model

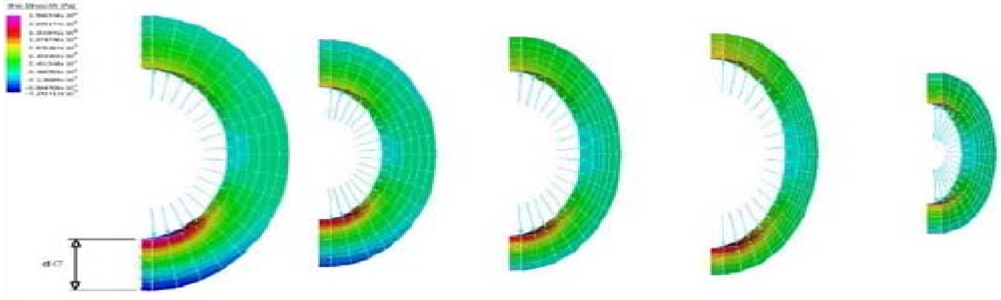




Combined Stress (longitudinal version)



Combined Stress (different pipe sizes)



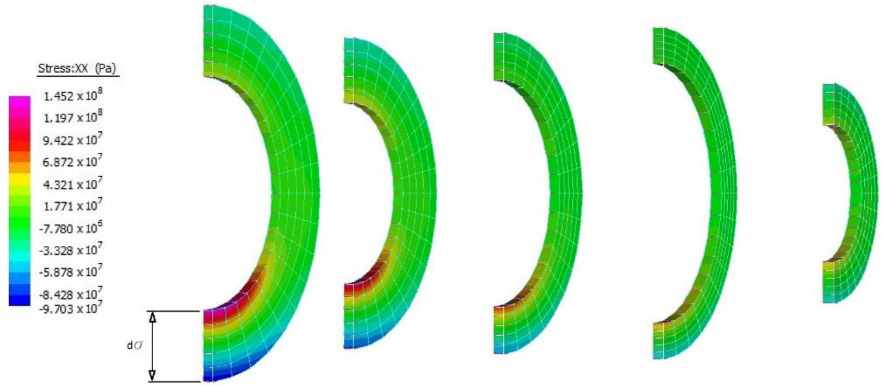
Results and Tube Size Selection

The tangential stress for thermal gradient is highest where the delta T is greatest.

In the XX direction the ID and OD stress is:

ID =   145 MPa

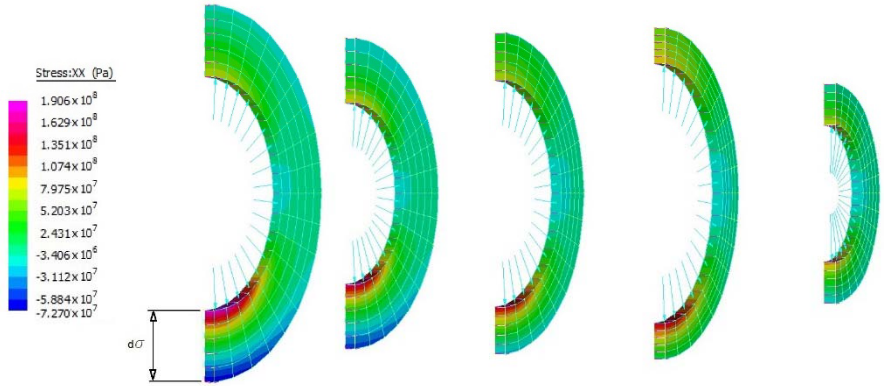
OD = -97 MPa



Hoop stress is:

ID = 45 MPa

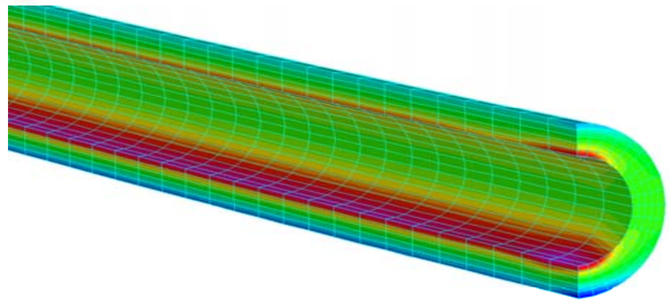
OD = 24 MPa



Combined stress:

ID = 190MPa

OD = -73MPa



Results and Tube Size Selection

FEA Study of Different Pipe Sizes for S-CO2 Receiver Pipes at Location of Highest Radiation of 300 kW/sq.m and lowest 100 kW/sq.m

Option	INLET END						Pipe Wall Temp.			Wall Tangential Stress (MPa)			Design	Stress limit (MPa)	MPa	Suitable up to ~	
	Material	Size	Schd	OD	WT	Location	°C	Ave	dT	Pressure	Thermal	Combined	Temp Range	Stress to rupture 1000 hrs	159	1,000 hrs	10,000 hrs
1	253 MA	3/8"	80	17.1	3.2	Outside	648	616	65	25.1	-38.9	-13.8	650	Stress to rupture 10,000 hrs	96.5	YES	NO
						Inside	583			46.3	56.4	102.7		1% creep at 10,000 hrs	75		
														Stress to rupture in 1000 hrs	295		
														Initial stress to produce 1% creep in 1000 hrs	180		
2	Haynes 230	3/4"	40	26.7	2.87	Outside	637	609	57	63.2	-49.1	14.1	650	Initial stress to produce 1% creep in 10,000 hrs	120	YES	NO
						Inside	580			84.3	60.8	145.1		Haynes ASME Vessel Code	101		
3			80	26.7	3.91	Outside	663	624	79	39.2	-61.9	-22.7	704			NO	NO
						Inside	584			60.3	83.1	143.4		Initial stress to produce 1% creep in 1000 hrs	125		
4			160	26.7	5.56	Outside	706	648	116	20.1	-76.2	-56.1		Initial stress to produce 1% creep in 10,000 hrs	85	NO	NO
						Inside	590			41.2	117.6	158.8		Haynes ASME Vessel Code	69		
5		1"	160	33.4	6.35	Outside	723	657	133	24.3	-96.6	-72.3				NO	NO
						Inside	590			45.4	143.8	189.2					
6	Small Pipe Type 316SS	1/4"	40	13.7	2.24	Outside	623	601	44	32.3	-19.5	12.8	650			YES	YES
						Inside	579			53.6	33.1	86.7					
7			80	13.7	3.02	Outside	643	613	60	17.6	-25.5	-7.9		Stress to rupture in 1000 hrs	159	YES	YES
						Inside	583			38.8	44.6	83.4		Stress for creep rate of 1% in 10,000 hrs	95		
8		1/8"	40	10.3	1.73	Outside	609	592	34	30.8	-8.3	22.5		At 650 C as per AS1228	51	YES	YES
						Inside	575			52.0	22.8	74.8					
9			80	10.3	2.41	Outside	627	603	48	15.3	-13.8	1.5				YES	YES
						Inside	579			36.5	28.6	65.1					

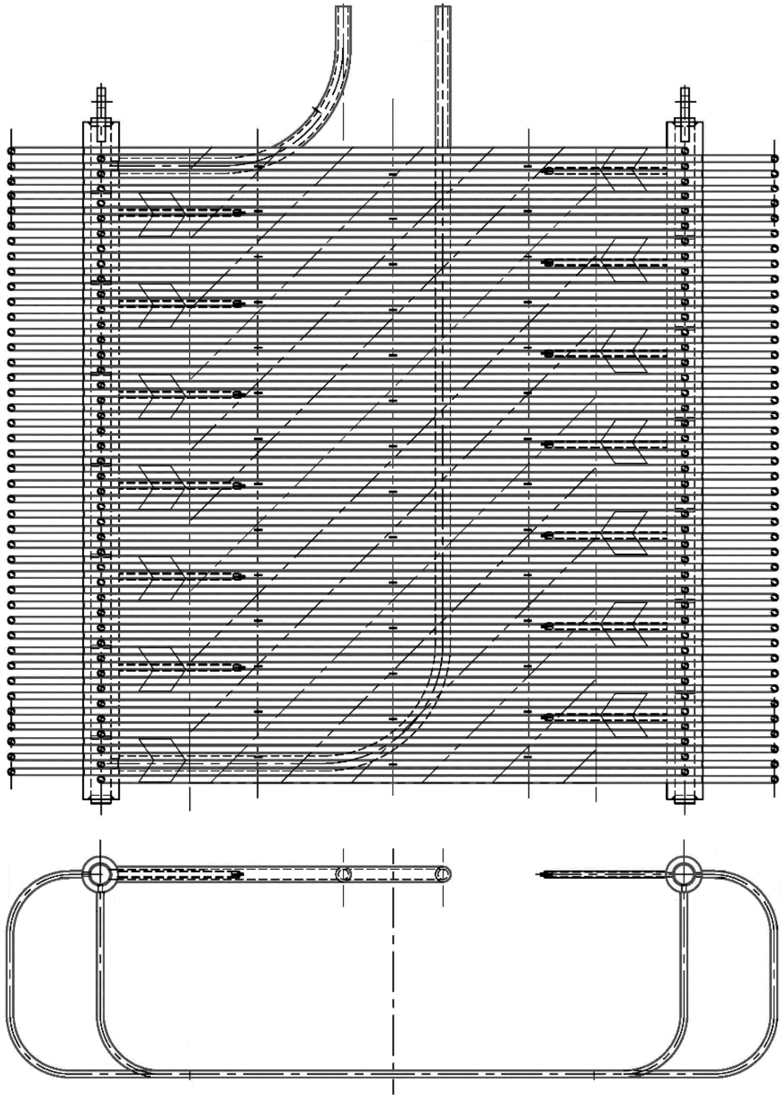
Option	OUTLET END						Pipe Wall Temp.			Wall Tangential Stress (MPa)			Design	Stress limit (MPa)	MPa		
	Material	Size	Schd	OD	WT	Location	°C	Ave	dT	Pressure	Thermal	Combined	Temp	Stress to rupture 1000 hrs	63.4		
1	253 MA	3/8"	80	17.1	3.2	Outside	749	739	21	25.1	-13.0	12.1	750	Stress to rupture 10,000 hrs	35.9	Marginal	NO
						Inside	728			46.3	18.8	65.1		1% creep at 10,000 hrs	34.5		
2	Haynes 230	3/4"	40	26.7	2.87	Outside	746	737	19	63.2	-16.4	46.8	760			YES	NO
						Inside	727			84.3	20.2	104.6		Stress to rupture in 1000 hrs	140		
3			80	26.7	3.91	Outside	754	741	26	39.2	-20.6	18.6		Initial stress to produce 1% creep in 1000 hrs	79	YES	NO
						Inside	728			60.3	27.7	88.0		Initial stress to produce 1% creep in 10,000 hrs	55		
4			160	26.7	5.56	Outside	769	750	39	20.1	-25.4	-5.3		Haynes ASME Vessel Code	48	YES	NO
						Inside	730			41.2	39.2	80.4					
5		1"	160	33.4	6.35	Outside	774	752	44	24.3	-32.2	-7.9				YES	NO
						Inside	730			45.4	47.9	93.3					
6		1/4"	40	13.7	2.24	Outside	741	734	15	32.3	-6.5	25.8				YES	NO
						Inside	726			53.6	11.0	64.6					
			80	13.7	3.02	Outside	748			17.6	-8.5	9.1		Stress to rupture in 1000 hrs	71		

Conclusion – Tube Size Selected

- Selected pipe size of 3/8” schedule 80 in 253MA was chosen.
- Pipe wall stress still high enough to limit the life of the solar receiver in the order of 1,000 hours to rupture due to high temperature material creep.
- This outcome is suitable for short lived experimental work but not suitable for commercial projects.
- A commercial solar receiver with s-CO2 htf would require very high strength and creep resistant materials, or a to allow simple “swap-out”, or alternative receiver designs and construction techniques.

Option	Material	Size	Schd	Ave. Stress	Placing
1	253 MA	3/8"	80	55.3	3
2	Haynes 230	3/4"	40	103.5	9
3			80	75.8	8
4			160	59.3	4
5		1"	160	67.5	7
6	Small Pipe Type 316SS	1/4"	40	63.3	6
7			80	46.1	2
8		1/8"	40	61.6	5
9			80	41.1	1

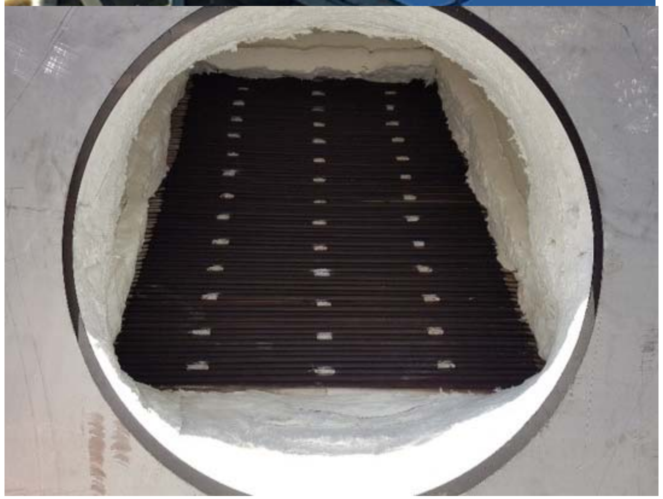
Final Receiver Design and Construction



250 kWth supercritical CO2 receiver final design

- 6 parallel horizontal flow paths as a result of the 3/8” schedule 80 pipe size.
- 84 identical high temperature absorber tubes (6 x 14).
- Absorber tube total length 1-m x 14 passes (fired tube length).
- 13 turnaround chambers and two end headers formed as a continuous manifold on each side. Allows for mixing and temperature averaging.
- 13 immersion thermocouples at each turnaround, or each 1-m intervals to determine the working fluid temperature.
- 42 front (solar side) surface wall thermocouples.
- On megawatt scale power plants this design is scalable on a modular panel basis.

Final Receiver Design and Construction



The sCO2 receiver is now mounted to the top of the 30m tower in CSIRO solar field 2.

In summary

In all cases the calculated combined stresses exceed the published code compliant time-independent stress limits.

The calculated stress was therefore compared to the time-dependent stress limit of either (a) stress to rupture in 1,000 hours, or (b) stress to produce 1% creep in 10,000 hours, as these two stress limits provided a common basis for comparing the three materials.

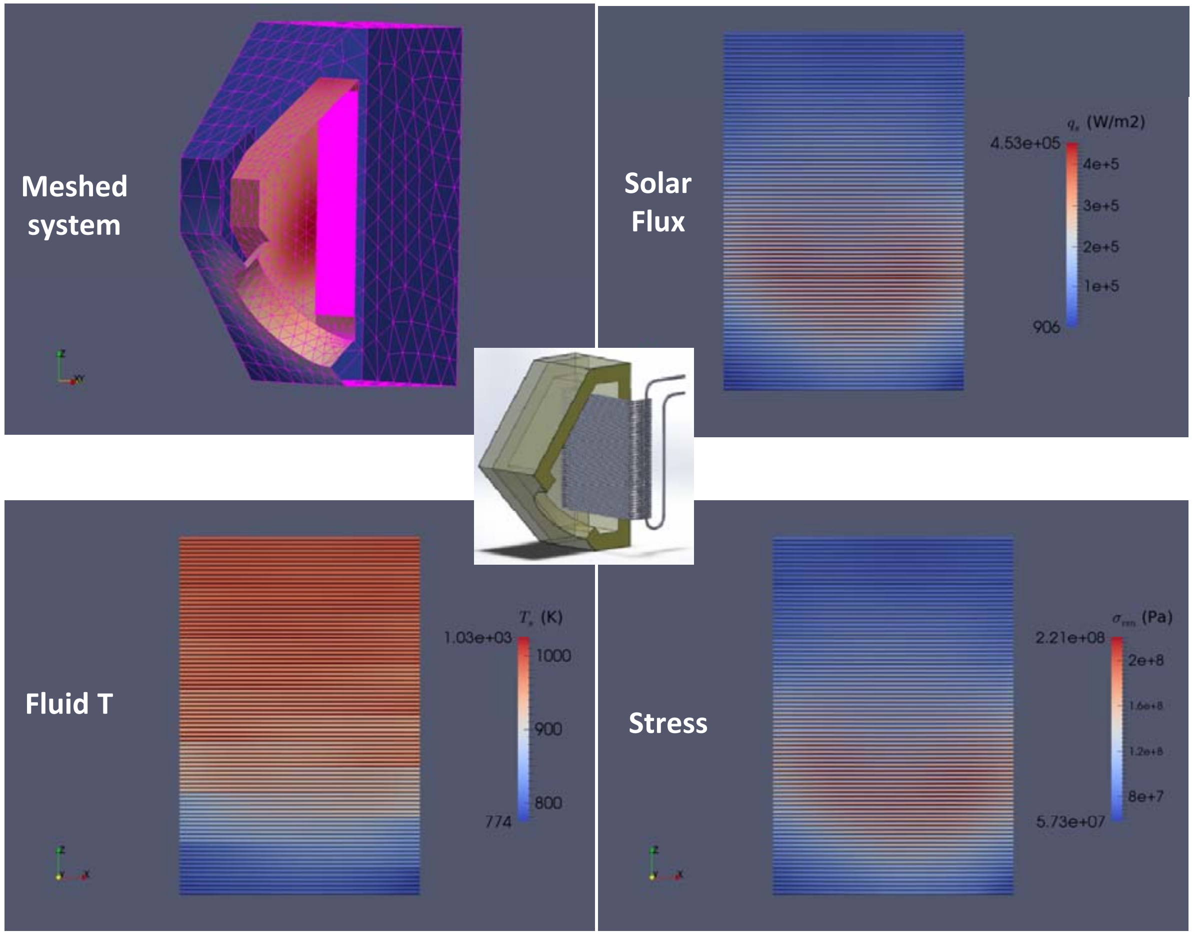
Stress limit data for 100,000 hours are available for 253MA and 316SS but not available for Haynes230.

Although Haynes230 is generally 1.8 times stronger than 253MA, both materials compared equally in terms of the ratio of stress to their respective stress limit. They were comparable in their expected life limit. Had Haynes 230 being available in 3/8" size the choice would be Haynes 230. The obvious choice was 253MA due to cost and availability for generally the same life expectancy.

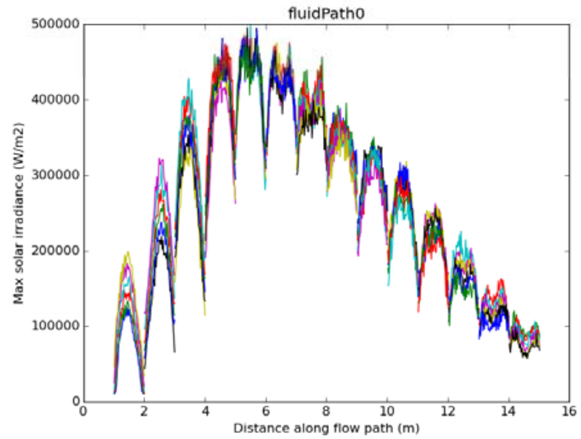
Where to from here?

- Asks Haynes nicely if they would mill a small pipe size in 230 Alloy?
  Custom pipe! Higher Cost!
- Investigate a concept design for a second generation sCO2 receiver using
  ¼" or 1/8" pipe sizes.
- Move away from tubular type receivers and develop alternative types of receiver construction; different material in different zones.

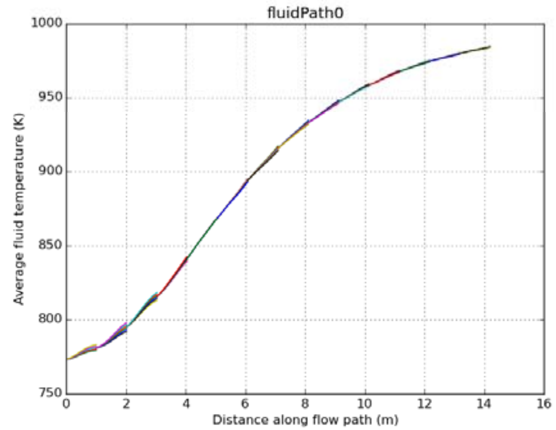
Design flux for 250 kW_t S-CO_2 Receiver

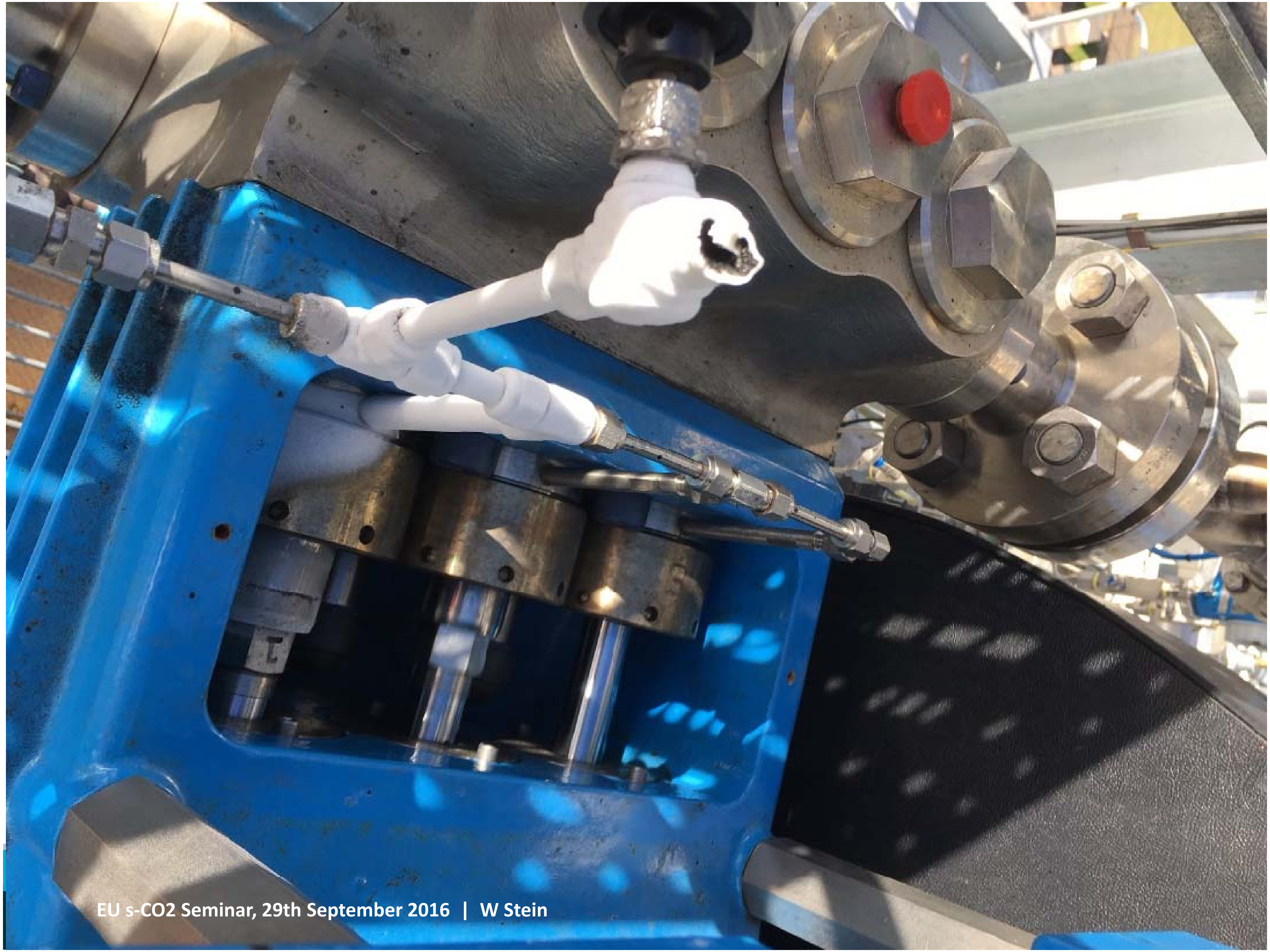


Solar flux of 6 parallel pipes along flow path



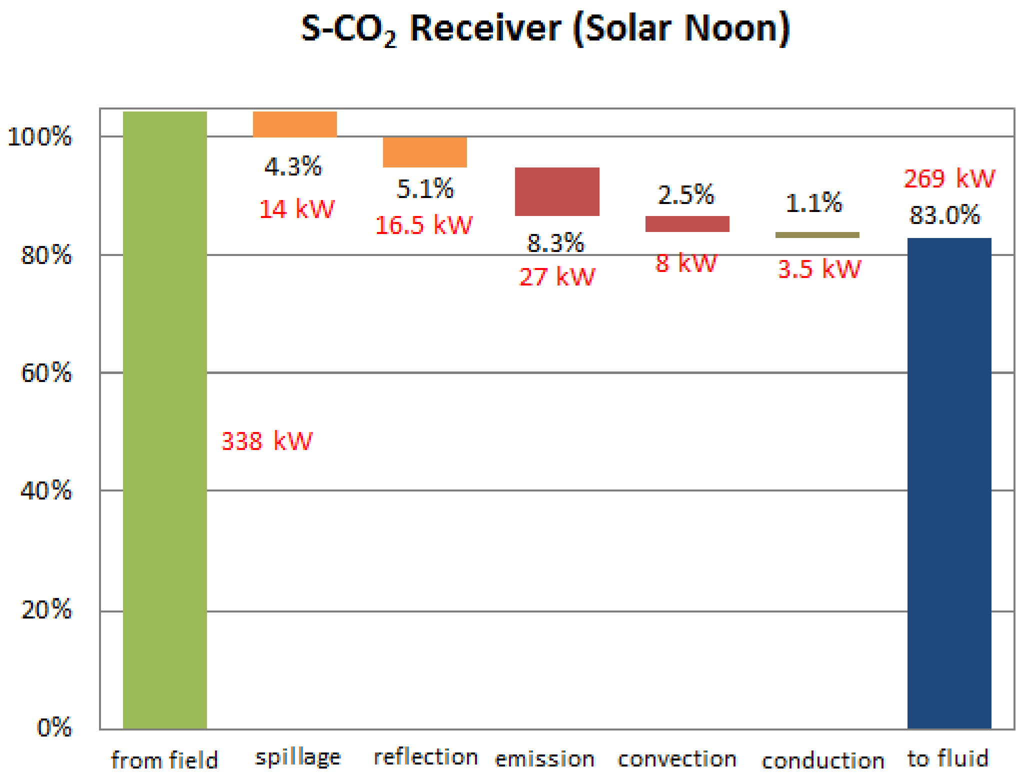
Temperature 6 parallel pipes along flow path





Plunger pump seals/ packing

Receiver Performance at solar noon in March 1st, 2016



In the reflection energy loss, more than 5kW is from unnecessary side walls.
Emission heat loss also includes the energy from unnecessary side walls.
Side walls are not likely to be in the real receiver. (or its view factor to aperture will be close to zero)

Next steps

- Fully commission at steady state conditions
- Gain experience under transient conditions

- Integration of high temperature thermal storage
- Source expansion device to demonstrate complete loop and install

- Validation of models using test data
- Continued analysis of material chemical/ metallurgical performance/ life at varied conditions

- Parallel paths for alternative heat transfer fluids

Thank you

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