Australian Government

ansto Australian Nuclear Science & Technology Organisation

OPAL : Cold Neutron Source Commissioning, Operation and Heat Load

Outline

1. The OPAL Reactor and its Utilisation
2. CNS Systems.
3. Installation and Commissioning 2005-07.
4. Operational Issues.
5. Heat Load Measurement.

OPAL Reactor

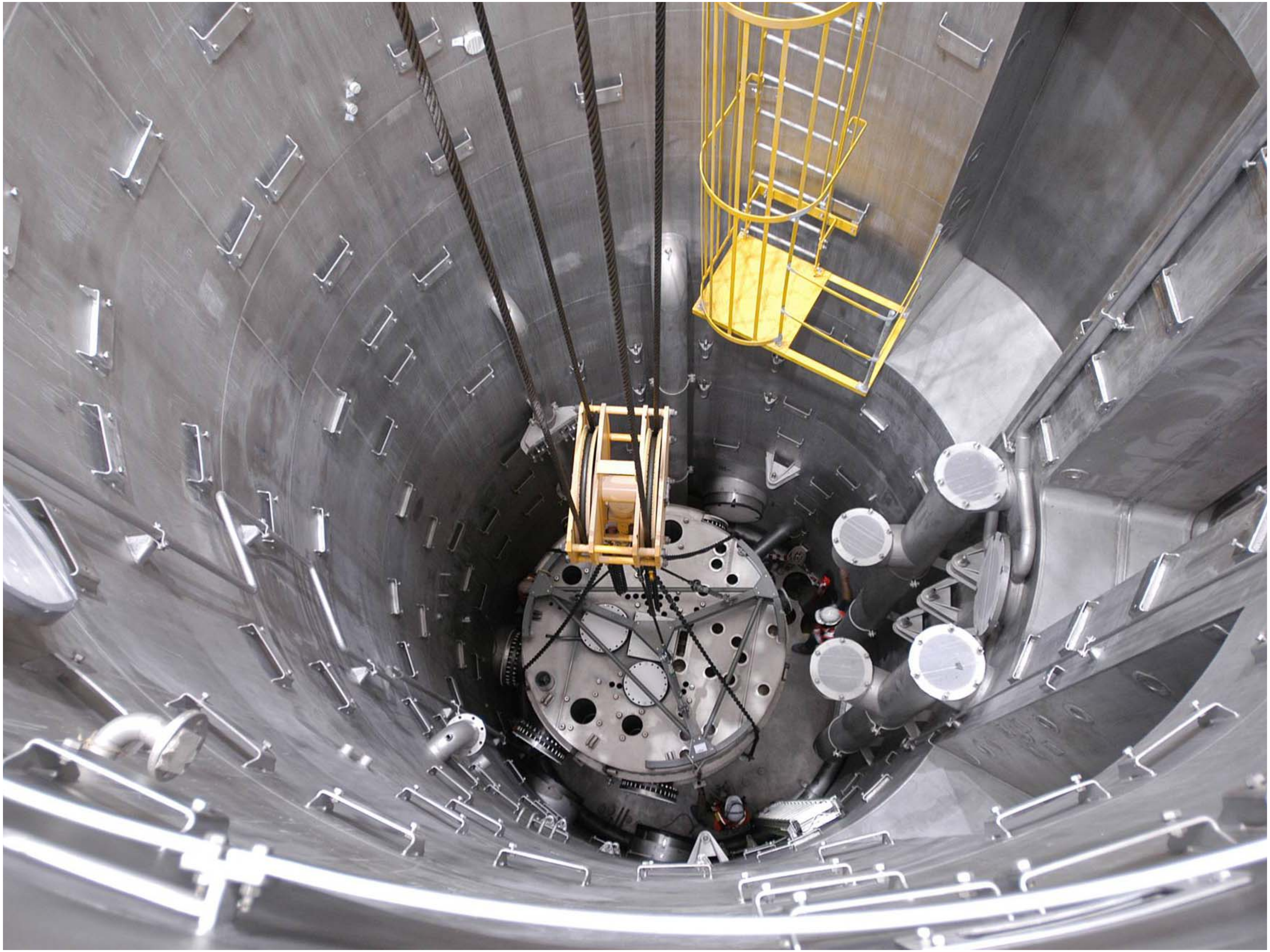
- 20 MW thermal open pool reactor
- Light water cooled and moderated
- Plate type compact LEU fuel
- Heavy water reflected

- Utilisation:
  - Radiopharmaceutical production
  - Beam research
  - Silicon doping

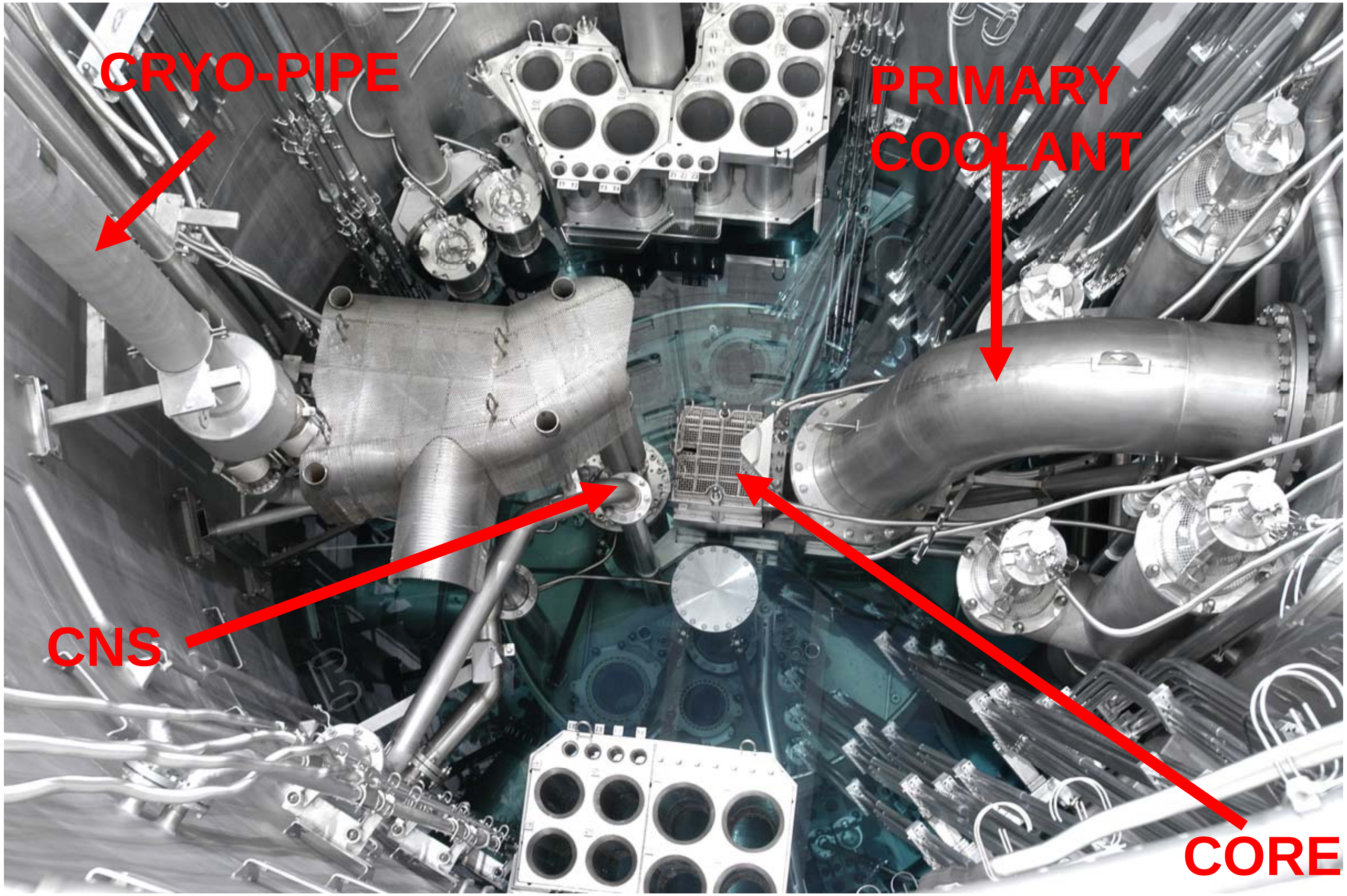

THE
WIRREL
ATCO
ATCO


WHEELERS CRANES
JON MONOCRANE


7 10 2003

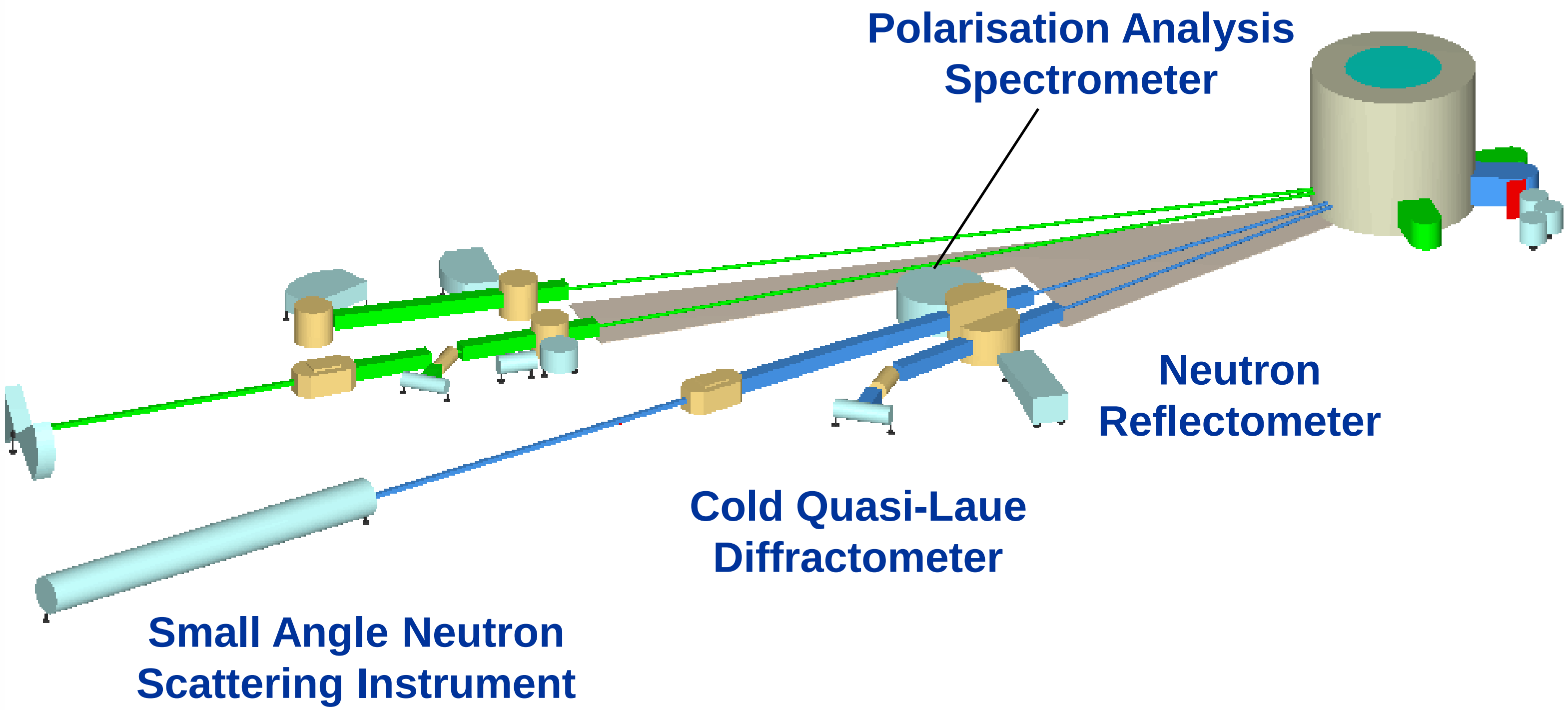


OPAL Reactor



Reactor pool during initial water fill

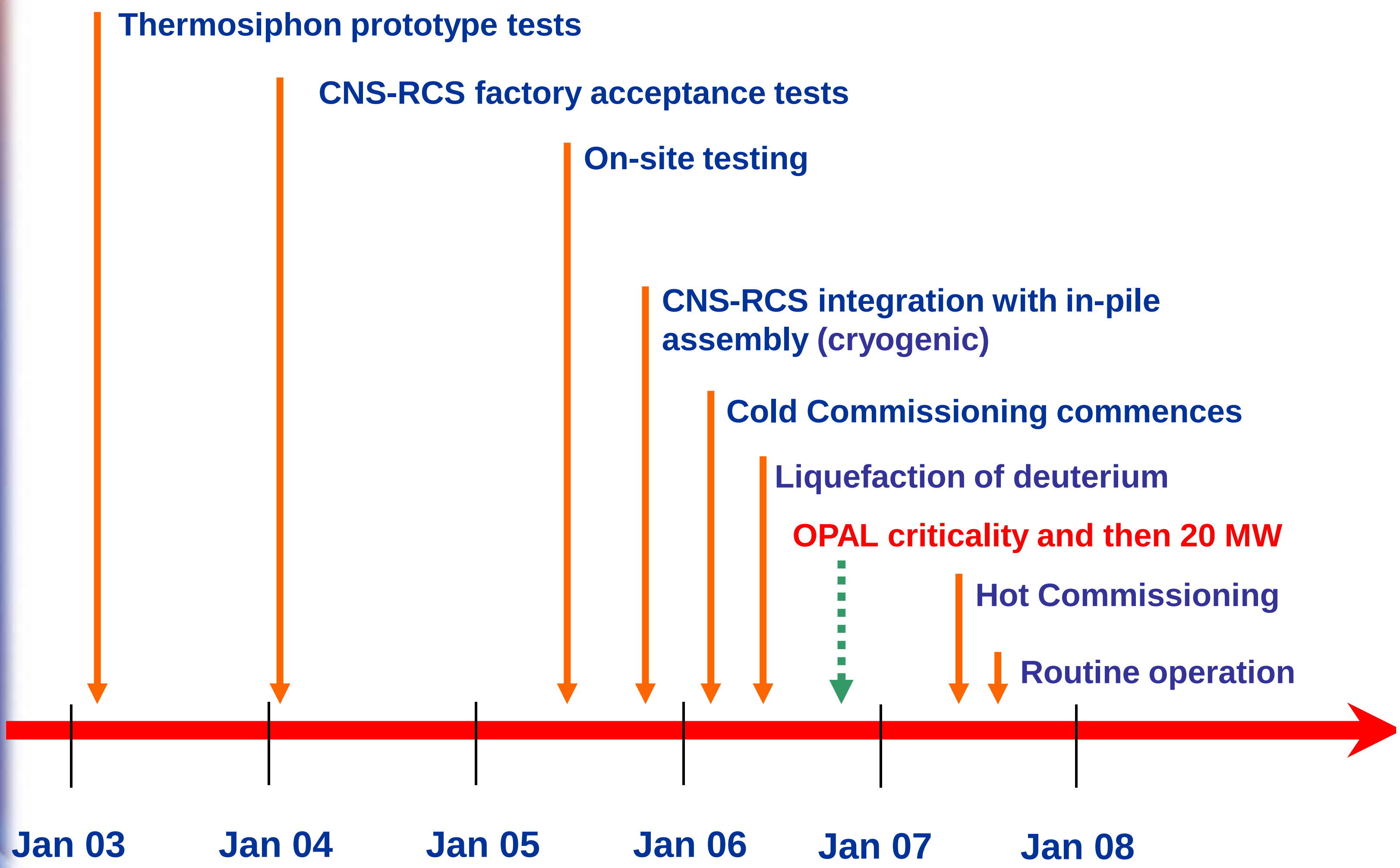
Cold Beams Facilities



Cold neutron flux of 2.5*E10 n/cm2/s at the reactor face (energy spectrum peak at 2.4meV).

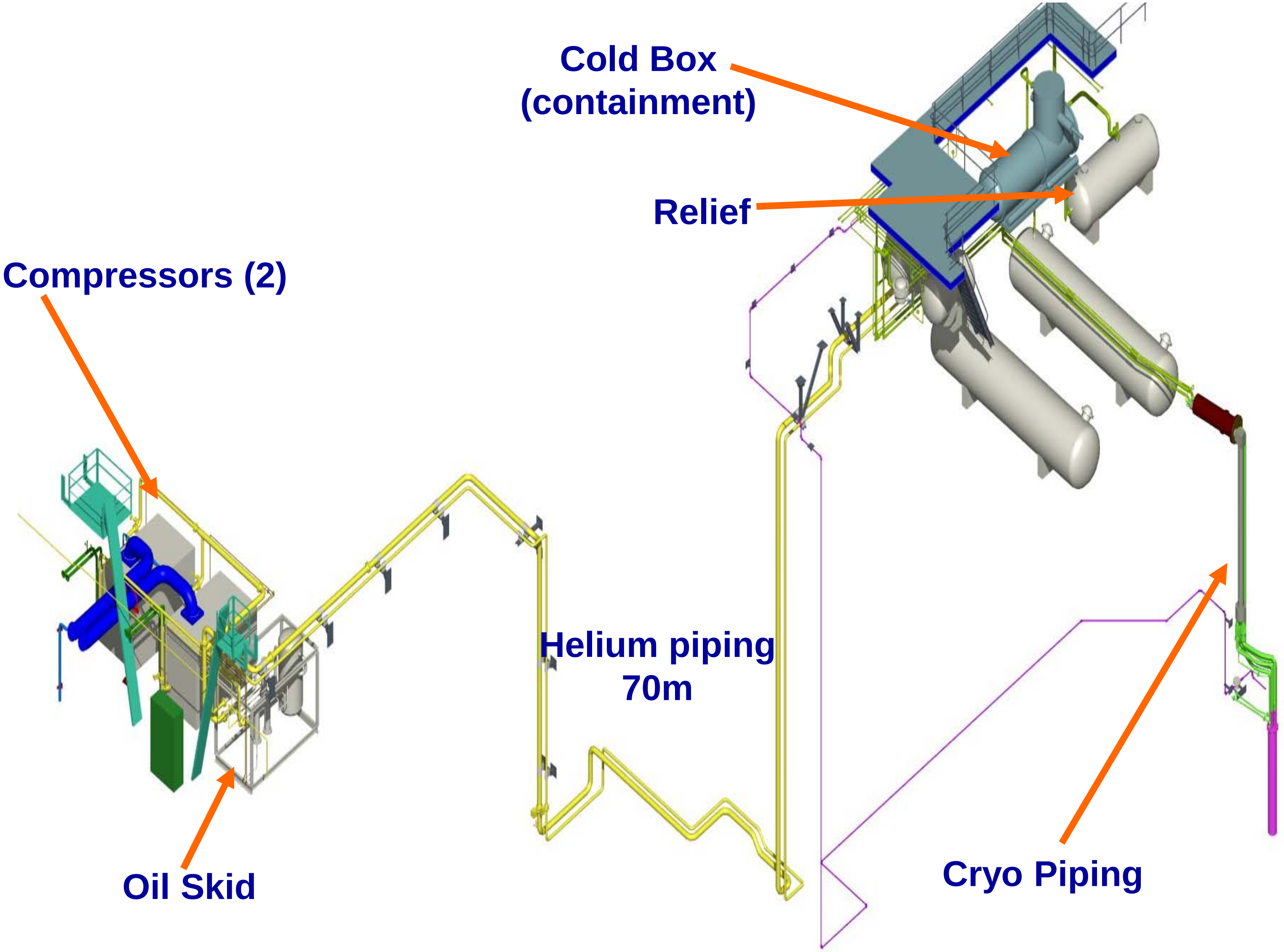
CNS Development Schedule

2001 – Project Initiation / Design



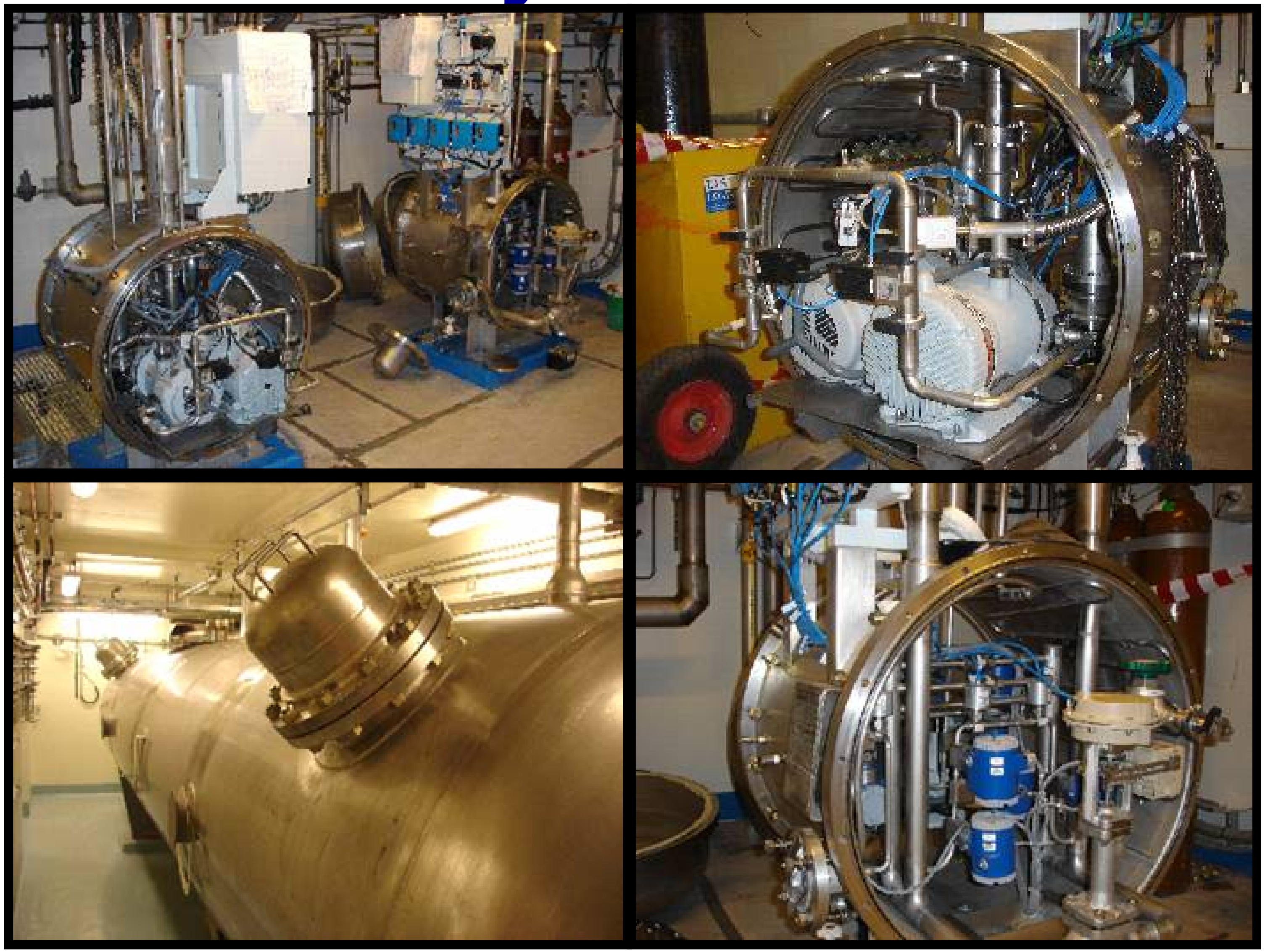
Contractors

Cryo Refrigeration System



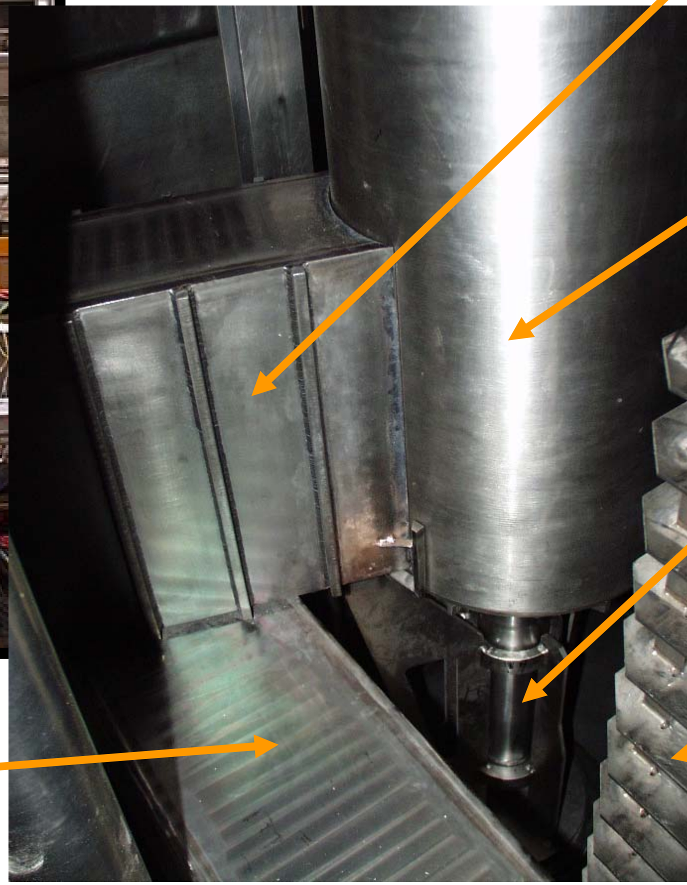
Cryo Refrigeration System

Vacuum & Moderator Systems



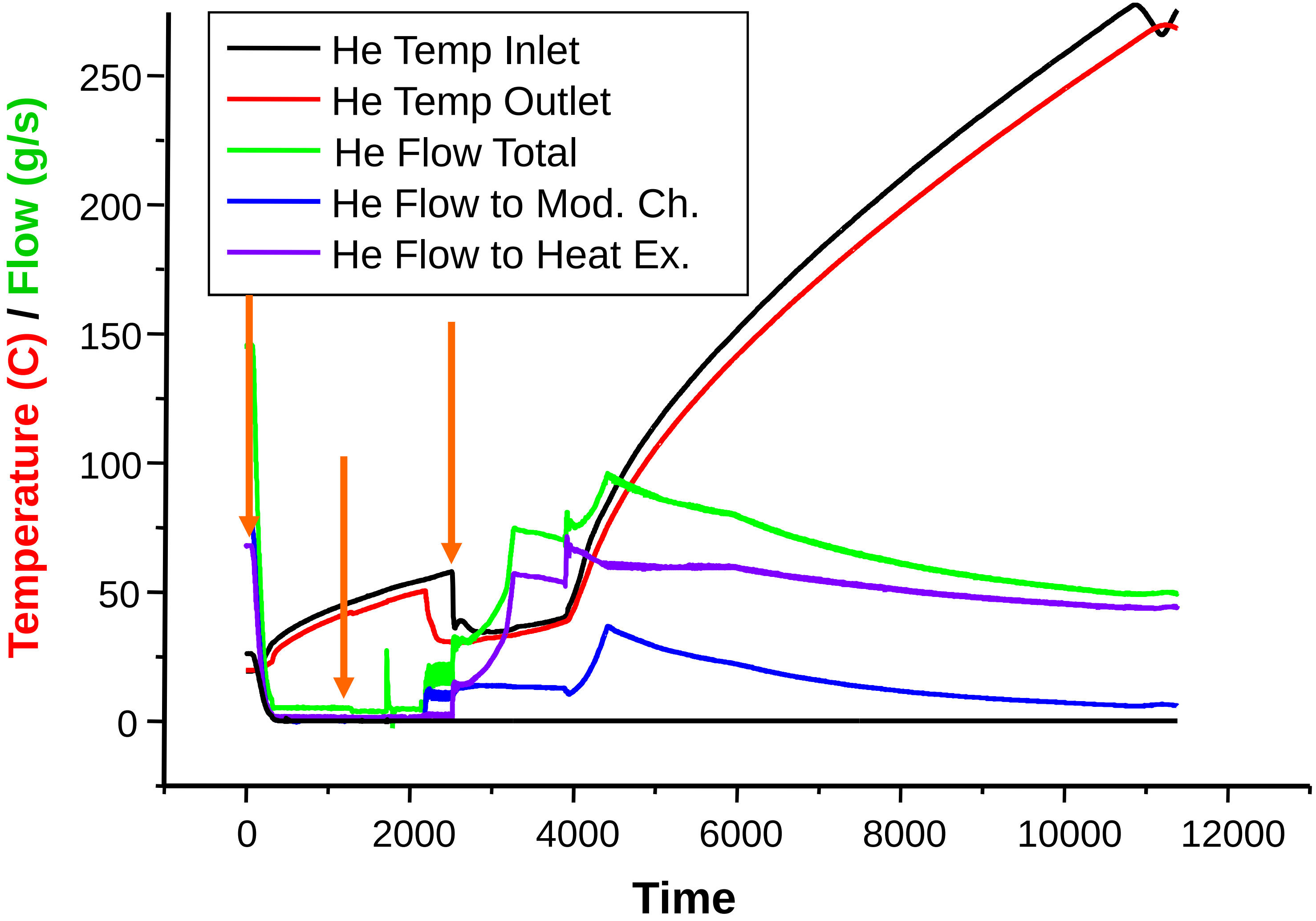
CNS In-pile


DANGER


CNS Beam tube
Vacuum containment
Alignment pin
Core
HNS Beam tube

Reactor Recovery

Forced Evaporation – a transition from NO (cryogenic) mode to SO (warm) mode following system trip



Turbine Failure

- Turbine failure during transition from cryogenic conditions.
- Inferred cause - air contamination in He.
- Air ingress traced to D2 instrumentation.
- Instrumentation modified.

Turbine Failure Investigation

- 2 further failures at bearings ('06)
- Oil separation efficiency improved
- REGEN not performed in July '07 due to other engineering tests.
- Routine sampling discovered in 500 ppm of N2.
- Such N2 identification not typically possible (continuous cold operation).

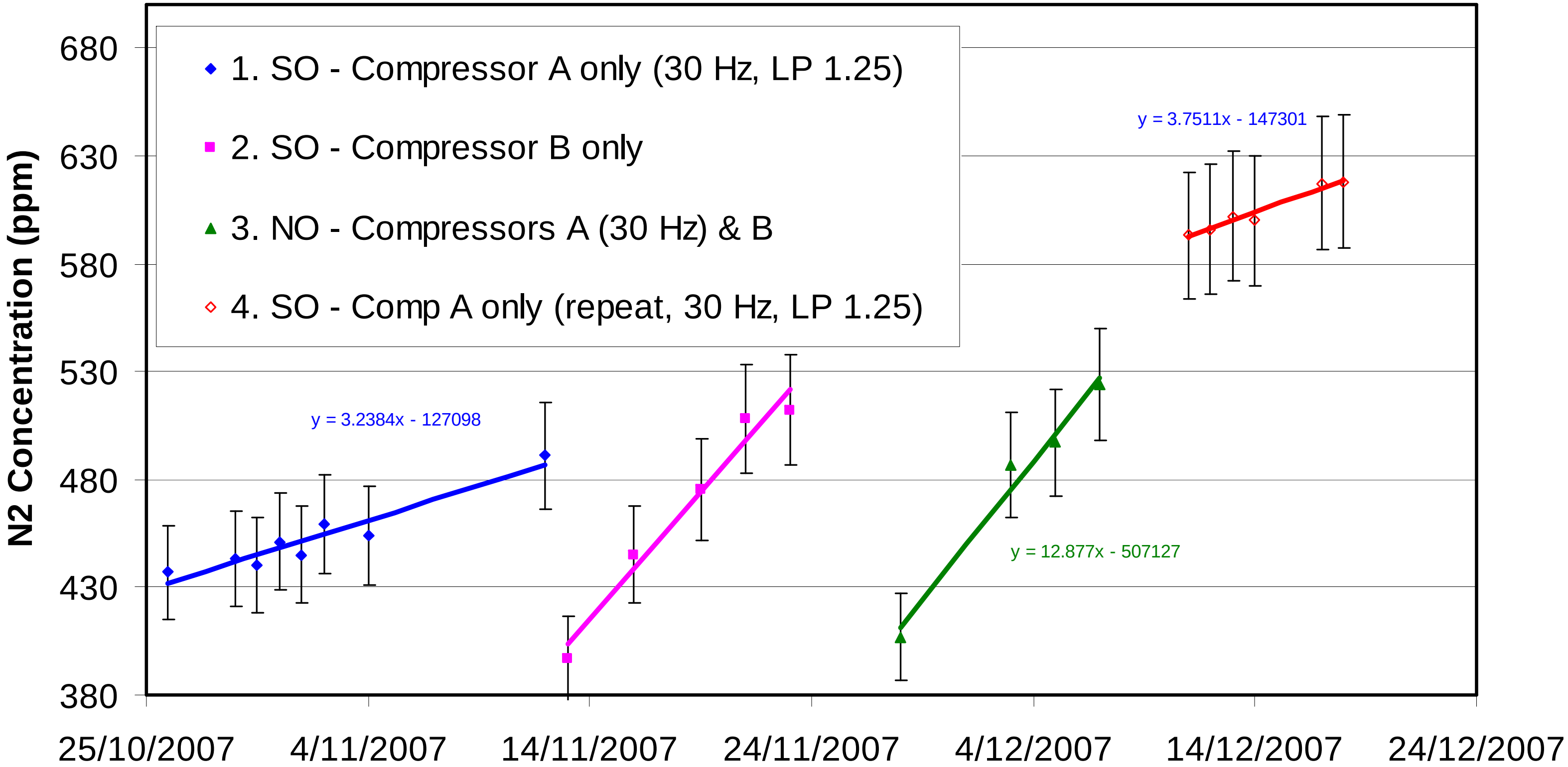
What we knew

- Plant entirely pressurised
- Some leaks (outgoing) have been found ~ 150 L/day
- Helium dew point on the high side
- N2 contamination not high enough to cause turbine failure(?)

Investigation

- Air in-leak verified to be CONTINUOUS
- Air in-leak rate measured at ~ max. 0.5 L/day under different operating conditions, e.g. flow rates, compressor status, pressure setpoints…
- Oxygen/nitrogen ratio variable (analytical error).
- Large in-leaks previously responsible for turbine damage masked the current problem

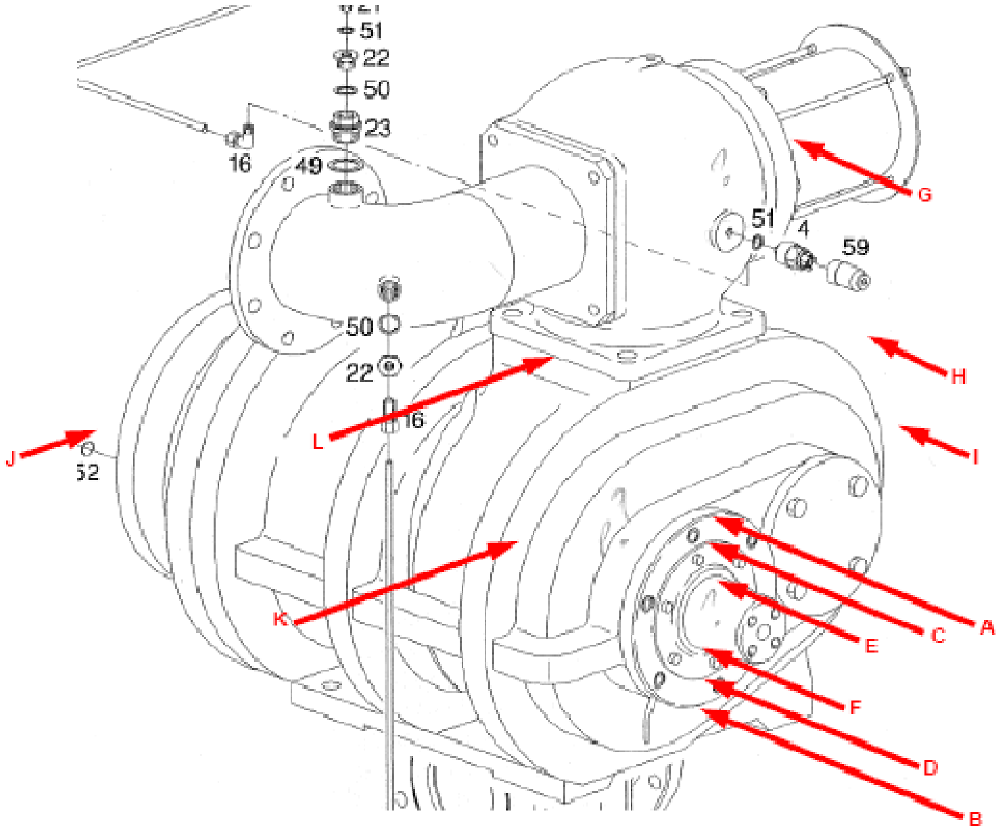
Turbine Failure Investigation



Turbine Failure Investigation

CNS-RCS Operating Mode	In-Leakage (ppm /day)
Comp A, 30 Hz	3.5
Comp A, 30 Hz, 1.5 bar	5.6
Comp A, 50 Hz	8.3
Comp B, 50 Hz	12
Comp B, 50 Hz, 1.4 bar	12
NO mode	13
Comp A, with CO_2 injection into shaft seal, ~ 10 ml/min	No change
Comp A, with He injection into shaft seal, ~ 10 ml/min	No change
Comp A, with He injection into shaft seal, ~ 100 ml/min	No change (TBC)

Turbine Failure Investigation

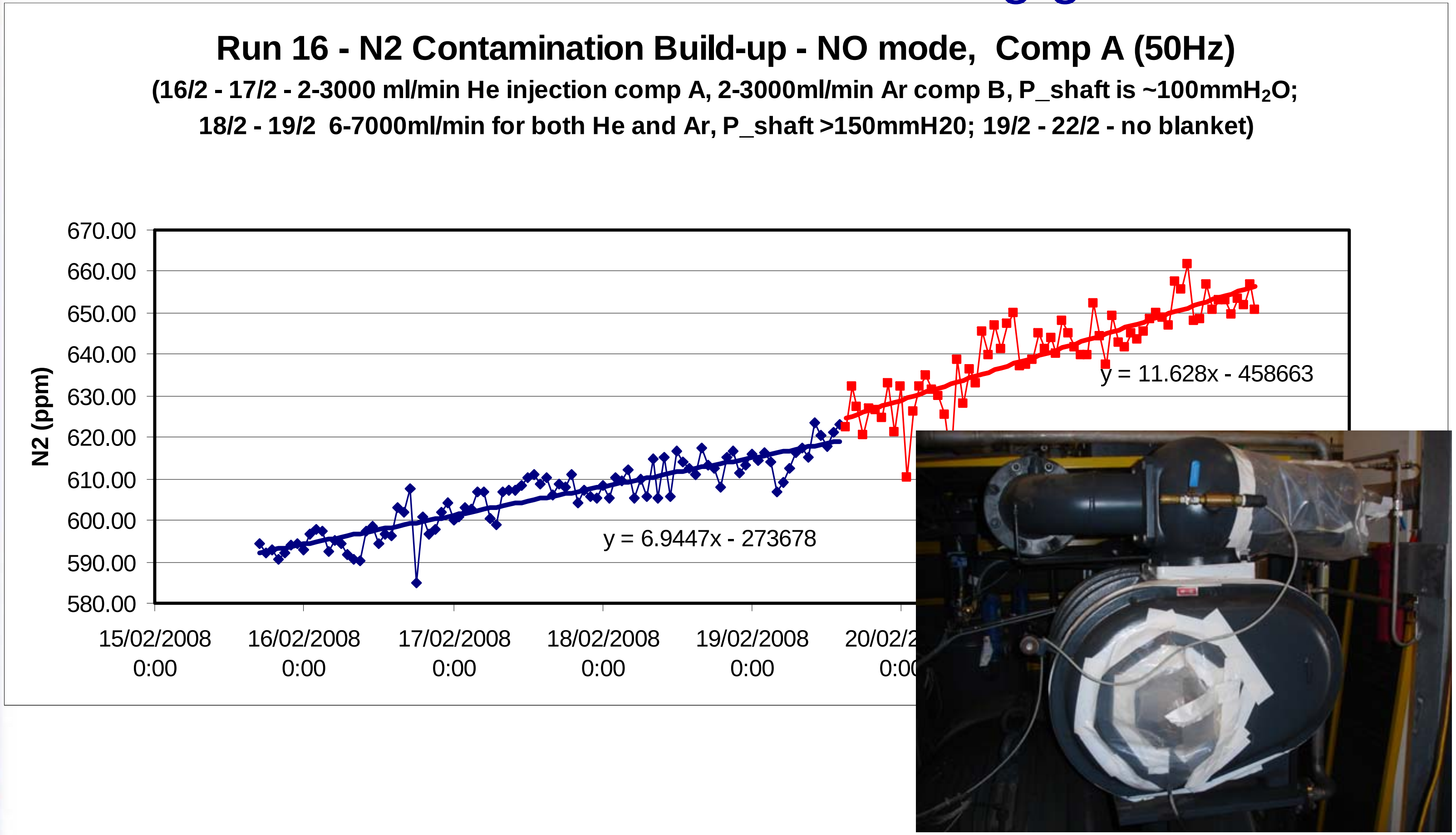


Background: $1*10^{-8}$ mbar.l.s

Position	Description	Leak Rate (mbar.l.s)
A, B, C, D	Seal Rings (general area, bagged)	$8*10^{-3}$
E, F	Shaft (general area, bagged)	$6*10^{-3}$
G	Inlet Valve (general area, bagged)	$1.4*10^{-4}$
H	Helium Outlet Flange	$1*10^{-8}$
I	Oil Inlet Flange	$1*10^{-8}$
J	HP Flange	$2*10^{-7}$
C	Seal Ring, inner (upper section)	$1*10^{-3}$, $5.5*10^{-5}$
A	Seal Ring, outer (upper section)	$3*10^{-5}$
D	Seal Ring, inner (lower section)	$1*10^{-5}$
B	Seal Ring, outer (lower section)	$1*10^{-8}$
K	Compressor Head Flange	$2*10^{-7}$
L	Inlet Valve Flange	$3*10^{-7}$

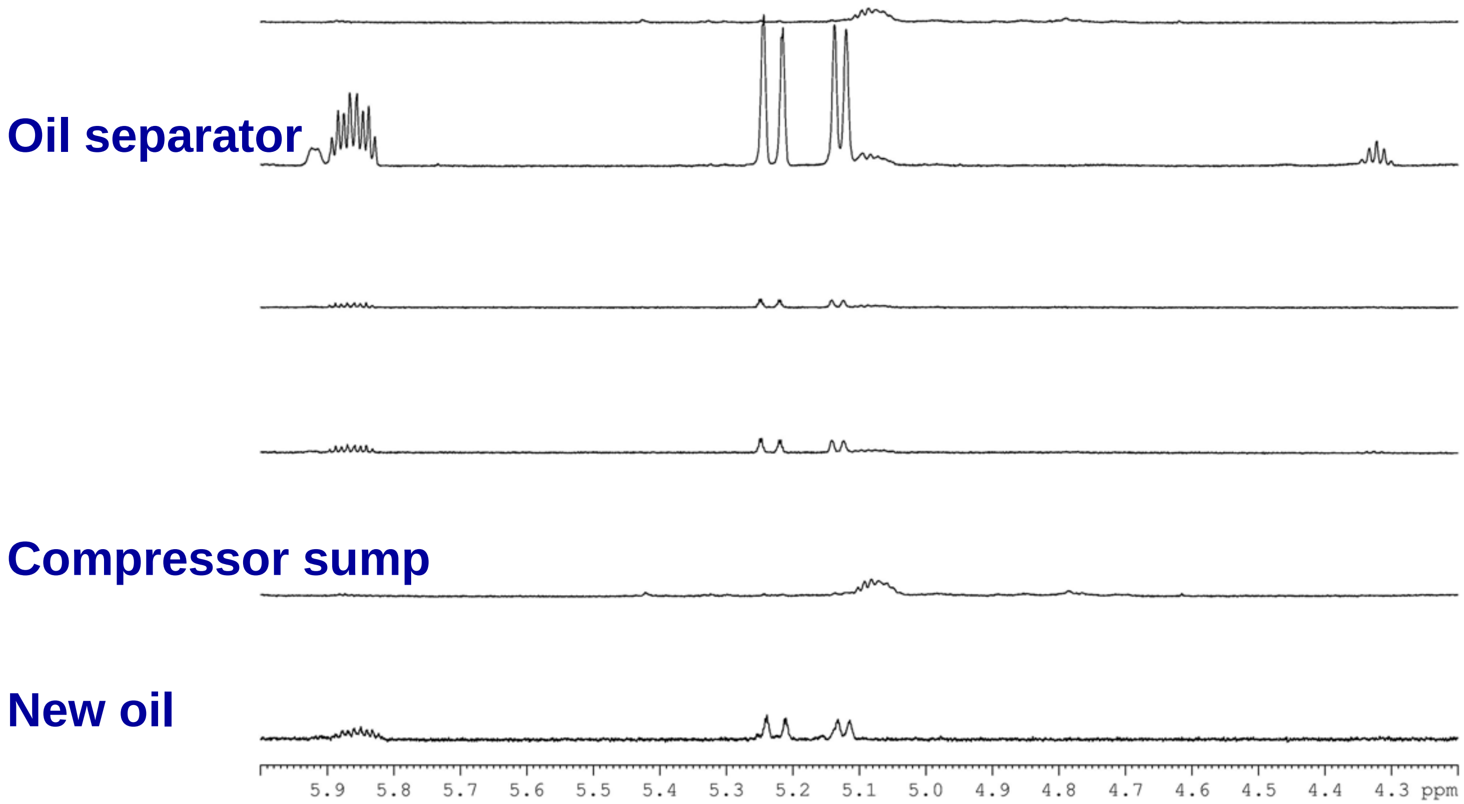
Turbine Failure Investigation

- To pin-point leak mechanism
  - Vacuum test
  - Leak tests
  - Tracer gases
  - Blanketing gases



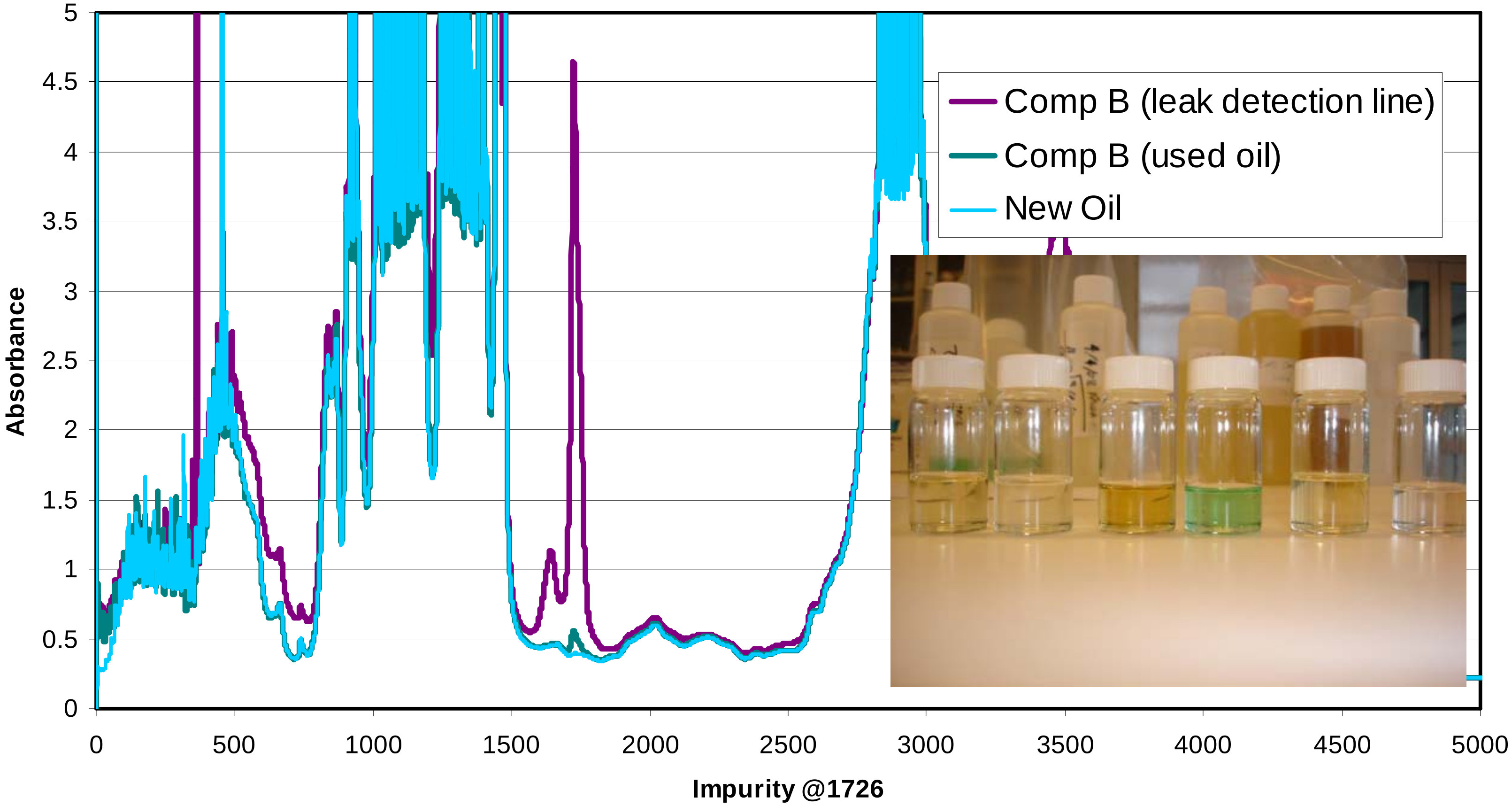
Turbine Failure Investigation

- NMR analysis of oil – doublet absent (implying oxidation)

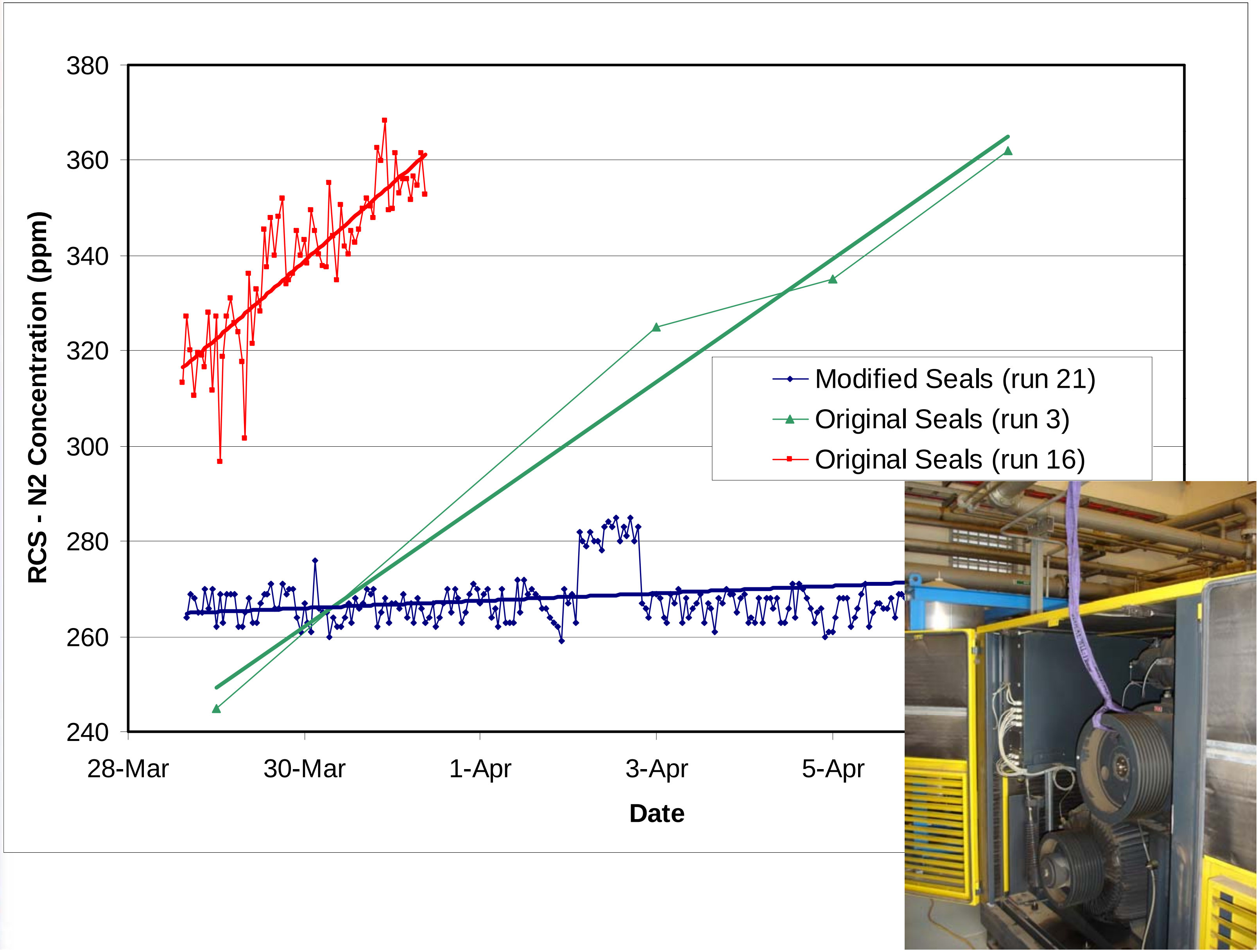


Turbine Failure Investigation

- Compressor oil oxidation (acetaldehyde CH3CHO) verified by FT-IR – cause of 2 turbine damages in 2006

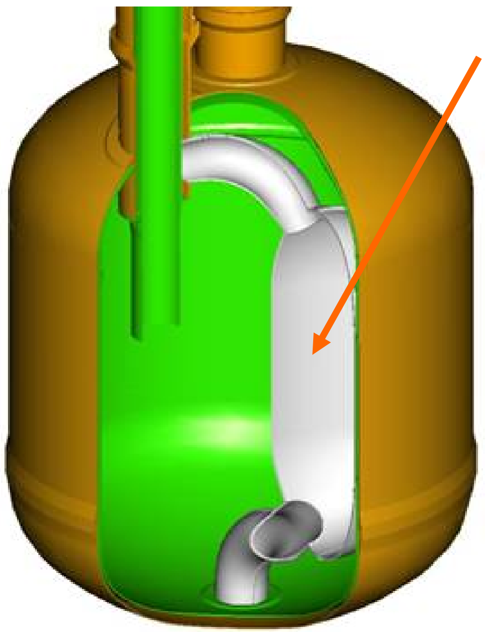


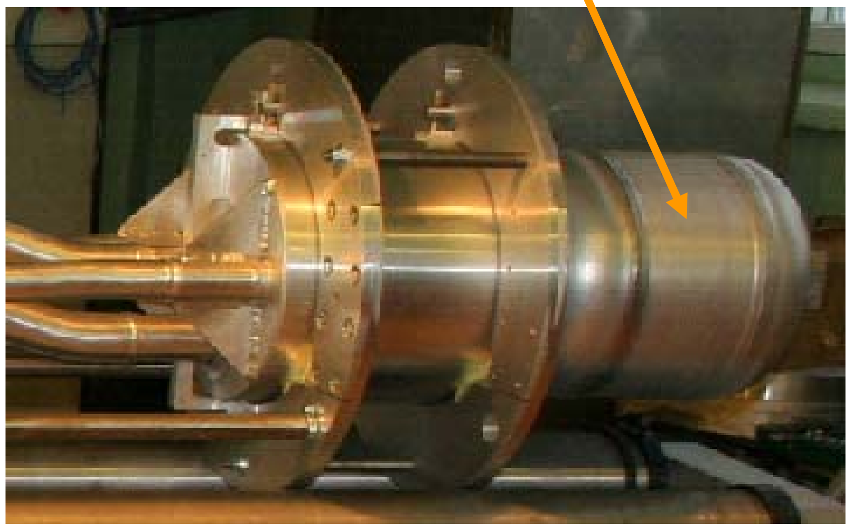
Turbine Failure Investigation



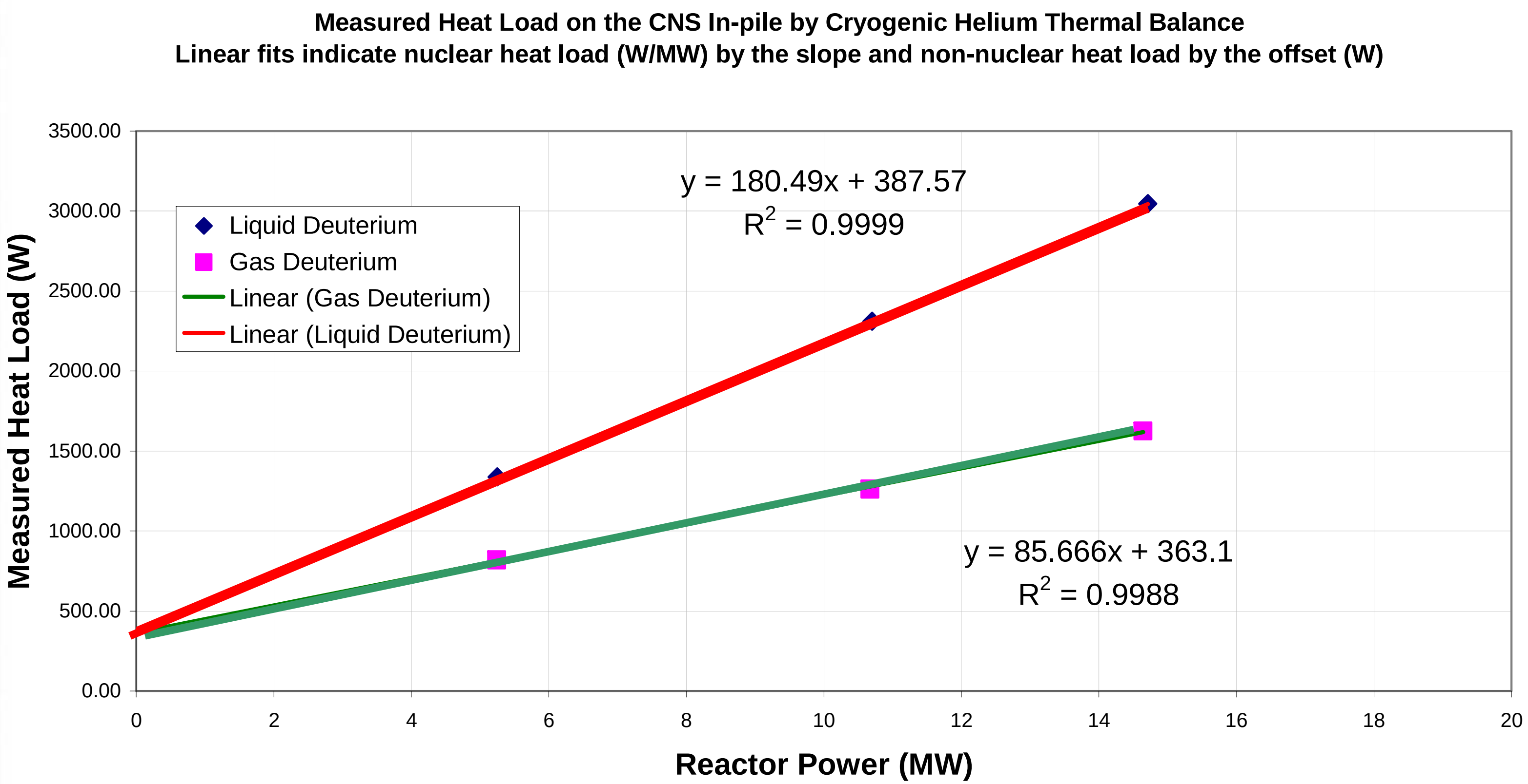
CNS In-pile

Moderator and Displacer	AlMg5	3741 gram
Moderator	D2	19.62 litre
Nominal D2 Temperature		25 K
Nominal D2 Pressure		330 kPa a





Heat Load



Measured Heat Load on the CNS In-pile by Cryogenic Helium Thermal Balance
Linear fits indicate nuclear heat load (W/MW) by the slope and non-nuclear heat load by the offset (W)
y = 180.49x + 387.57
R2 = 0.9999
y = 85.666x + 363.1
R2 = 0.9988
Liquid Deuterium
Gas Deuterium
Linear (Gas Deuterium)
Linear (Liquid Deuterium)
Measured Heat Load (W)
Reactor Power (MW)
3500.00
3000.00
2500.00
2000.00
1500.00
1000.00
500.00
0.00
0
2
4
6
8
10
12
14
16
18
20

Heat Load

Element	Heat Load		
	Total (D2 Liq. 20K)	Total (D2 Vap. 35K)	D2 only
Design conservative heat load (W)	(178.7) 293.1		
Non-nuclear Heat Load (W)	388	363	25 (6%)
Nuclear Heat Load (W/MW)	180.5	85.7	94.8 (53%)

0.023 W/MW/g - for AlMg5 heat load

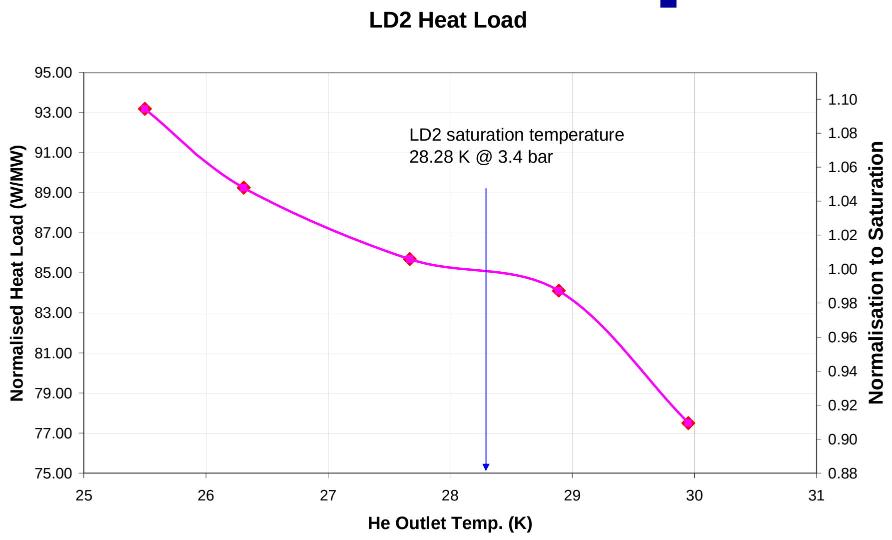
0.030 W/MW/g - for D2 heat load

Heat Load

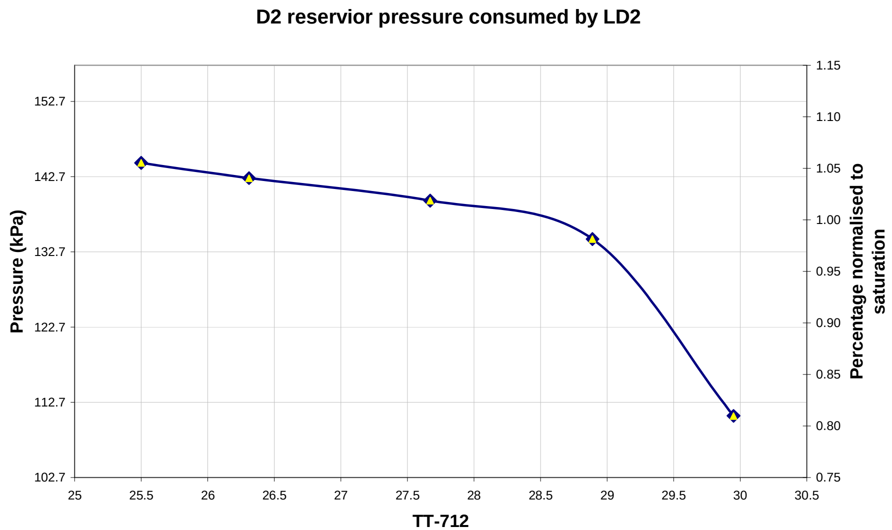
	Size	Design Heat load (2002) BOC	Design Heat load (2002) EOC	Measured (2008)
Liquid D_2	19.6 l	1397	1376	1921
D_2 Cell	1533 g		998	
Displacer	600 g		391	
Jacket	1537 g		995	
Metal		2337	2300	2076
Thermal rad.		350	350	388
Total (less isotope source)		**4084 W**	**4026 W**	**4385 W (7%)**

Moderator Temperature

Normalised Heat Load (W/MW)

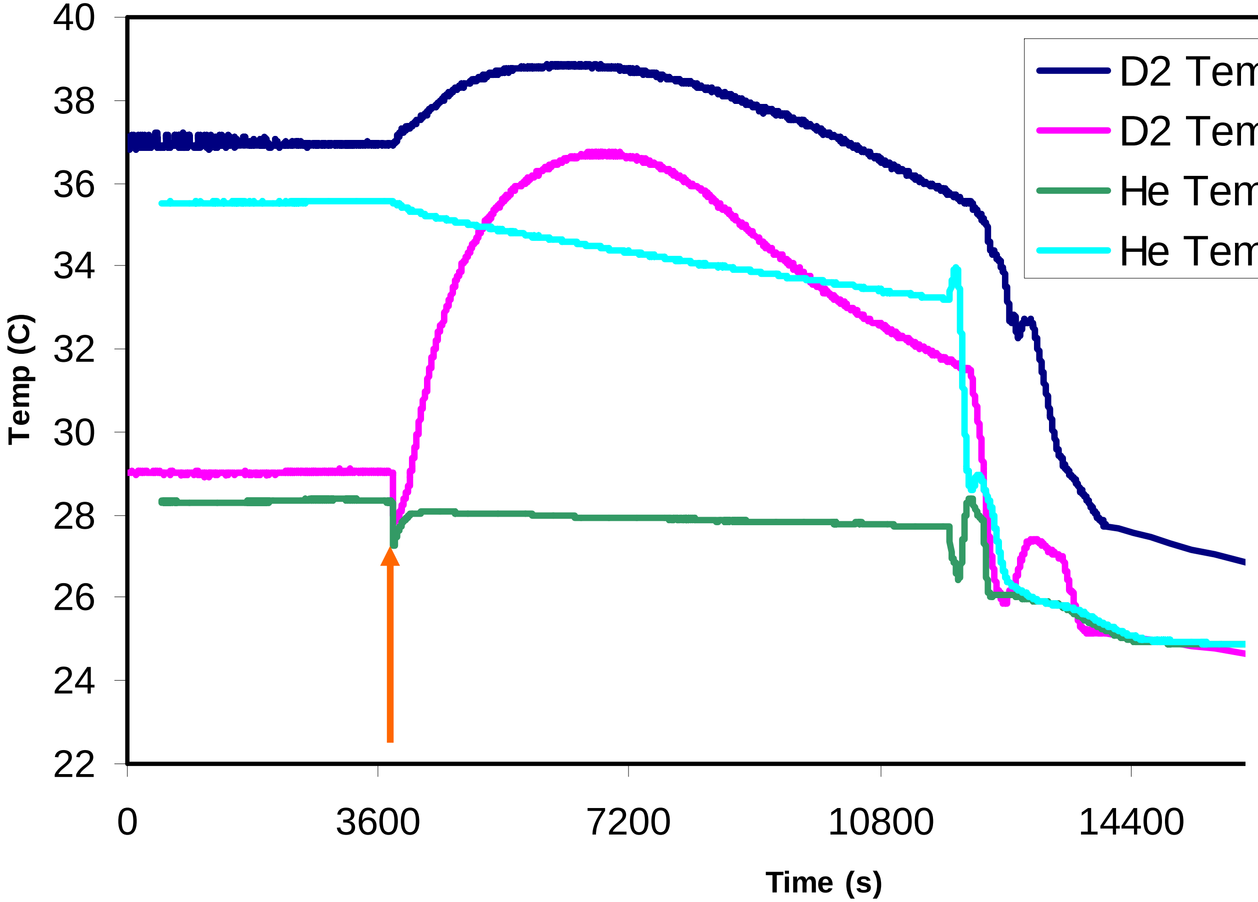


Pressure (kPa)

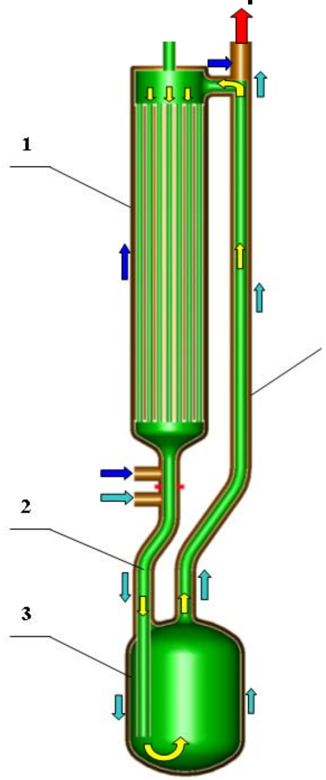


Helium Outlet Temp (K)

Thermosiphon Temperature

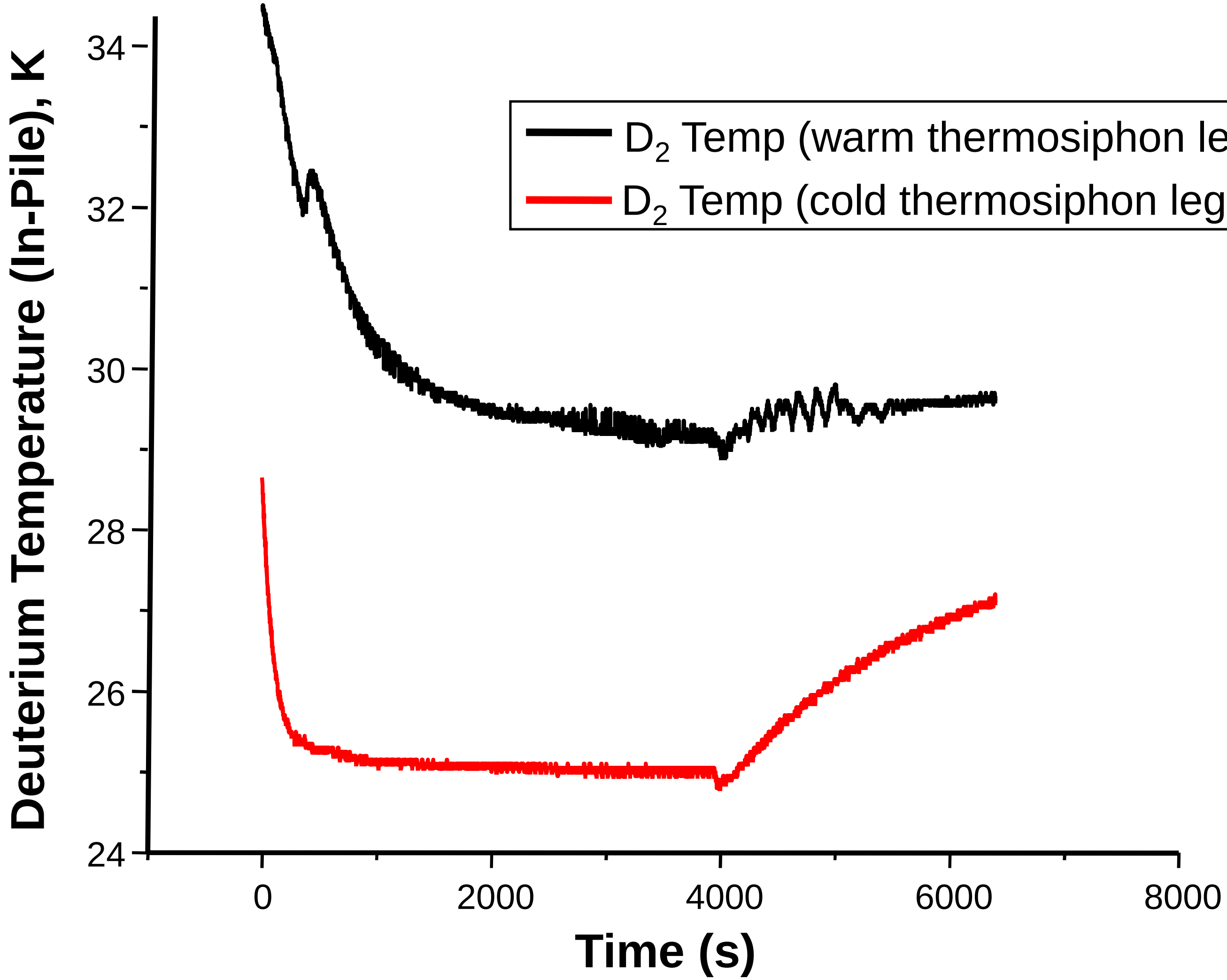


Reactor power - 15 MW. Loss of cooling

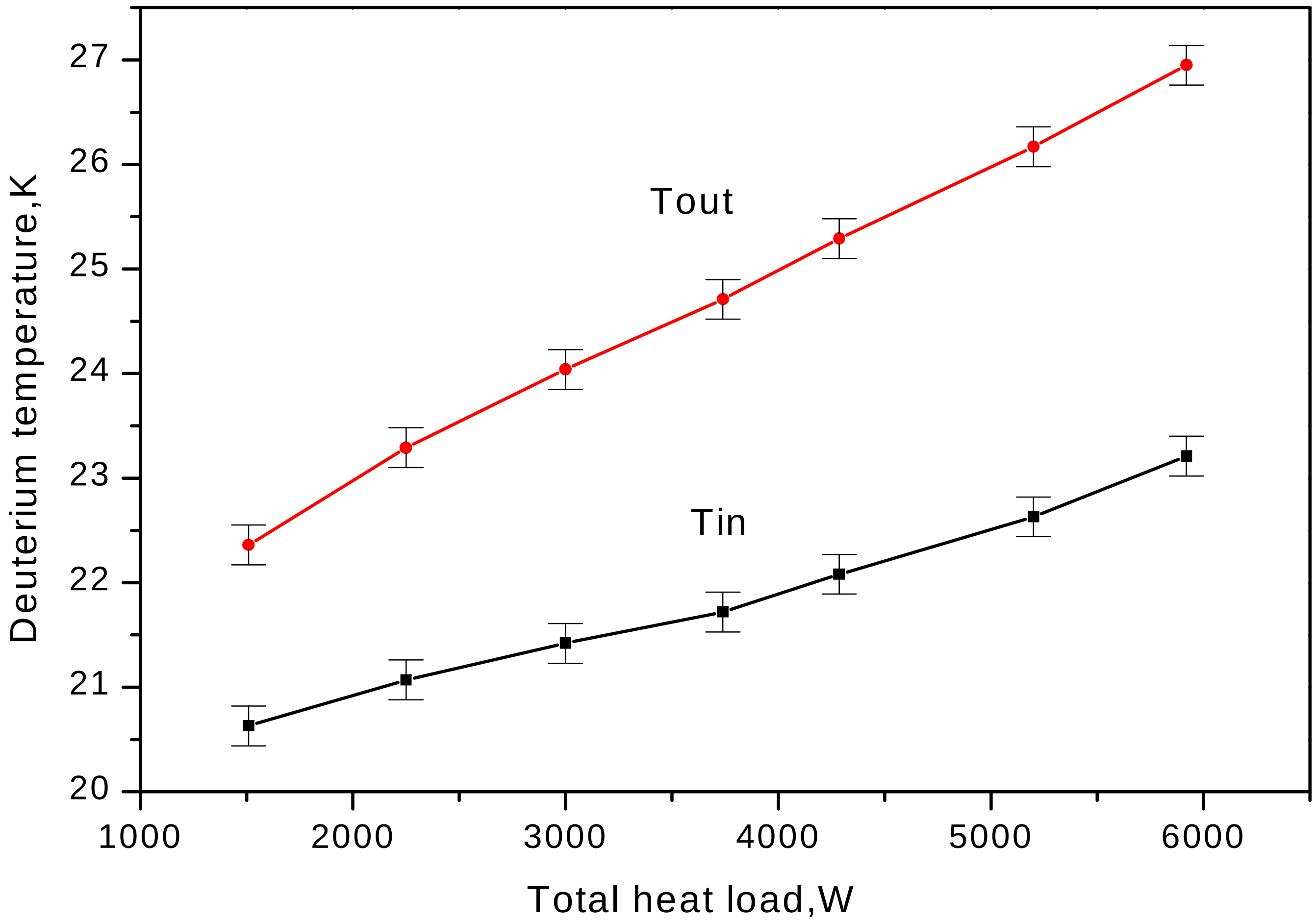


Thermosiphon Temperature

(He @ 24K, Reactor 1MW, 570 W heating)



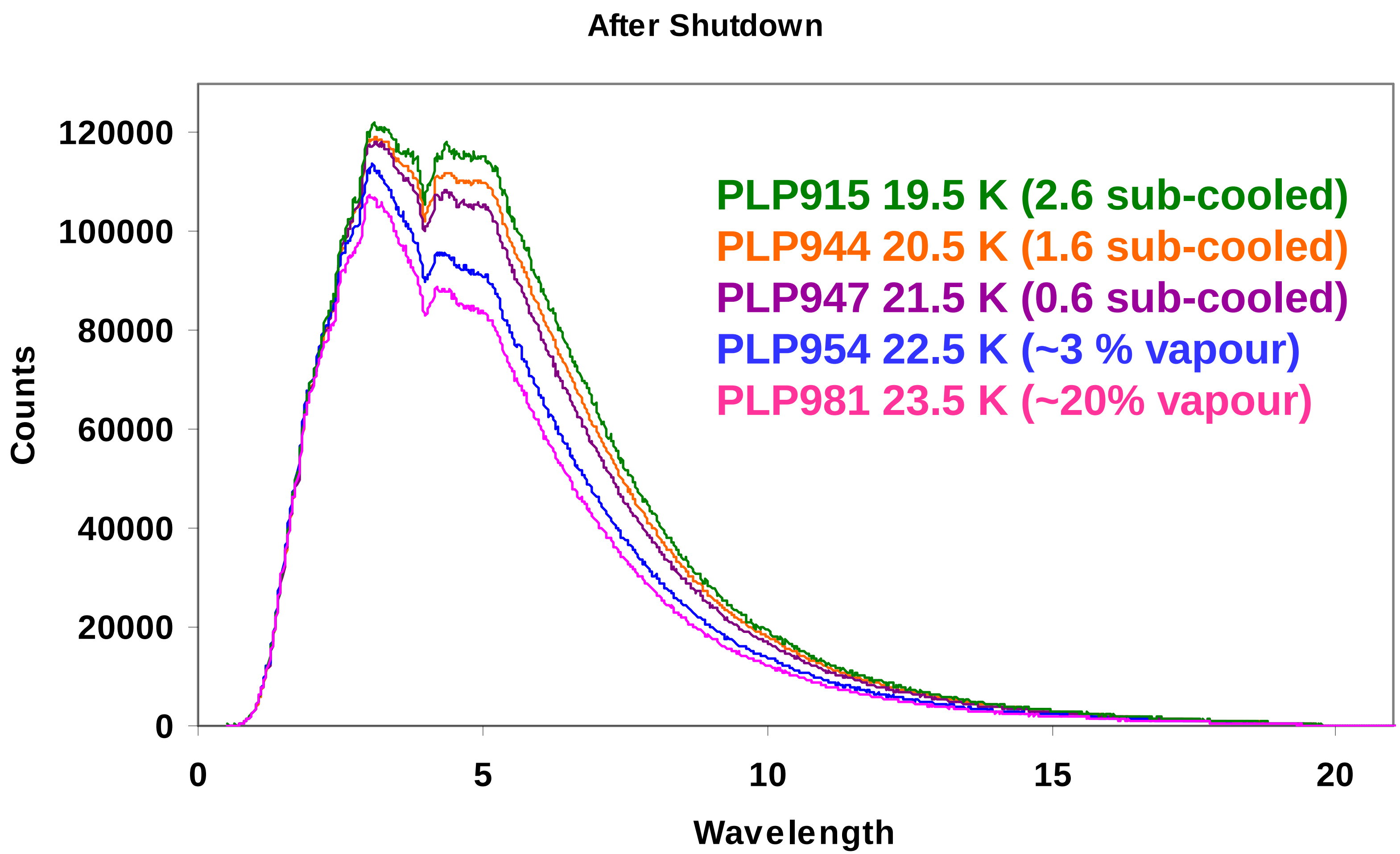
Thermosiphon Temperature



Cold Beams

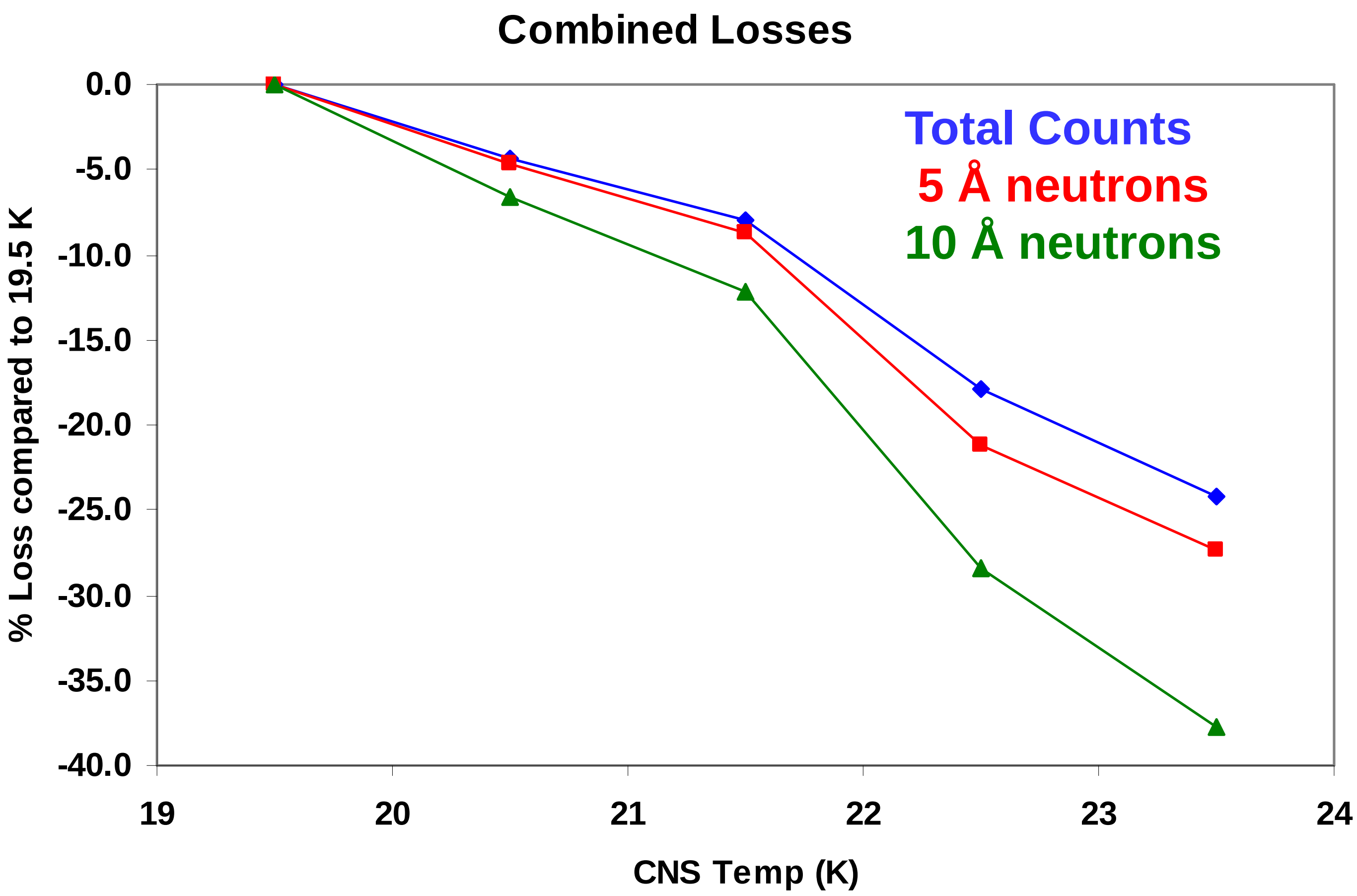
Heat Load	Contract Requirement	Operation
CG 3 Flux at reactor face	1.4 E10 n/cm2/s	1.8 E10 n/cm2/s
CG 4 Flux at reactor face	1.4 E10 n/cm2/s	2.49 E10 n/cm2/s
CG 3 Spectrum peak	< 4.2 meV	3.05 meV
CG 4 Spectrum peak	< 4.2 meV	2.35 meV

Spectrum



After Shutdown
Counts
120000
100000
80000
60000
40000
20000
0
0
5
10
15
20
Wavelength
PLP915 19.5 K (2.6 sub-cooled)
PLP944 20.5 K (1.6 sub-cooled)
PLP947 21.5 K (0.6 sub-cooled)
PLP954 22.5 K (~3 % vapour)
PLP981 23.5 K (~20% vapour)

Spectrum



Total counts and long wavelengths drop substantially above 21.5 K

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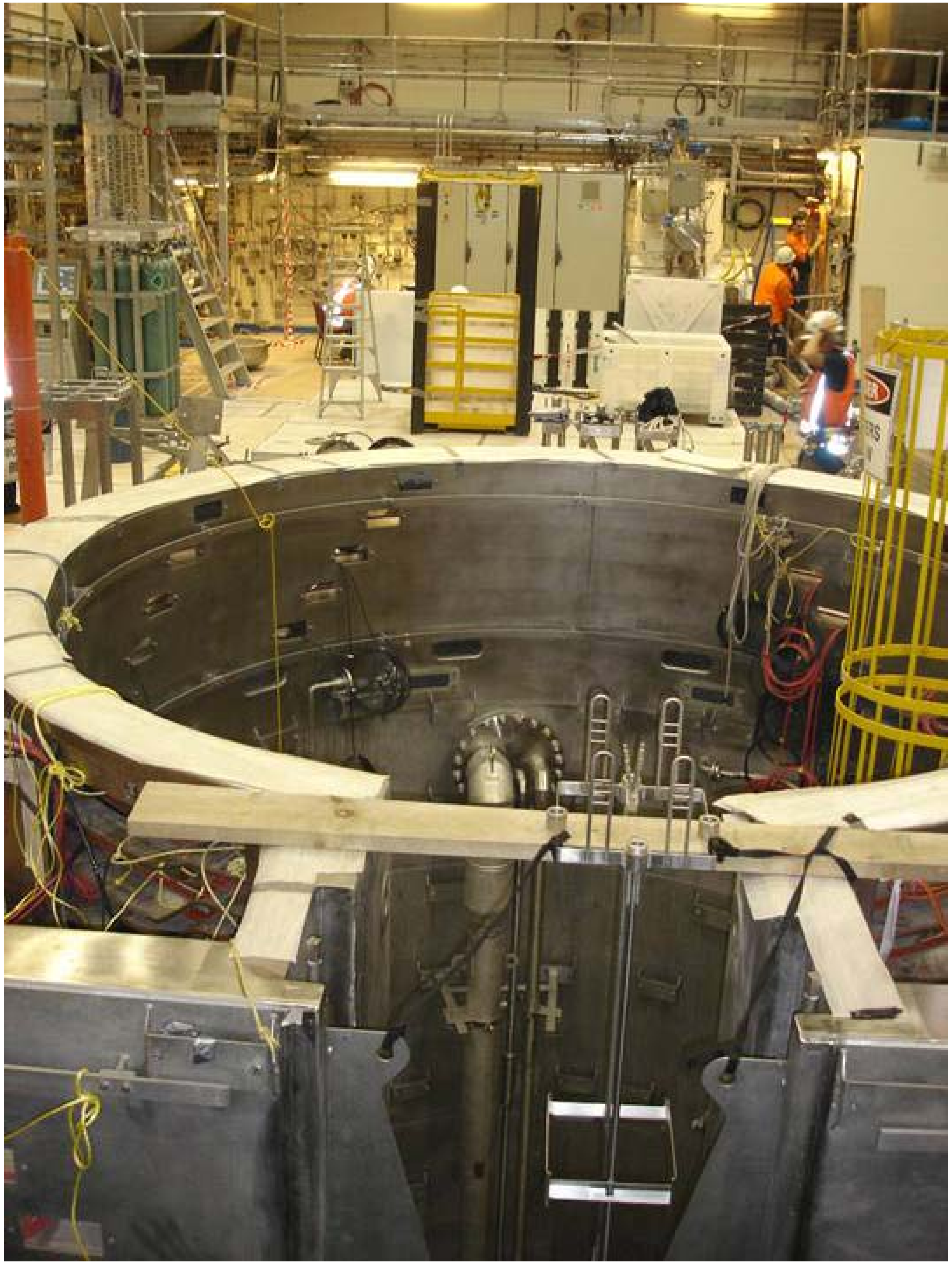
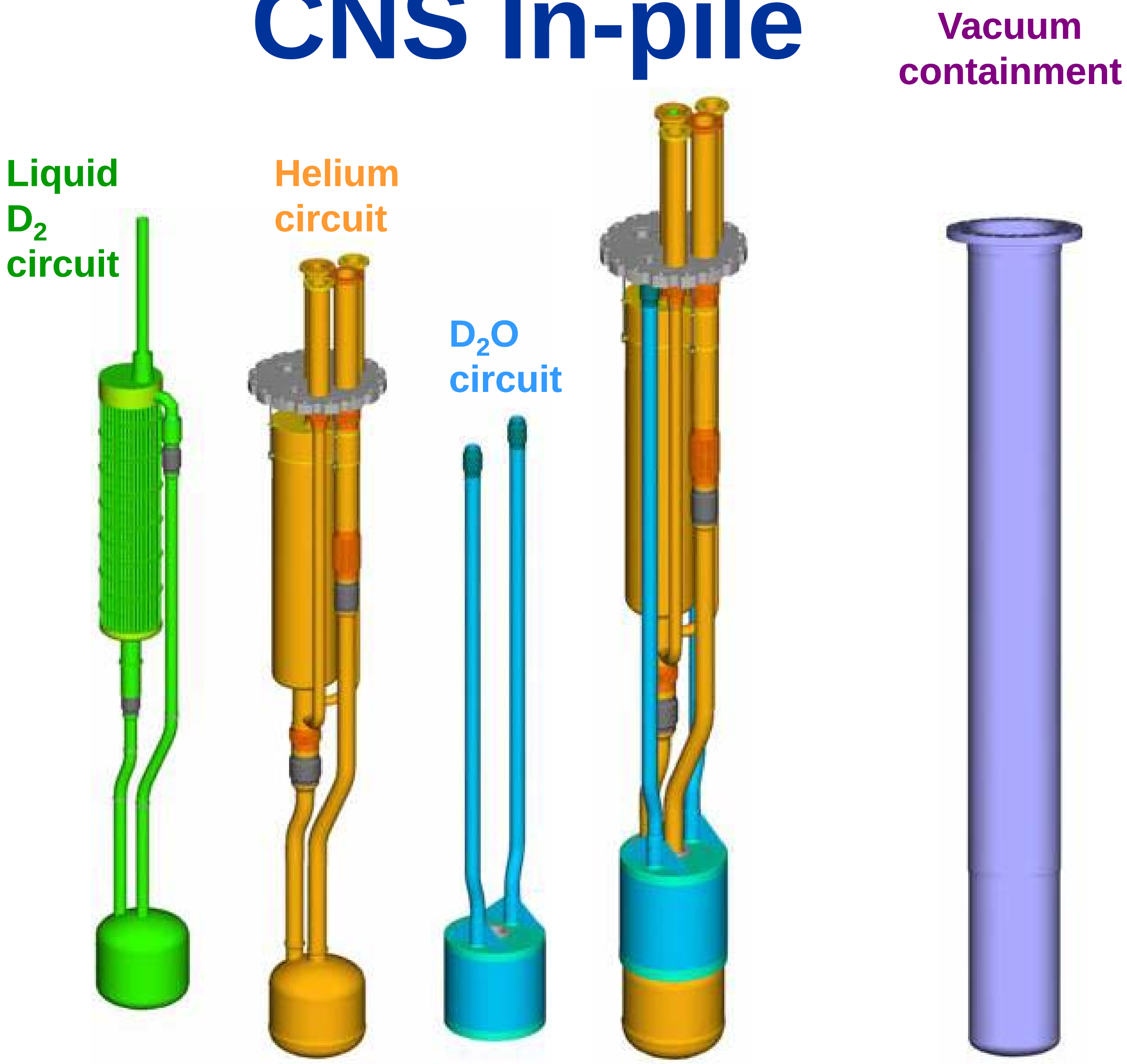


CNS Characteristics

Parameter	Value
Reactor power	20 MW
Moderator type	Liquid Deuterium
Moderator volume	20 litres
Moderator Temperature	~ 23 K
Moderator circulation / cooling	By natural circulation in a sub-cooled Deuterium Thermosiphon, He cooled.
Nominal heat removal capacity	5000 W
Average Cold Neutron Flux in Cell	$7.3\ 10^{13}\ \cdot cm^{-2} \cdot sec^{-1}$
Cold Neutron Flux at Reactor Face	$1.4\ \ 10^{10}\ \ cm^{-2} \cdot sec^{-1}$
Moderator Cell material	AlMg5 Alloy
VC material	Zr-Nb Alloy
VC design pressure	1.6 MPa
Commissioning	Year 2005

CNS In-pile



Liquid D_2 circuit
Helium circuit
D_2O circuit
Vacuum containment

CNS Description

1. In-pile Components (also combining a reflector plug)

    Vacuum containment: Zircadyne (ZrNb2.5%)

    Moderator chamber: Aluminium (AlMg5)

    Sub-contracted: PNPI

2. Cryogenic Refrigeration System

    He circuit, Brayton cycle, 19.8K at 5000W

    Sub-contracted: Air Liquide

3. Moderator System

    Liquid deuterium, ~ 24K, 20 m^3, passive

4. Vacuum System

    2 off (redundancy)

5. Gas Blanketing System

    He / N_2

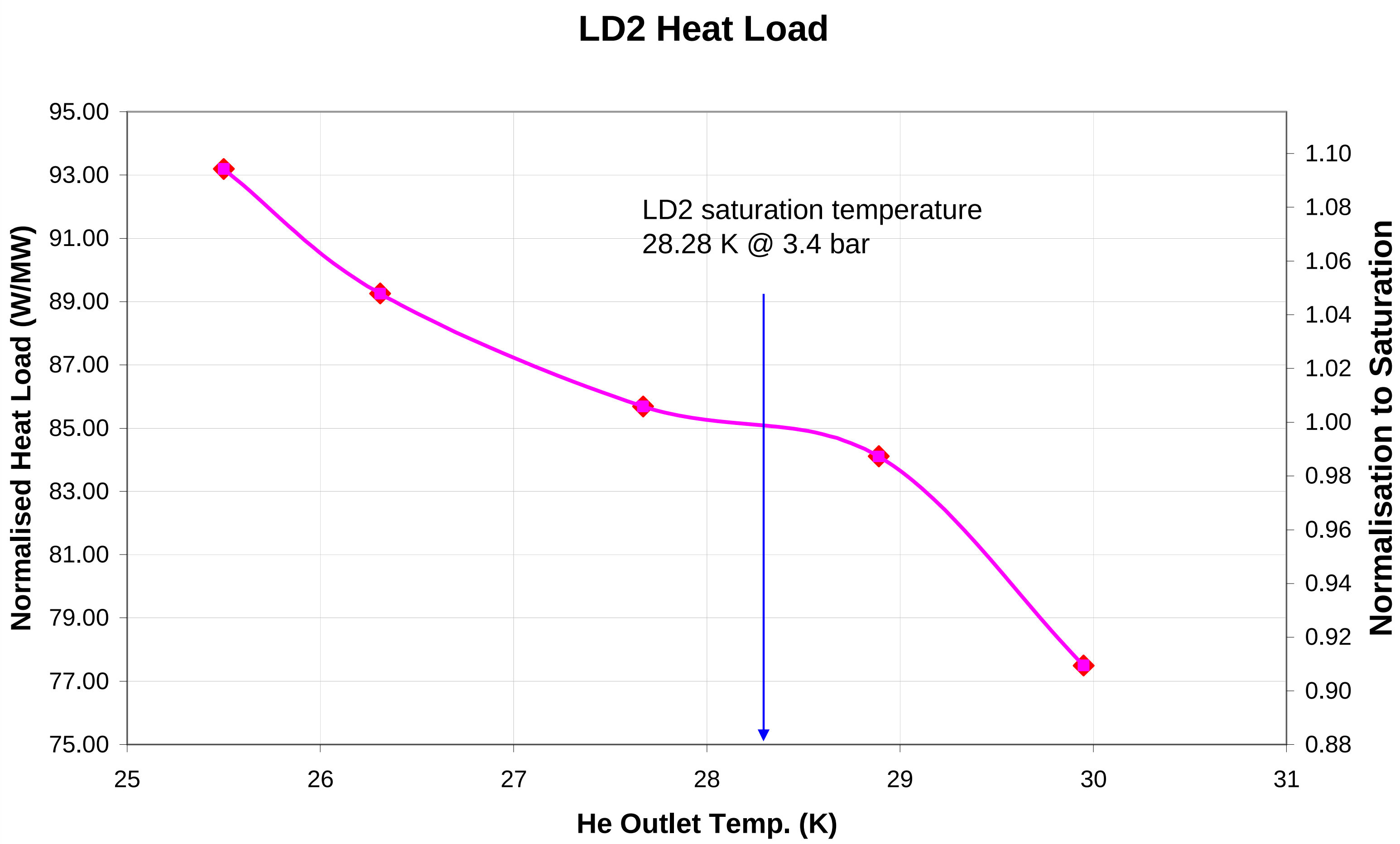
Heat Load

	Size	Design Heat load (2001)	Measured (2008)
Liquid D_2	19.6 l	1357 W	1921 W
D_2 Cell	1533 g	998 W	
Displacer	600 g	391 W	
Jacket	1537 g	995 W	
Metal		2384 W	2076 W
Total		**3741 W**	**3997**

CNS In-Pile Characteristics

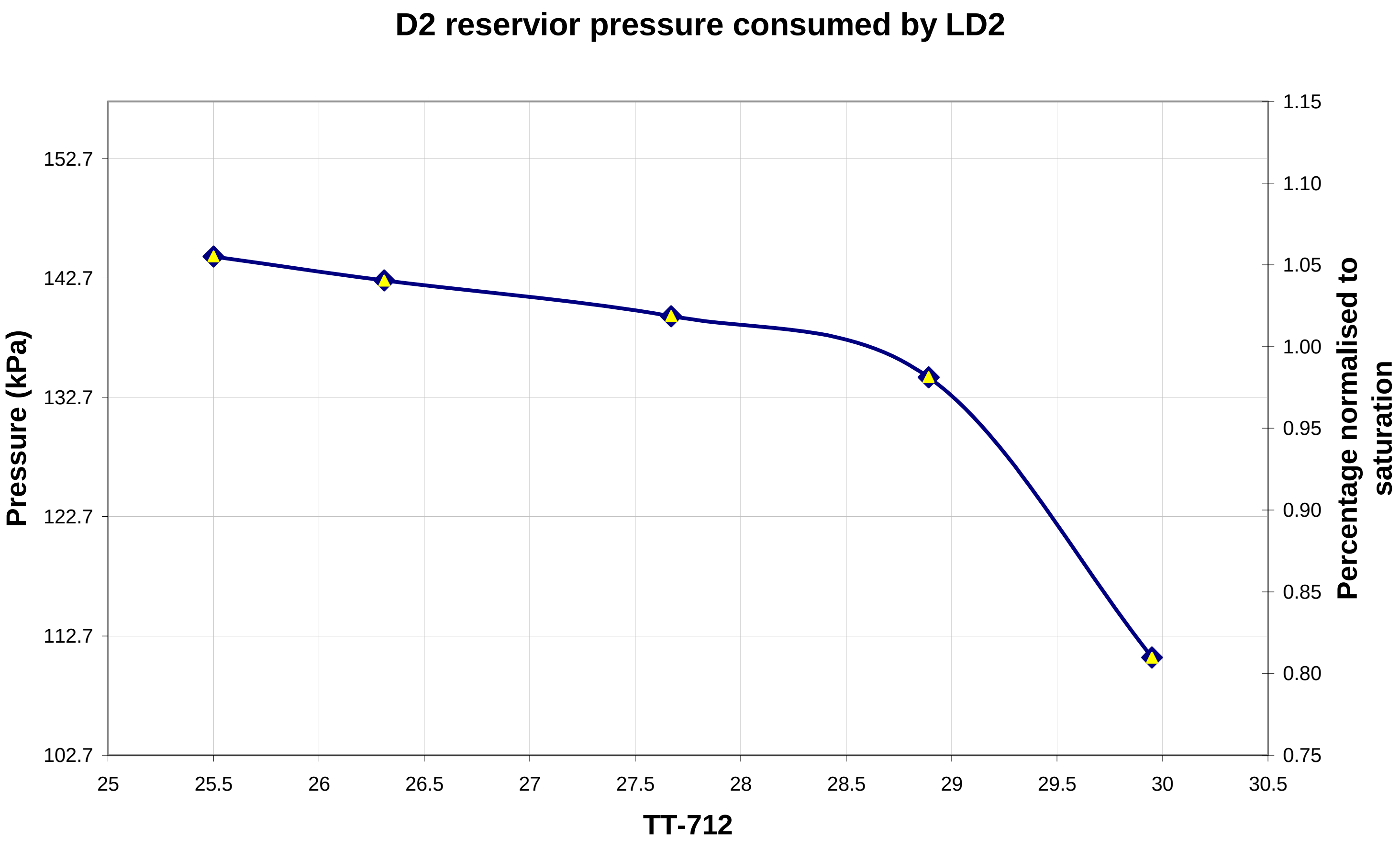
Parameter	Nominal Value
Heat load on the Moderator Chamber	4300 W
D2 pressure	330 kPa
He T to the Chamber	19 K
He T to the HX	19 K
Total cooling He flow rate	160 g/s
He pressure after the TS	150 kPa
Vacuum around the Thermosiphon	$1.3 \cdot 10^{-2}$ Pa

Heat Load

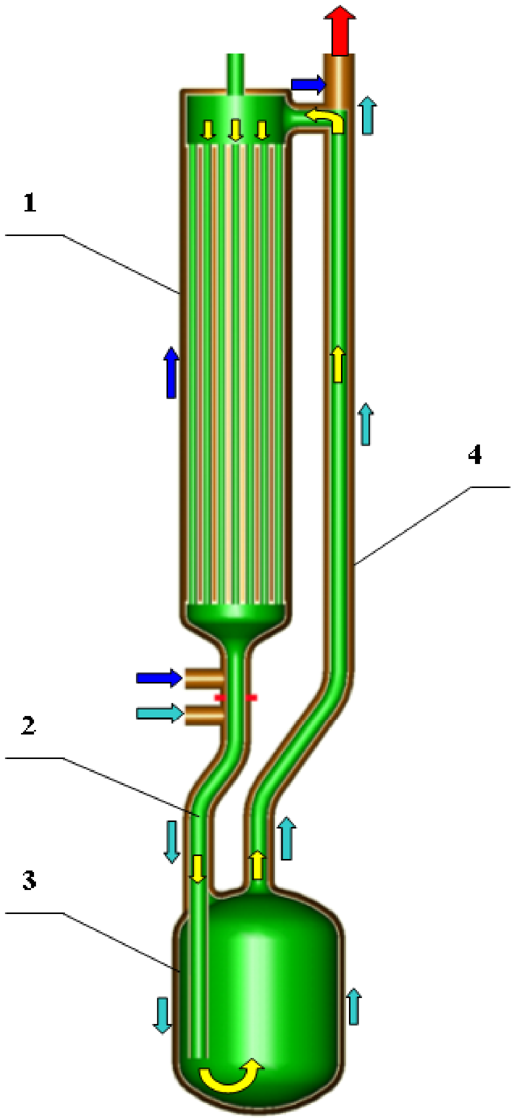


LD2 Heat Load
95.00
93.00
91.00
89.00
87.00
85.00
83.00
81.00
79.00
77.00
75.00
Normalised Heat Load (W/MW)
1.10
1.08
1.06
1.04
1.02
1.00
0.98
0.96
0.94
0.92
0.90
0.88
Normalisation to Saturation
LD2 saturation temperature
28.28 K @ 3.4 bar
25
26
27
28
29
30
31
He Outlet Temp. (K)

Heat Load



D2 reservior pressure consumed by LD2
Pressure (kPa)
152.7
142.7
132.7
122.7
112.7
102.7
Percentage normalised to saturation
1.15
1.10
1.05
1.00
0.95
0.90
0.85
0.80
0.75
25
25.5
26
26.5
27
27.5
28
28.5
29
29.5
30
30.5
TT-712



liquid deuterium flow

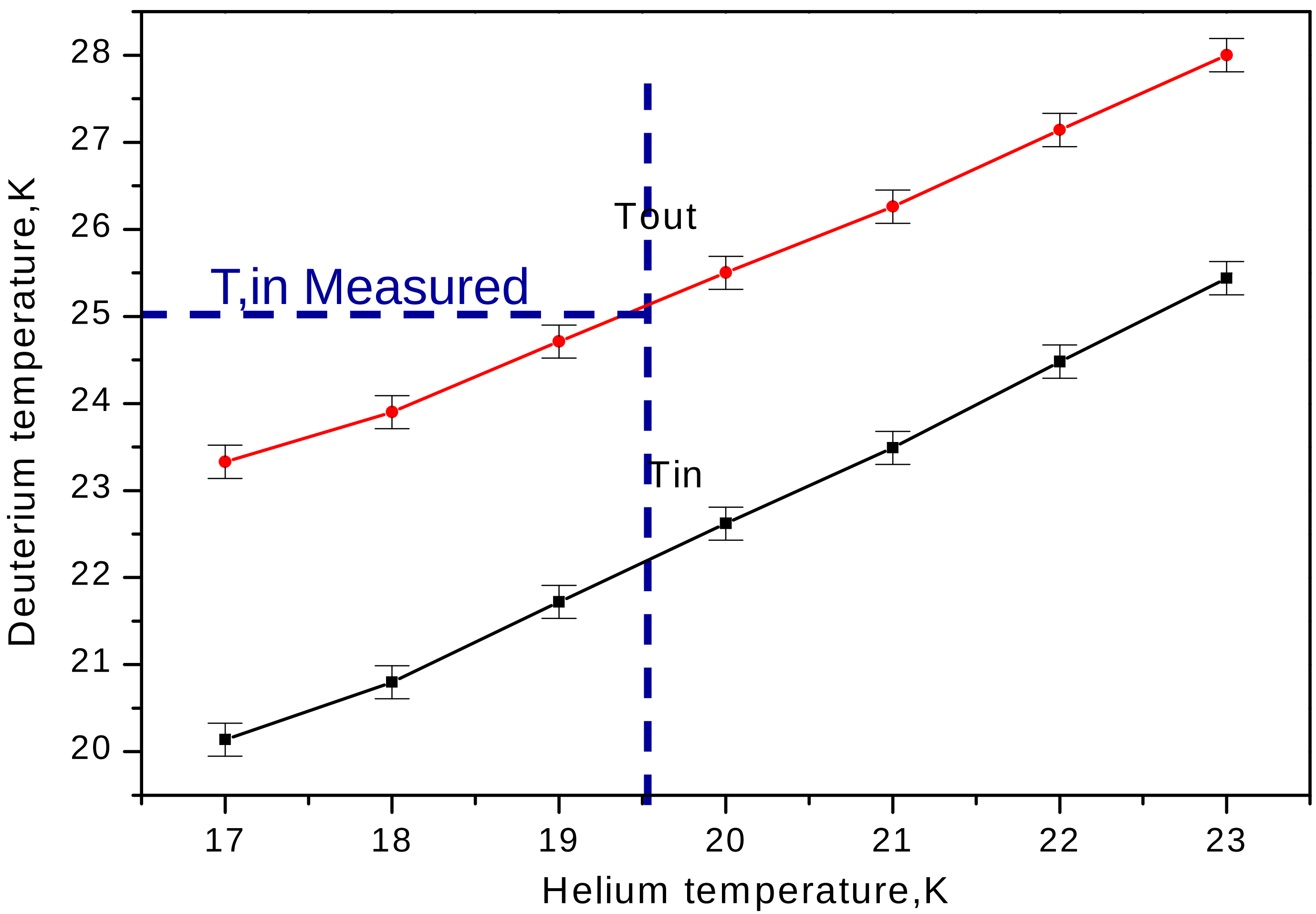
cold helium flow through the Heat Exchanger

cold helium flow through the Moderator Chamber

helium flow to the refrigerator

1 - shell and tube counter flow heat exchanger,
2 - tube-in-tube parallel flow heat exchanger as a downwards tube,
3 - moderator chamber,
4 - tube-in-tube parallel flow heat exchanger as an upwards tube.

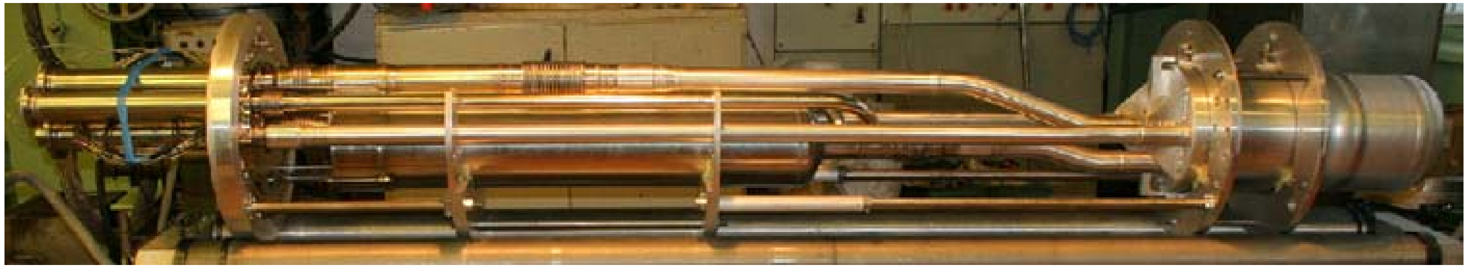
Thermosiphon Temperature



In-pile Prototype Testing (PNPI)

AIM: To prove heat removal by thermosiphon

PROTOTYPE: Moderator chamber and thermosiphon. Two electric heaters modelled nuclear heating.



RESULTS:

Operation in normal cryogenic mode with 4300 W heat input.

Operation in warm stand-by mode with 2650 W heat input.

RCS Factory Acceptance Test (Air Liquid)

RCS Factory Acceptance Test (Air Liquide)

TEST PROGRAM – Jan 2004

CONCLUSIONS

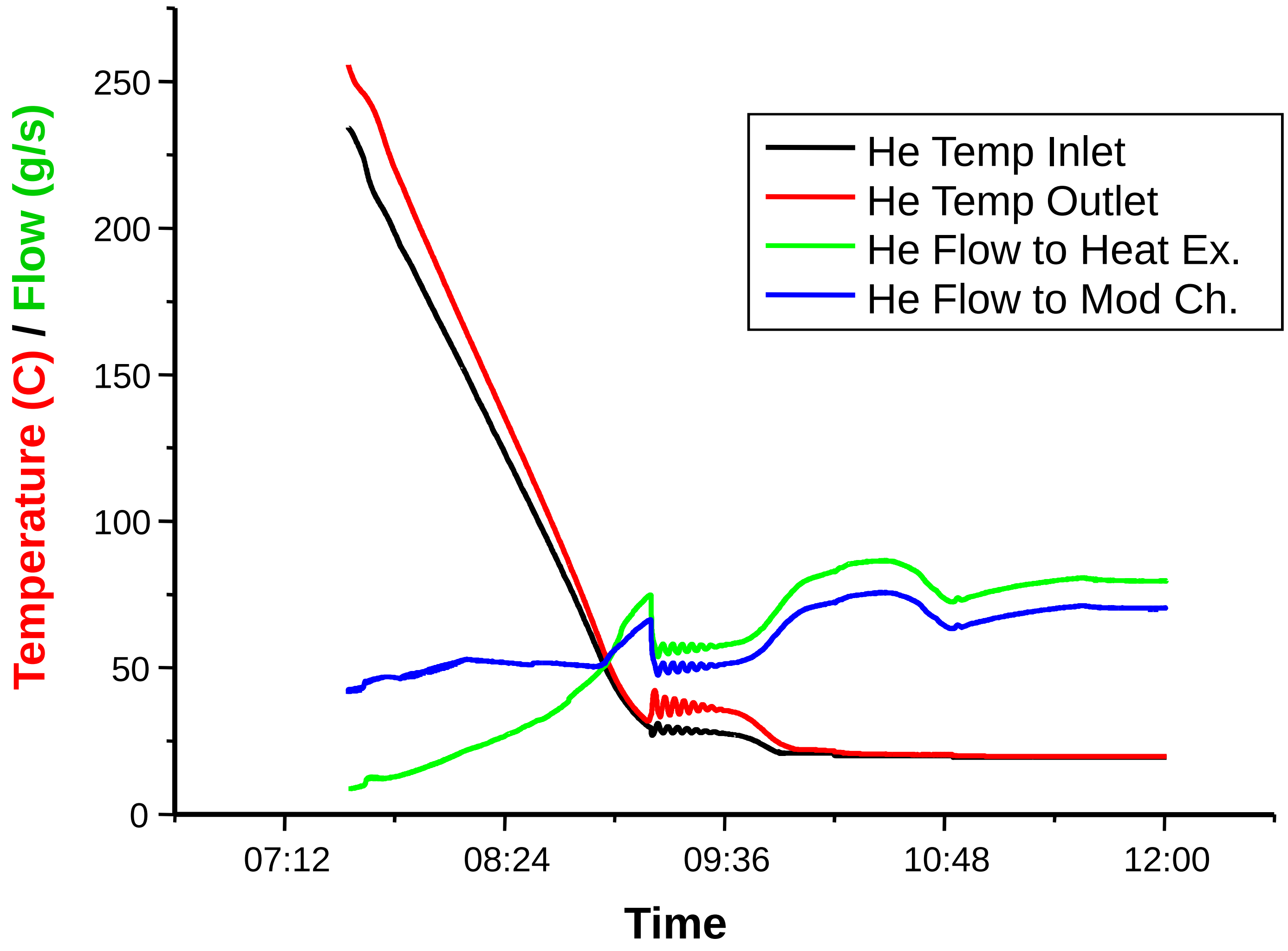
- 5.6 kW heat removal capacity.
- Stand-by operation, and transition between modes successful.

LESSONS LEARNT

- The cryogenic helium bypass loop
- Helium relief tank
- Helium contamination

Cold Commissioning

Transition from SO (warm) mode to NO (cryogenic) mode with simulated power

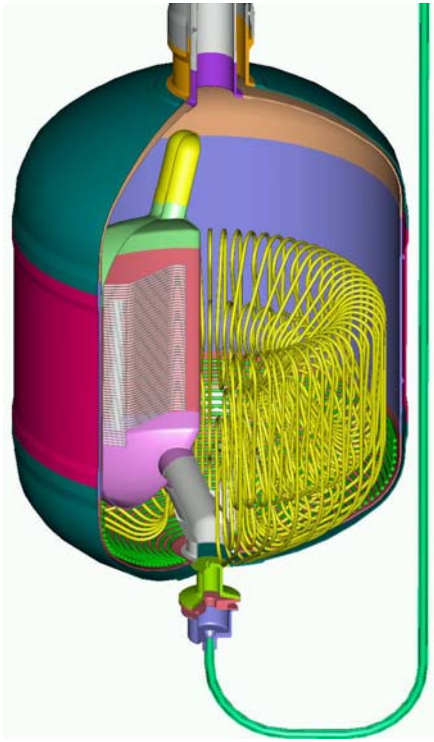


Turbine Failure Investigation

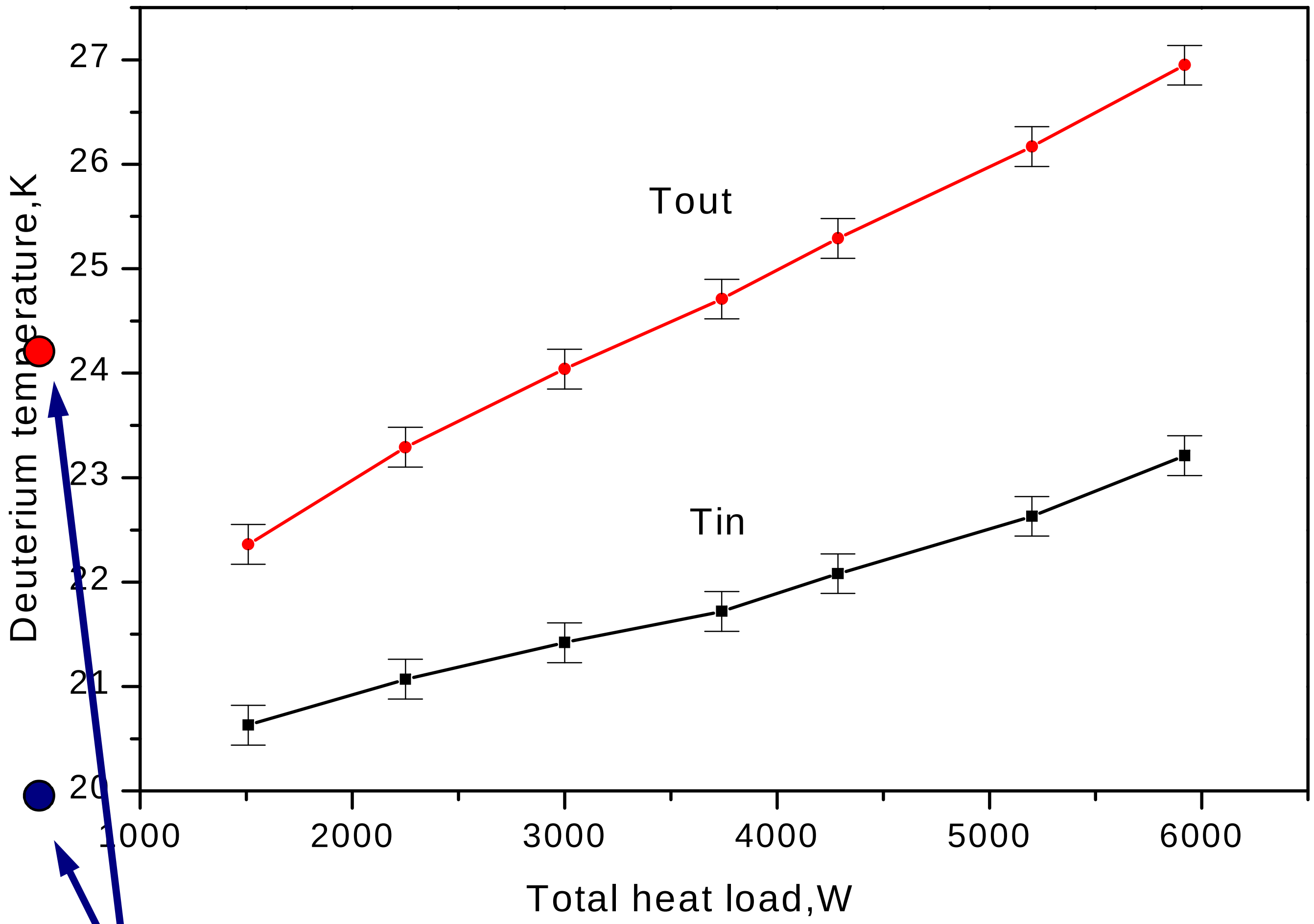
- Compressor shaft seal modified

Thermosiphon Temperature

Heat Load	Prototype tests	Operation
D2	2170 W	1921 W
Vessel	2648W	2076 W

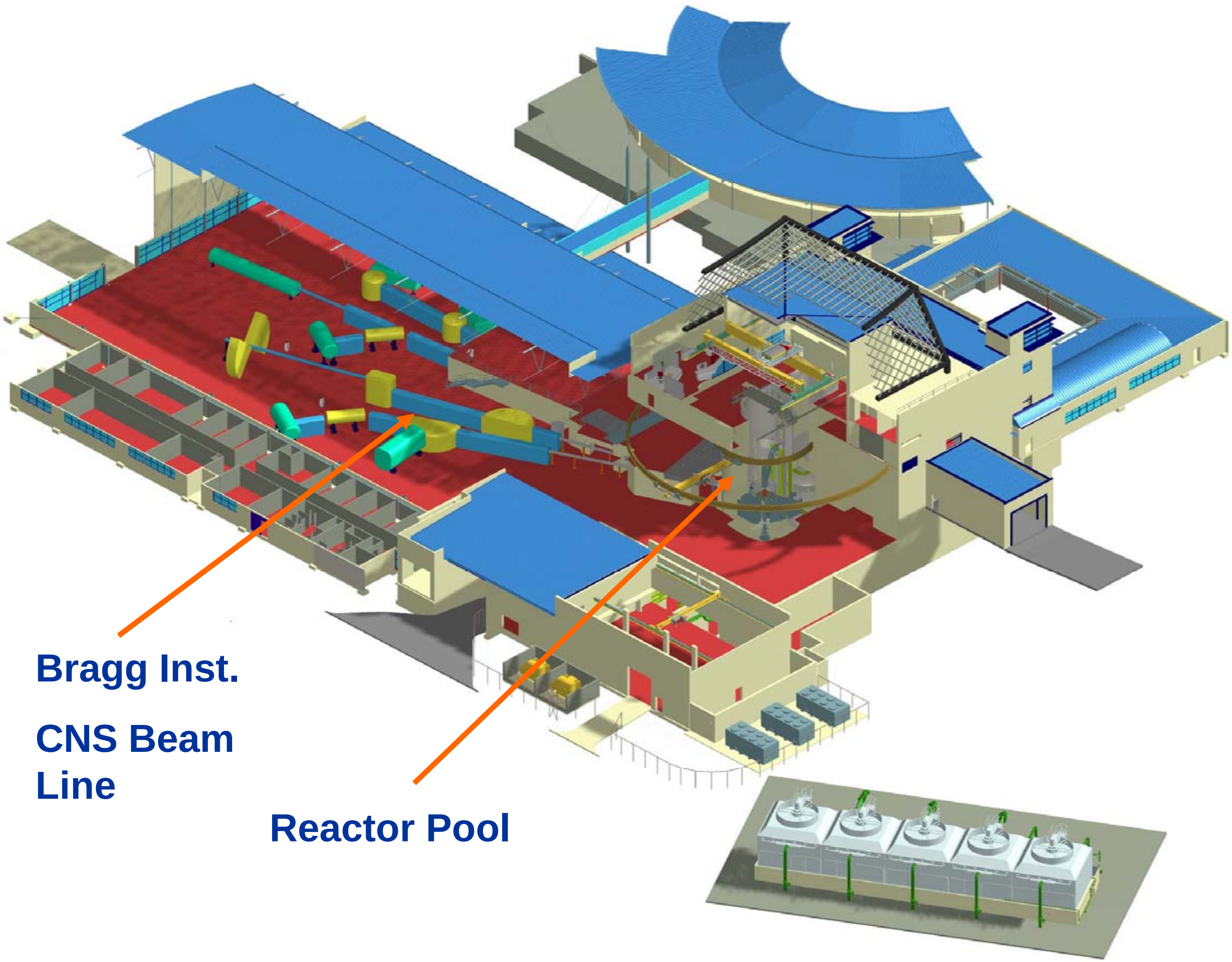


Thermosiphon Temperature

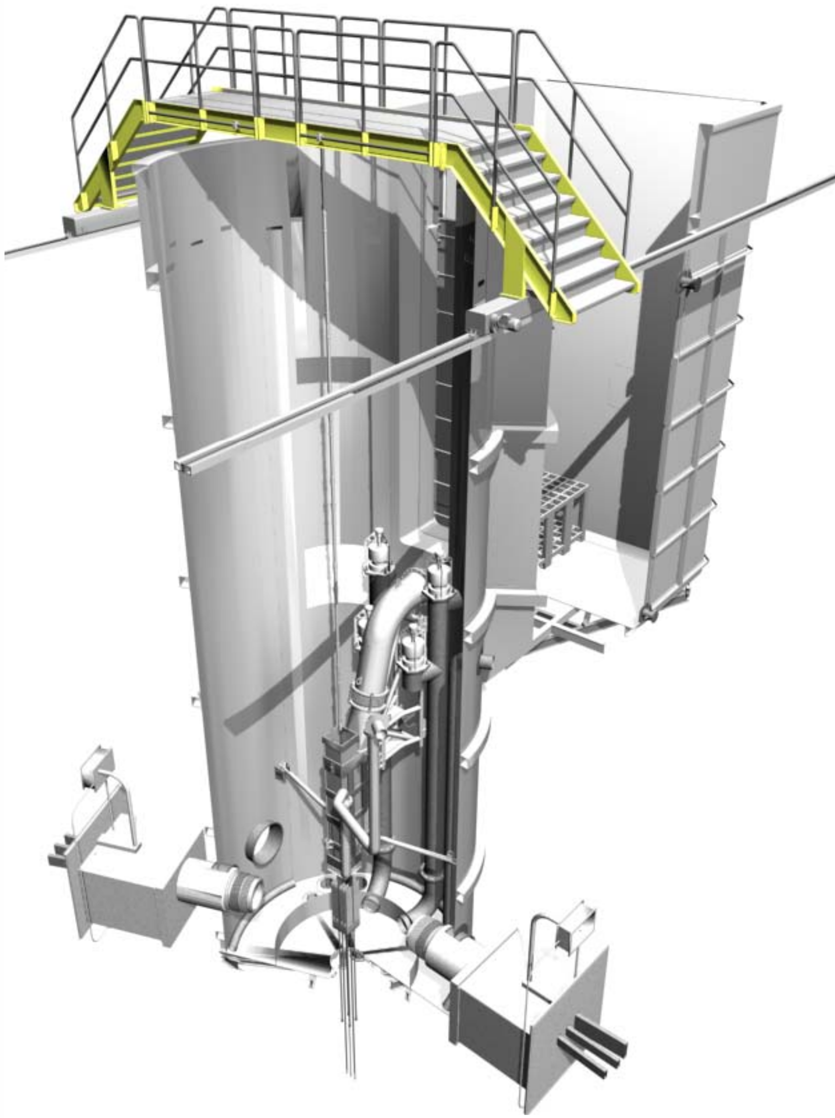


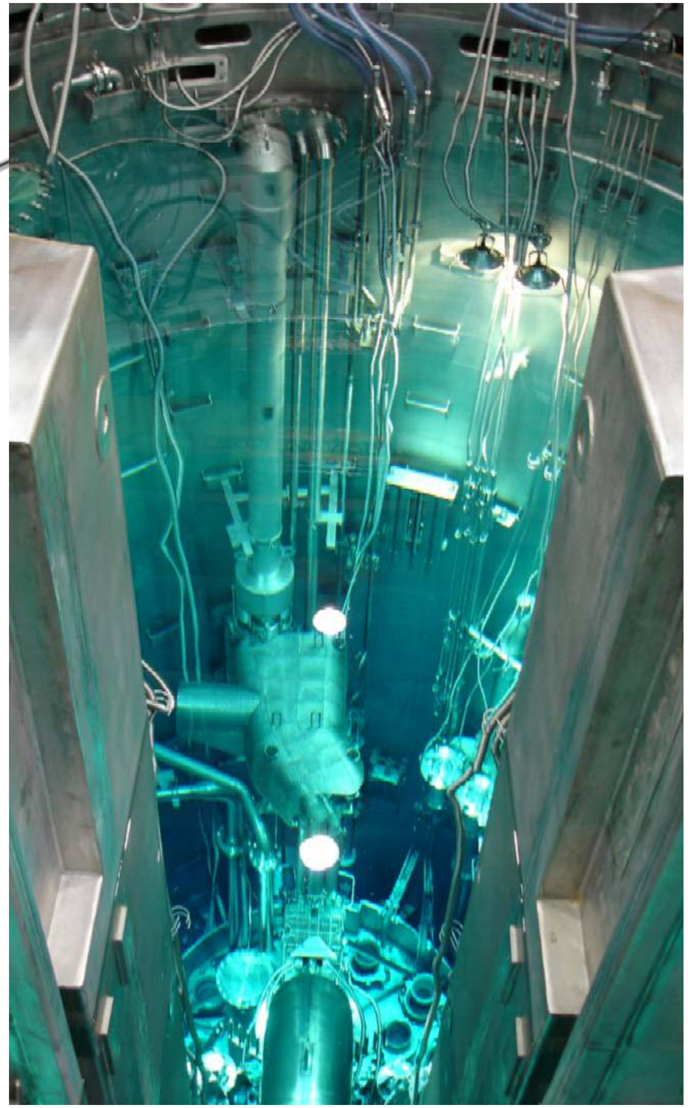
Measured value (corrected)

OPAL Reactor Facility



OPAL Reactor Facility





Operation

Normal Operating Mode (NO)

Stand-by Operating Mode (SO)

Halt Mode

Fast Warm-up – rapid deuterium vapour warm-up

Forced Evaporation – accelerated return to reactor power (reactor poison–out)

Helium injection into the vacuum containment