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Transient analysis of the new Cold Source at the FRM-II

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Abstract

The new Cold Source (CNS) at the FRM-II research reactor is completely installed. This paper reports on the results of the transient analysis in the design status for this facility for producing cold neutrons for neutron experiments, the implementation of the results in the design of the mechanical components, the measurements at the cold tests and the comparison with the data of the transient analysis.

The important load cases are fixed in the system description and the design data sheet of the CNS.

A transient analysis was done with the computer program ESATAN, the nodal configuration was identical with the planned system of the CNS and the boundary conditions were chosen so, that conservative results can be expected.

The following transients of the load cases in the piping system behind the inpile part

- normal storage of D_2 at the hydride storage vessel
- breakdown of cooling system of the CNS and transfer of D_2 to the buffer tank
- rapid charge of D_2 to the buffer tank with break of the insulation vacuum and flooding of Neon
- reloading of the D_2 from the buffer tank to the D_2 hydride storage vessel

were calculated. Additionally the temperature distribution for these transients in the connecting flanges of the systems to the inpile part were analysed. The temperature distributions in the flange region were take into account for the strength calculation of the flange construction. The chosen construction shows allowable values and a leak tight flange connection for the load cases. The piping system was designed to the lowest expected temperatures.
The load cases in the moderator tank were take into account in the stress analysis and the fatigue analysis of the vacuum vessel and the moderator vessel. The results shows allowable stresses. The results shows that a transient analysis is necessary and helpful for good design of the CNS.

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Transient analysis of the new Cold Source at the FRM II, Munich, Germany

1. Introduction

In the design of a Cold Neutron Source (CNS) the knowledge of all possible load cases of the CNS are very important from safety and operational point of view.
The load cases can be produced from the reactor side and from CNS side. Especially the load cases where liquid D_2 evaporate suddenly to gas and this gas shall be reloaded to a butter-tank, are very important to analyse. These transients can produced time dependent temperature variation in the connecting system and components parts.

In this paper the load cases of the new CNS of FRM-II were analysed, the temperature transient were calculated and the design results of the components were explained.

2. Features and System configuration of the CNS with auxiliary systems

Table 1 summarises the essential data of our CNS as compared with the CNS of the old Munich Research Reactor FRM, and with the vertical (“reference”) CNS at ILL Grenoble (in its 1985 version).

Table 1: FRM cold neutron sources: essential characteristic data

	FRM	FRM-II	ILL vertical CNS	Units
Nominal reactor power	4	20	57	MW
Integral neutron flux in CNS	2×10^{13}	4×10^{14}	4×10^{14}	cm^{-2}/s
Distance from core (axis to axis)	300	400	760	mm
Specific heat load at hot point/on axis	0.3/0.1	2.6/1.2	1/0.5	W/g
Size of the moderator cell	146 x 250	∅ 300 x 240	∅ 360	mm
Material of the moderator cell	AlMg (3)	Al 6061	Al (99.5)	%
Moderator cell: mean wall thickness	1	1.0	1.8	mm
Volume of the moderator cell/insert	0.9	20/6	24/4.5	1
Moderator fluid	H_2	D_2^+ (5 %) H_2	D_2	liquid
Mass of H_2/D_2 in the moderator cell	65	2000	3000	g
Temperature of the cold moderator	18	25	25	K
Pressure in the cold moderator	3.5	150	150	kPa
Pressure in the warm H_2/D_2-system	4.5	~ 0	300	kPa
Expected refrigeration power	400	5000	6000	W
Hydnde forming time (for 95 % D_2)	N/A	6	N/A	min
Volume of the gas buffer	7.5	15	18	m³
Number of tubes in the thermal siphon	2	1	3	
Material of the in-pile vacuum thimble	AlMg (3)	Zircaloy (Zry)	Zircaloy (Zry)	
Mean wall thickness of the thimble	10	4	6	mm
Vertical beam tubes for VCN/UCN	0	1	1	
Horizontal beam tubes	1	3	1	
Horizontal cold guides or collimators in-pile	1	10	5	

The integral cold neutron flux in our CNS will be comparable to that in the vertical one at ILL although the ILL reactor runs at a power nearly three times as high. This is possible because:

- the core of the FRM-II is light water cooled and more compact,
- the axis of the CNS is much closer to the core,
- the flux depression in the CNS due to voids is less,
- the cooling power needs can be kept small by reducing size and wall thickness of the CNS.

The centre of the CNS is so close to the core that the cold moderator volume is partly located in the thermal neutron flux maximum. At this location the epi-thermal and fast neutron flux is considerable, in spite of the light water cooling of the core. the moderator fluid therefore has to absorb a high specific heat load of up to 4 W/g, leading to a high bubble content and a strong internal fluid circulation.
In order to keep the refrigeration needs below 5 kW, the mass of the cold moderator fluid has been limited to 2000 g, of which about 100 g will be hydrogen, the rest deuterium (D_2).

The vacuum vessel of the in-pile part will be made from zircaloy, the moderator cell and tubing from the aluminium alloy 6061 T6. The insert, which optimises the geometry of the cold moderator volume, will be made from magnesium. The deuterium condenser has a 10 m² heat-exchanger area made from aluminium tubing. Bi-metallic junctions (Al/stainless steel) are used at the 25 K level in different places to take advantage for thermal insulation from the low thermal conductivity of the stainless steel. The in-pile part will be connected to the gas handling system via flexible stainless steel tubing throughout in order to guarantee vibrational decoupling of the in-pile part to the rest of the reactor building in case of an external shock (e.g. earth quake or air craft accident).
The main feature of the gas handling system is the double containment of deuterium throughout. All vessels and tubes, including the metal hydride storage tanks, which do (or could eventually) contain D_2, are surrounded be at least one envelope containing pure nitrogen as an inert gas at a pressure slightly higher than ambient. Such a system allows a continuous leak testing and makes impossible the build-up of an (explosive) D_2-air mixture.
The refrigerator has to move 5 kW of nuclear radiation heating away from the cold source at the 25 K temperature level.
Two rooms on the 11.70 m floor or the reactor building are dedicated for the CNS cold box, gas handling and control desk. Additional floor space is foreseen inside and near the compressor building. First test operation started in November 2002.

3. Load cases of the CNS

The load cases of the CNS are fixed in the system description during the liscensing procedure.
The load cases are divided in load cases in the moderator tank from the reactor side and in specific load cases of the CNS with his auxiliary systems.
The load cases are pointed out in table 2.

Table 2

a) Load Cases of Reactor System

Plant condition	Load Cases Reactor System	Service level	Design time (h)	Frequency of occurance	T (max) °C	Remarks
Operation	<u>Normal operation</u>					30 years Load factor 0,7
	Steady state	A	185.000	-	60	
	Start up	A	-	1500	60	
	Shut down	A	-	900	60	
	<u>Upset operation</u>					
	Reactor Trip	B	-	600	60	
	Breakdown of Main Heat Sink	B B	- -	20 10	60 45	
	(Emergency power < 2 h)					
	Testing conditions	P				
Emergency operation	<u>Emergency operation</u>					
	Breakdown of Main Heat Sink (Emergency power > 2 h)	C		1	80	
	<u>Faulted condition</u>					
	Earth quake	D [1]		1	60	
	Airplane Crash	D		1	60	Outside of Design
Foot notes:	[1] Functionability after earth quake Level C Functionability during earth quake Level D					

b) Load Cases of Cold Neutron Source

Plant condition	Load Cases CNS	Service level	Design time (h)	Frequency of occurance	T (max) °C	P (max) kPa	Remarks
Normal operation	<u>Normal operation</u>						30 years Load factor 0,7
	Cold (Reactor on)	A	185.000	1500			
	Cold (Reactor out)	A	-	1500			
	Non operation	A	-	300			
	Cooling down	A	-	300			
	Heating up	A	-	300			
	Test conditions	P	-				
Upset/Emergency operation	Loss of cooling	B	-	100			
	Loss of hydrid storage cooling	B	-	30			
	Leak in cold D_2-System	C	-	1			
	Leak in vacuum vessel (Va-1)	C	-	1			
	Leak in Central channel	C	-	1			
	Loss of SG-4	C	-	1			

	Break of vacuum pipe (Va-1	C	-	1			

4. Design data sheet of the components

During the detailed design Design Data Sheets were prepared with more information of the load cases. Especially the specific load cases of the CNS were specified with pressure - and temperature variation of the systems and components parts. These load cases are now the base for the detailed design. The design data sheet for the Inpile part load cases “Upnormal Operation” are presented for example in table 3.

Table 3:	**Design Sheet** Transient Loads	Sheet: 6/3 Rev.: 0
Identification Coding JBB10, JBB30, JBB40, QKQ20	**Designation** CNS, Inpile Part, Load cases	Plant FRM-II OS-Nr. 8100
Load Cases and Service Levels / References		

No.	Designation	Frequency of Occurrence	Service Level	Diagr. Nr. Diagr. No.	p_{max} bar	Δp bar	t min	t °C	Δt K	t min
2.1.2	Upnormal Operation									
	Loss of cooling with reactor shut down 1)	100 (30a)	B							
	Vacuum vessel									
	Begin				-1			100		
	End				-1	-		50	50	
	Time									1
	Moderator Vessel, Thermosiphon									
	Begin				0,5			-248		
	End				1,5	1,0		100	348	
	Time						1			6
	Heat Exchanger JBB10 AC001 with Piping									
	Begin				3			-248		
	End				9	6		100	348	
	Time						1			60
	Gas Protection Room SG4 SR13)									
	Begin				-1			-248		
	End				-1	-		100	348	
	Time									6
	Loss of Cooling without Reactor Shut Down 2)									
	Vacuum vessel									
	Begin				-1			100		
	End				-1	-		50	50	
	Time									1
	Moderator Vessel, Thermosiphon									
	Begin				0,5			-248		
	End				1,5	1,0		150	398	
	Time						1			3
	Heat Exchanger JBB10 AC001 with Piping									
	Begin				3			-248		
	End				9	6		40	348	
	Time						1			60
	Gas Protection Room S64 (SR13)									
	Begin				-1			-248		
	End				-1	-		150	398	
	Time									3

1) D_2 evaporate in 360 s (conservative)

2) D_2 evaporate in 180 s

5. Choises of the transients for the design phase

The important transients for the CNS are the time depending transient, where cold D_2 of 18 K runs from the inpile part to the connecting systems. The important operation modes are:

5.1 Normal storage of D_2 at the hydride vessels

By this operation mode the reactor stops , while the cooling system of the CNS is running further. After some minutes the cooling system of the CNS is switched off and the D_2 evaporate to the D_2 pipes which lead to the hydride storage vessels. The vacuum insulation of the inpile part is working.

5.2 Breakdown of the cooling system of the CNS

After breakdown of the cooling system the reactor get a shut down signal (RESA) and the D_2 evaporate with the following mass flow, see figure 5-1. There are at maximum 2,5 kg of liquid D_2 in the moderator-vessel inside of the inpile part. The time of the total evaporation lasted nearly 30 minutes.

5.3 Rapid charge of D_2 to the buffer tank with break of the insulation vacuum and flooding of Neon inside of the vacuum volume

In critical situations the operator can press a special button to start rapid reloading of the D_2 to the buffer tank and in the same time flooding of Neon occur.

The mass flows is nearly identical figure 5-1. For comparison a constant evaporation flow of 1.344 g/s was taken into account.

5.4 Reloading of the D_2 from the buffer-tank to the D_2 hydride storage vessel

After loading of the buffer-tank the D_2 shall be loaded than to the hydride storage vessels. The waiting time of the D_2 in the buffer-tank is important before charging the hydride storage vessels, because the piping system is SG2 are cooled down and the charging of the hydride storage vessels shall take place with temperature above 0 °C to prevent freeze up of the heat exchanger placed in the entrance of the hydride storage vessels.

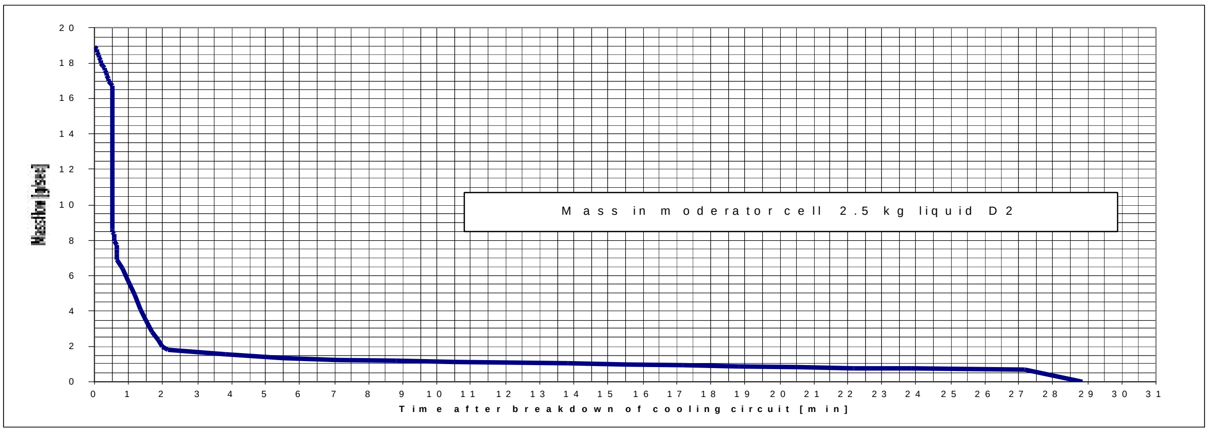

Figure 5-1: Mass flow of D_2 at transfer to the buffer tank
(Breakdown of cooling circuit with reactor shut down)

6. Boundary conditions of the transient analysis

6.2.1 Program description and methodology of the used computer program

For the transient analysis of the CNS the program ESATAN was used.

ESATAN is a comprehensive thermal analysis package based on the lumped parameter formulation. It provides the following capabilities:

- steady state and transient analysis
- one, two and three dimensional models
- conduction, convection and radiation heat transfer
- condensation and boiling heat transfer
- facilities to allow the user to model phase change phenomena

Since its release in 1985 it has been the standard thermal analysis code of the European Space Agency (ESA) and is used throughout the European space industry. An ongoing product development program leads to the release of a new version of ESATAN at approximately yearly intervals, ensuring that the program keeps abreast of evolving industry requirements.

Methodology

ESATAN uses the lumped parameter approach (also known as the network or finite difference approach) in which a structure is discretised into “nodes” with a network of “conductors” linking these nodes. A conductance matrix is determined from this network of “conductors” linking these nodes. A conductance matrix is determined from this network by the program and the resulting set of simultaneous algebraic equations forms the basis of either a steady state or transient analysis.

FORTRAN – like syntax is allowed within ESATAN input files enabling arbitrary algebraic expressions to be used to define non-constant material properties. This can vary from simple interpolation on temperature or time dependent data, through to complex control logic to model, for example, thermostatically controlled devices.

Users can choose the type and method of thermal solution from the selection of solution routines available in the ESATAN library. Alternative and matrix inversion routines are available for steady state solutions. Transient solutions may be obtained from a choice of explicit or implicit routines.

Special Features

- Syntax Checker provides fast verification of the input file syntax and connectivity.
- Submodelling: ESATAN models can be constructed in a hierarchical manner from existing component models. Provides logical model structuring and aids data input preparation through simple methods of model duplication.
- Library facilities are contained in over 130 user selectable subroutines, including:
  - Activation / deactivation of nodes, conductors, and submodels during solution.
  - Radiative conductance calculation for multiple reflections in enclosures.

Quality Assurance

ESATAN is being continuously upgraded. Since its inception strict coding standards have been imposed on the development and structured analysis and design techniques are employed on all extensions to the system. The source code and documentation are strictly controlled and under configuration management.

The supplier is audited to ISO 9001 and has been Tickit certified.

6.2.2 Nodal configuration of the systems and components

The nodal configuration of the D_2-systems begins at the flange of the flexible pipes at the inpile part to go to the protection-gas-vessel SG2, which contains the hydride storage vessels, and than with flexible pipes from SG2 to the buffer tank SG3. The flexible pipes consists of three volume areas, inside the D_2 – gas, than a vacuum insulation volume to minimize the heat transfer to the gaseous cold D_2 (18 K) and a protection gas volume outside.

The nodal configuration is listed up in the figure 6-1.

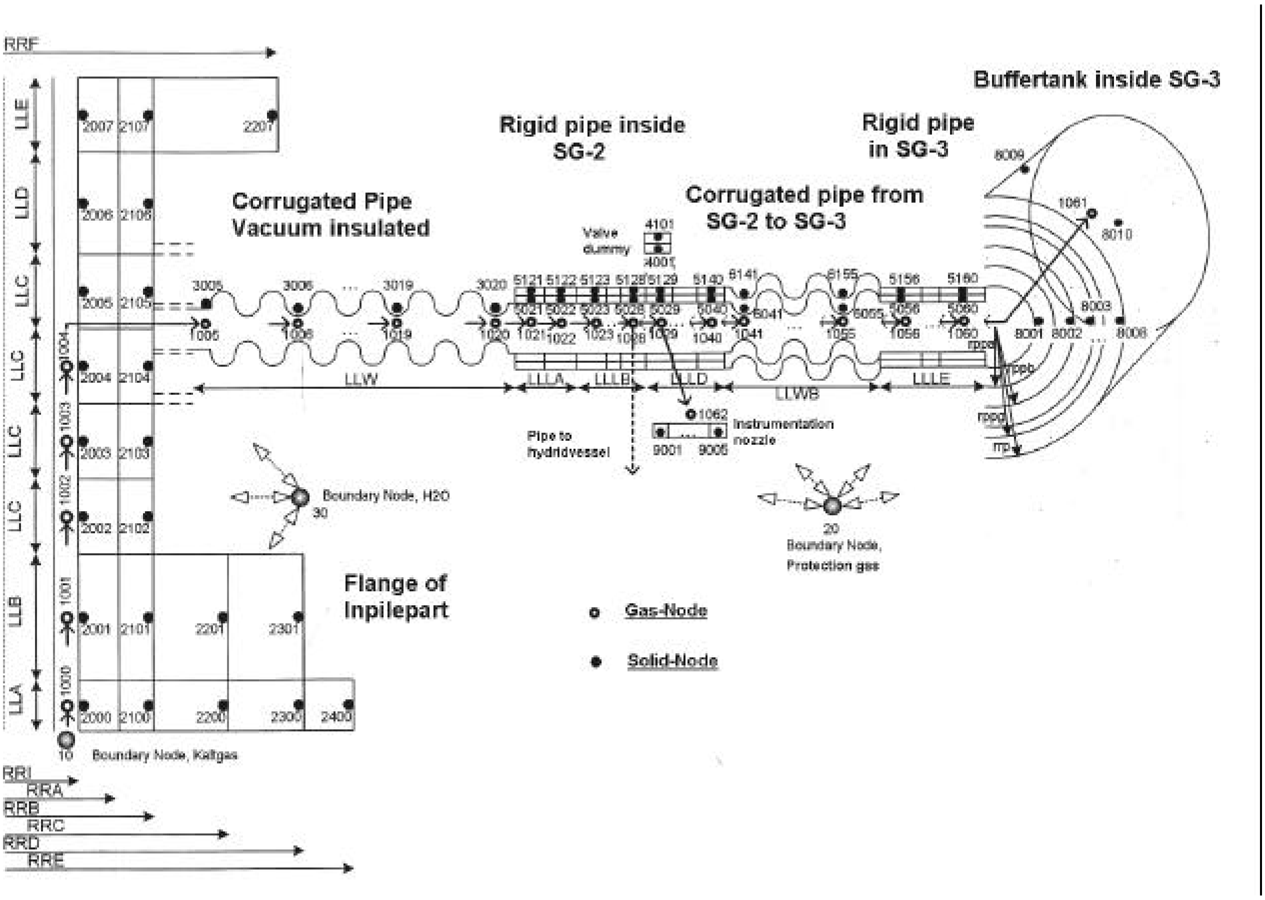

Figure 6-1: Nodal configuration from D_2 outlet at inpile part to the buffer tank

7. Results of the transients in the INPILE PART of the CNS in the moderator tank

For the Inpile part one conservative transient was chosen to covers all transients

- Cooling down from up to 25 K
- Heating up with loss of cooling, full power of reactor at 180 s and than reactor shut down.

The time dependent temperature curves are shown in figure 7-1 for the middle of the vacuum and moderator vessel.

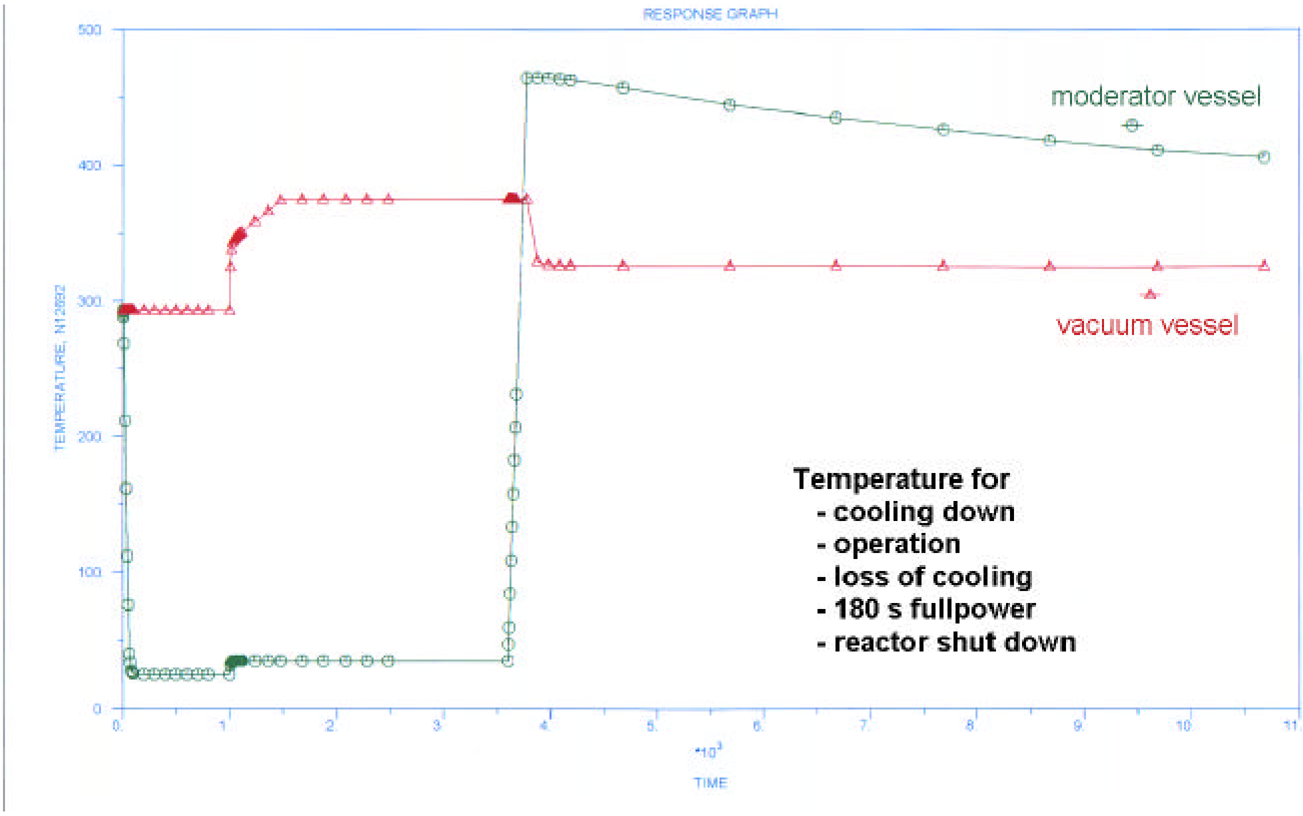

Figure 7-1: Vacuum and moderator vessel - middle part
Time dependent temperature curve

8. Results of the transient curves of the load cases in the systems

8.1 Normal storage of the D_2 at the hydride storage vessel.

The normal storage of D_2 from the inpile part to the hydride storage vessels can take place with a mass flow of $\leq$ 0,23 g/s. The mass flow is produced from a heat supply in the liquid D_2 of nearly 70 W. The loading of the hydride storage vessels takes ~ 3 h. The criteria of the maximum allowable heat supply in the liquid moderator vessels is to prevent a temperature lower 0 °C in the piping system to the hydride storage vessel after the valves JBB10 AA101/AA001.
A freeze up of the heat exchanger in the entrance of the hydride storage vessel can be excluded.

8.2 Break down of the cooling system of the CNS (Transfer of the D_2 into the buffer tank)

The temperature transients of the D_2 gas from the inpile part to the buffer tank are shown in figure 8.2-1. The temperature of the piping systems are shown in figure 8.2-3.

The gas temperature at the flange of the inpile part drops down to -230 °C and is identical the gas temperature of the D_2 at the inlet of the vessel SG2.
The temperature of the pipe inside of the SG2 are at the inlet part –175 °C and the outlet of SG“ at -170 °C, the inlet of the buffer tank are at –160 °C. The deuterium in the buffer tank is above –20 °C.

8.3 Rapid loading of the D_2 into the buffer tank with break of the insulation vacuum and flooding of Neon into the vacuum volume

The results of the rapid loading of the D_2 in the buffer-tank with flooding of Ne into the vacuum chamber is above the results of figure 8.2-1 and 8.2-3. A comparison to the calculation with a flow of figure 5-1 was done with a constant evaporation flow of 1.344 g/s, see figure 8.2-2 and 8.2-4. The results shows that the constant evaporation gives softer transition curves.

8.4 Reloading of the D_2 from the buffer tank to the D_2 hydride storage vessel

The temperature curves of the reloading of the D_2 from the buffer tank to the D_2 hydride storage vessel was calculated for the mass flow of figure 5-1. The transient and the expecting temperature at the piping crossing point to the storage vessel is shown in figure 8.4-1. After a waiting time of 10 min in the buffer-tank the loading of the hydride storage vessels can take place.

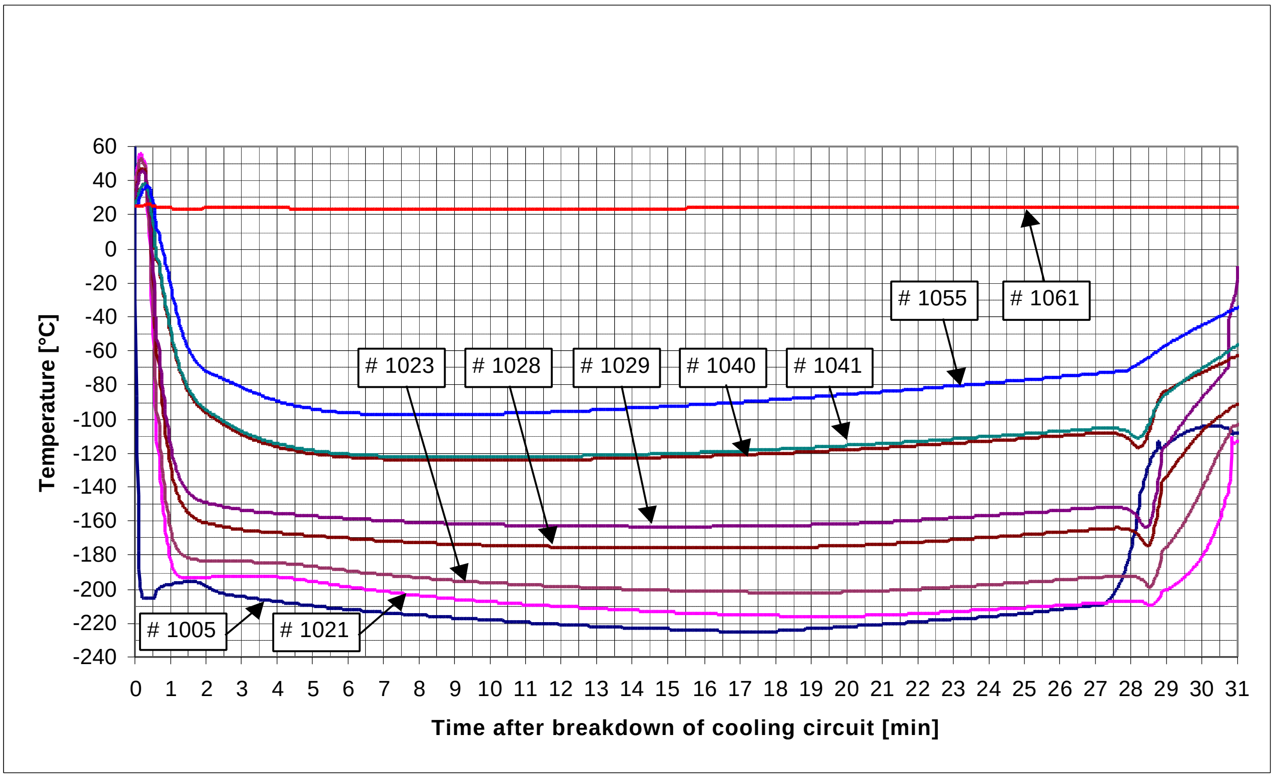

Figure 8.2-1: D_2-temperature at transfer to the buffer tank (Breakdown of cooling circuit with reactor shut down, dm_{D2}/dt = 19,0 g/s)

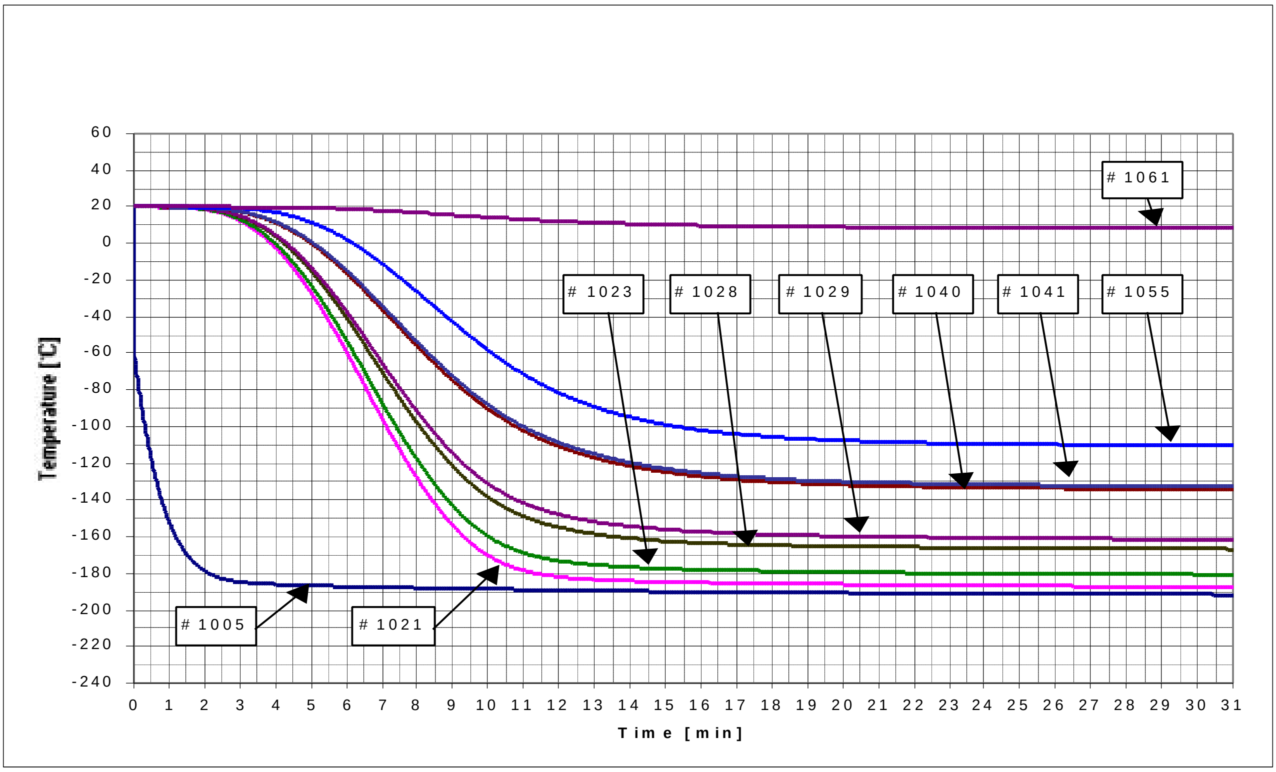

Figure 8.2-2: D_2-temperature at transfer to the buffer tank (Constant mass flow of 1,344 g/s)

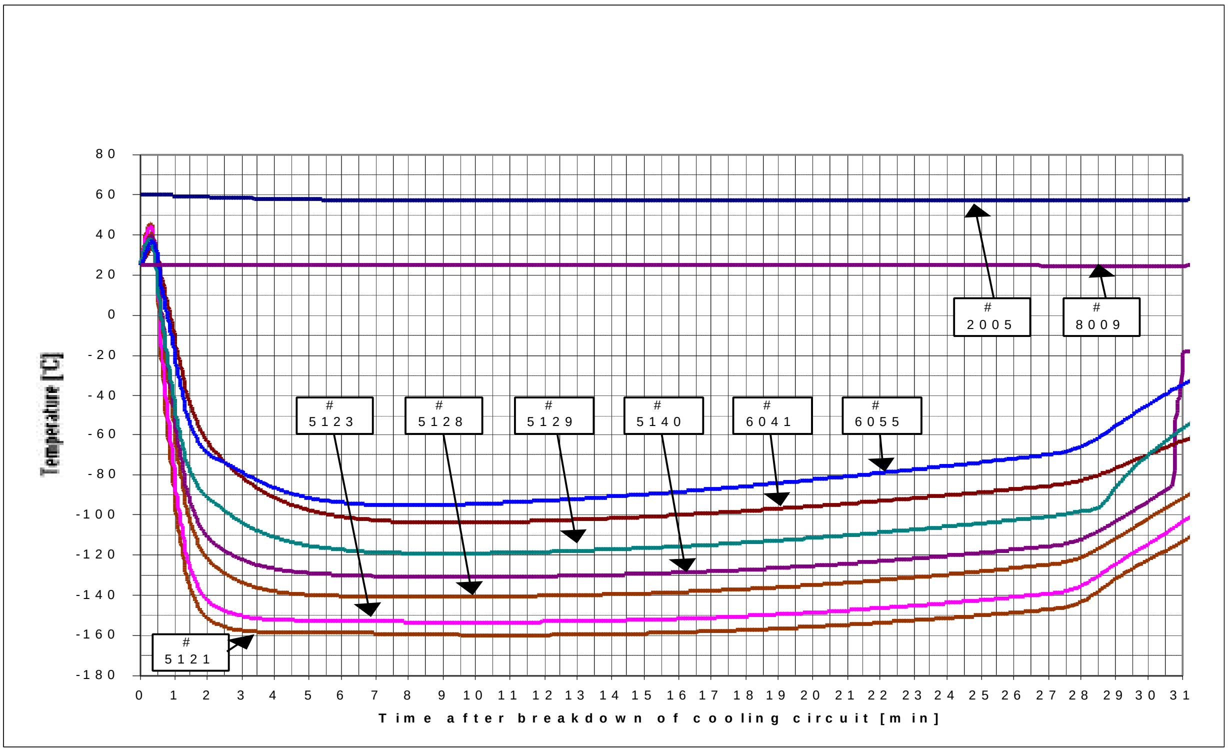

Figure 8.2-3: Temperature of the piping system at D_2-transfer to the buffer tank (Breakdown of cooling circuit with reactor shut down, dm_{D2}/dt = 19,0 g/s)

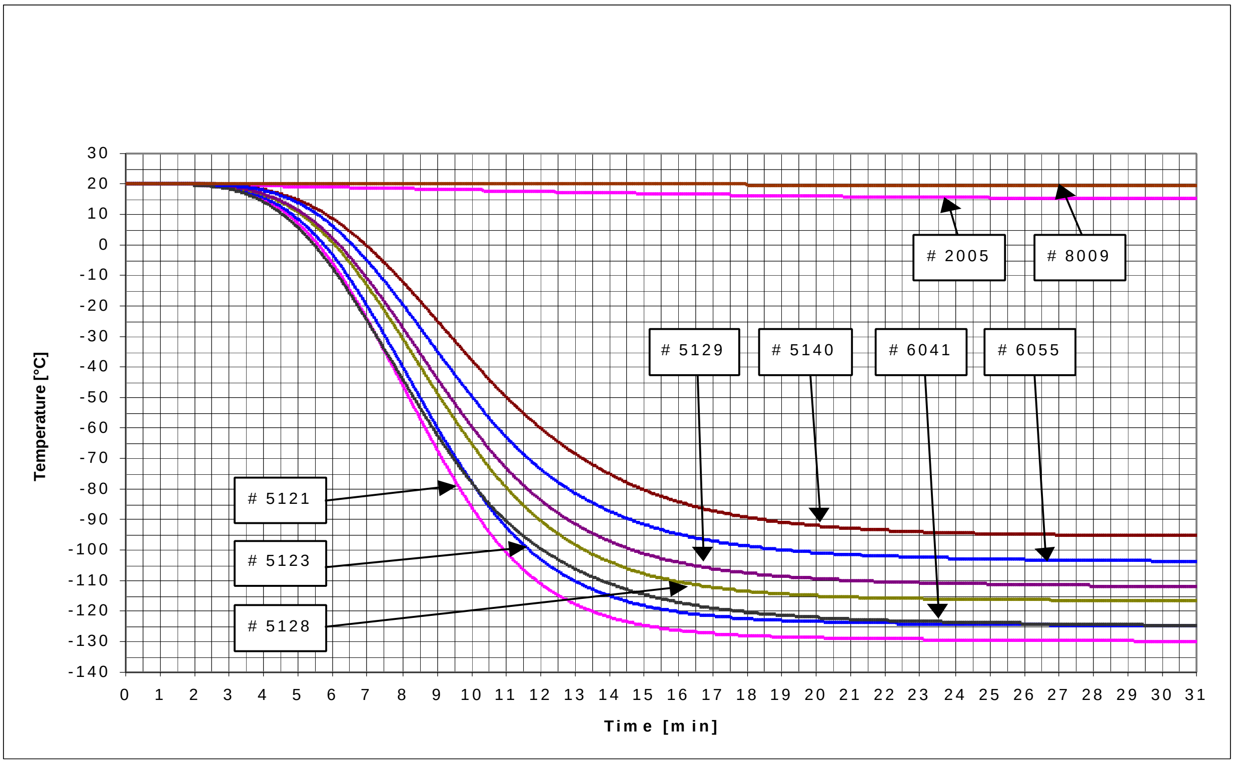

Figure 8.2-4: Temperature of the piping system at D_2-transfer to the buffer tank (Constant mass flow of 1,344 g/s)

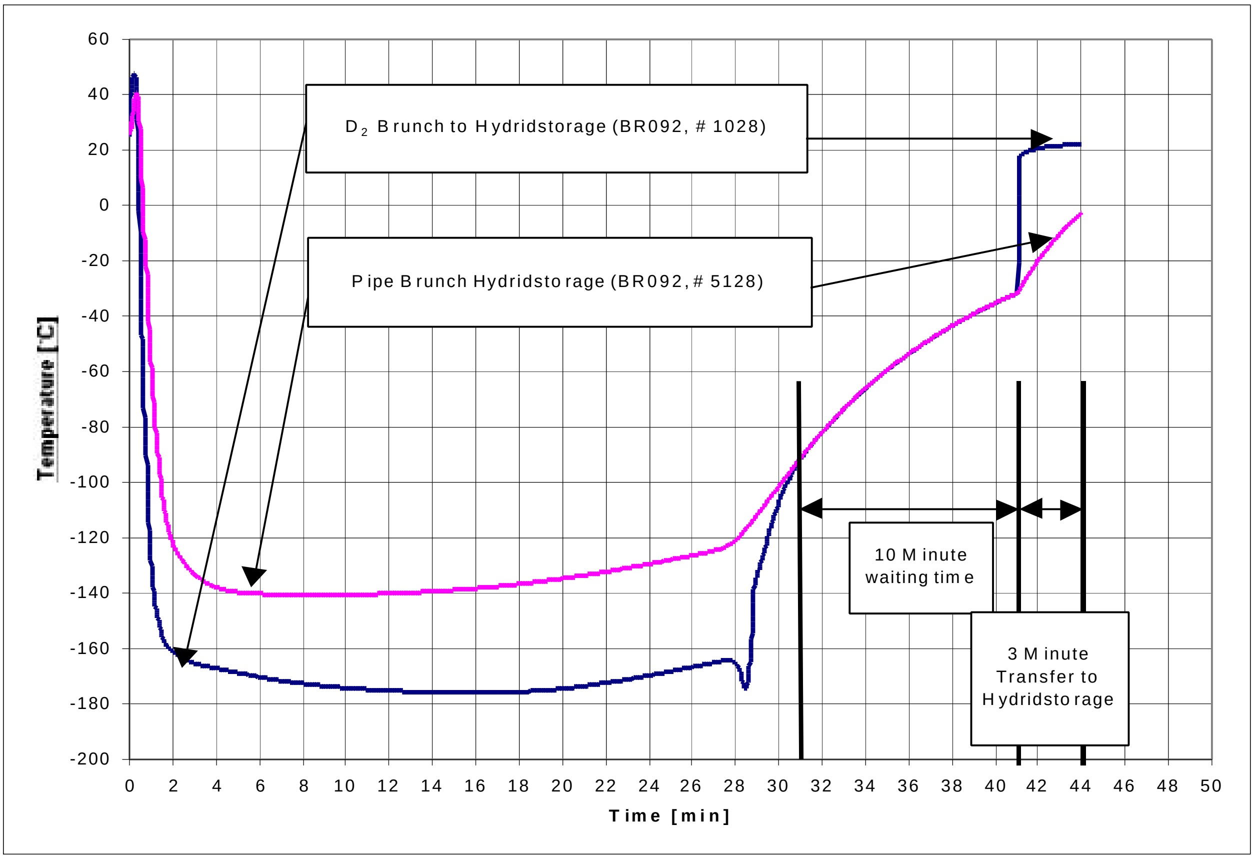

Figure 8.4-1: Recharging of the D_2:
Transfer from the buffer tank to the hydride storage vessel
(Breakdown of cooling circuit with reactor shut down, dm_{D2}/dt = 19,0 g/s)

8.5 Result of the temperature distribution in the flange region in the piping system

In the piping systems of the flexible pipes two different flange connections was used, a welding neck flange and a flexible flange.
The nodal configuration of the welded neck flange is pointed out in figure 8.5-1 and the temperature distribution in figure 8.5-2 and 8.5-3. The maximum temperature difference between the bolts and flange parts are 55 °C, the best fit calculation gives 46 °C, see figure 8.5-2. This maximum was reached after 1,5 minute starting the transient, the lowest temperature in the flange near the cold D_2 are –95 C.
The temperature difference in the flange region is important for the leak tightness of the flange connection with the choiced gaskets.

The nodal configuration of the lapped flange connection is showed in figure 8.5-4 and the temperature difference in figure 8.5-5 and 8.5-6. The maximum temperature difference between the bolts and the flanges are 46 °C, the best fit calculation gives 20 °C, see figure 8.5-5.

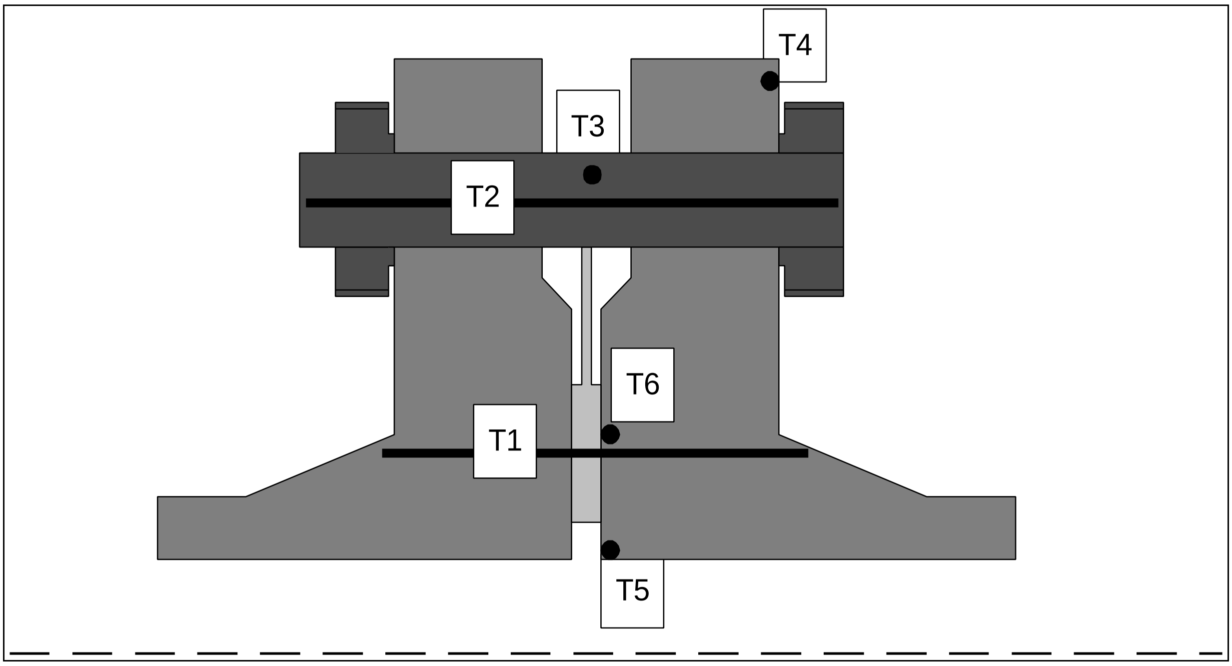

Figure 8.5-1: Nodal configuration of two welded neck flange

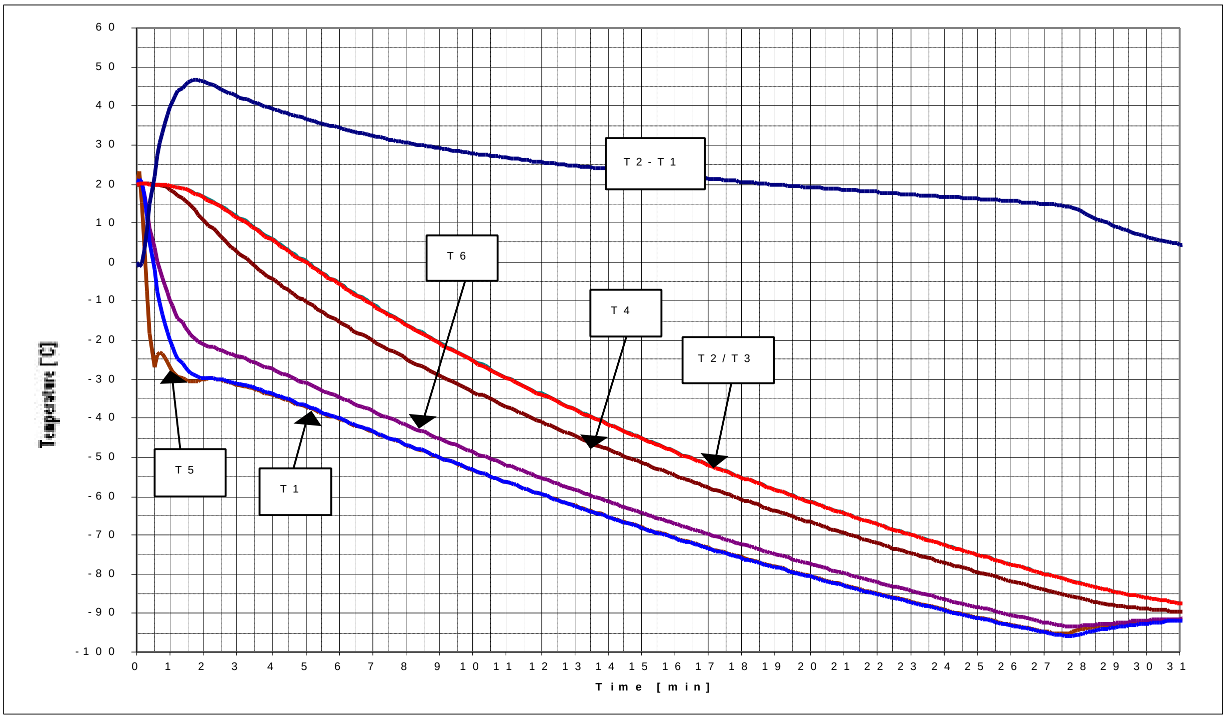

Figure 8.5-2: „Worst case“ temperature in welded neck flanges
(Breakdown of cooling circuit with reactor shut down)

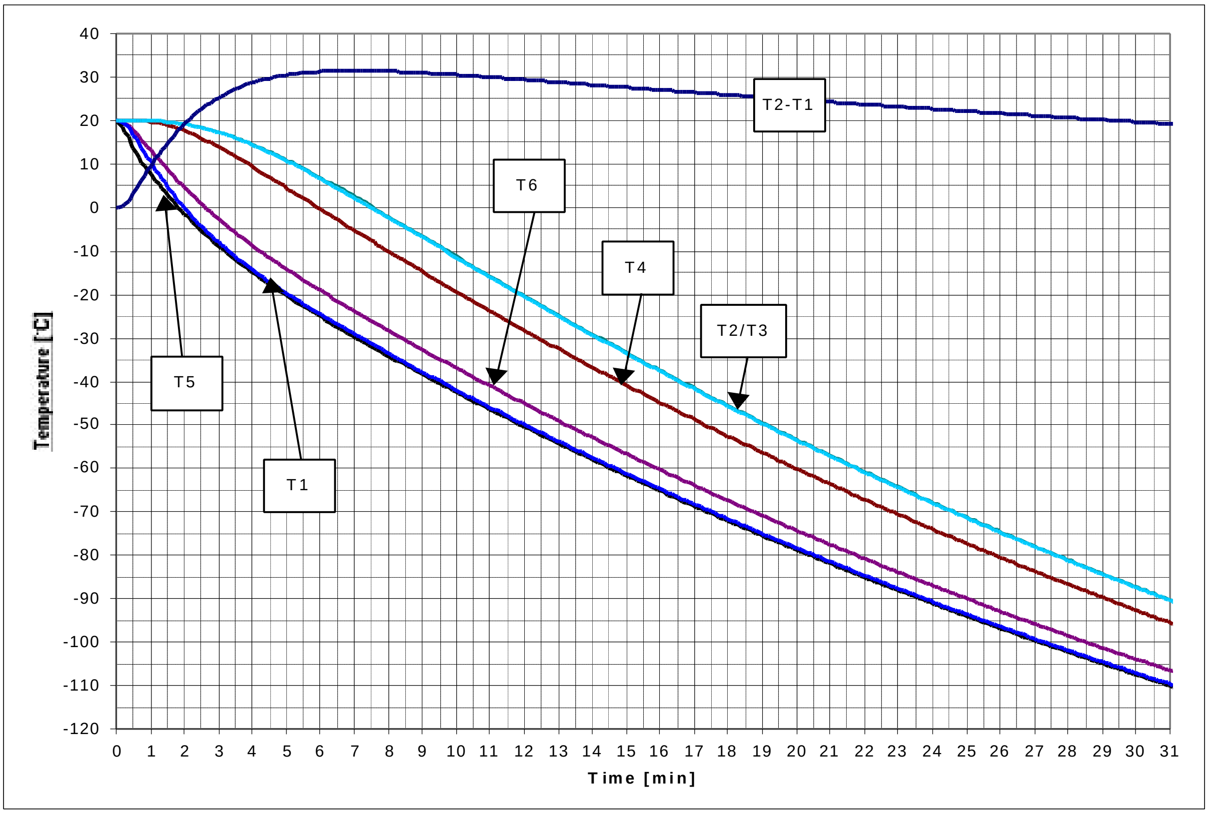

Figure 8.5-3: „Worst case“ temperature in welded neck flanges (Constant mass flow of 1,344 g/s)

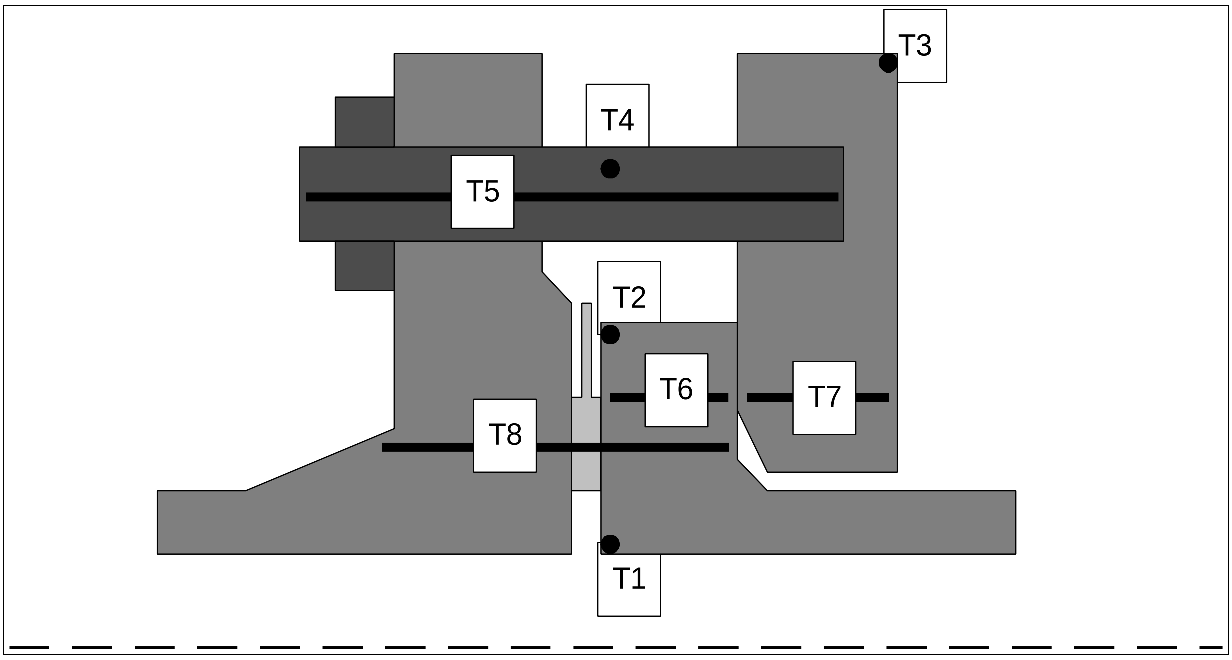

Figure 8.5-4: Nodal configuration of welded neck flange and lapped flange

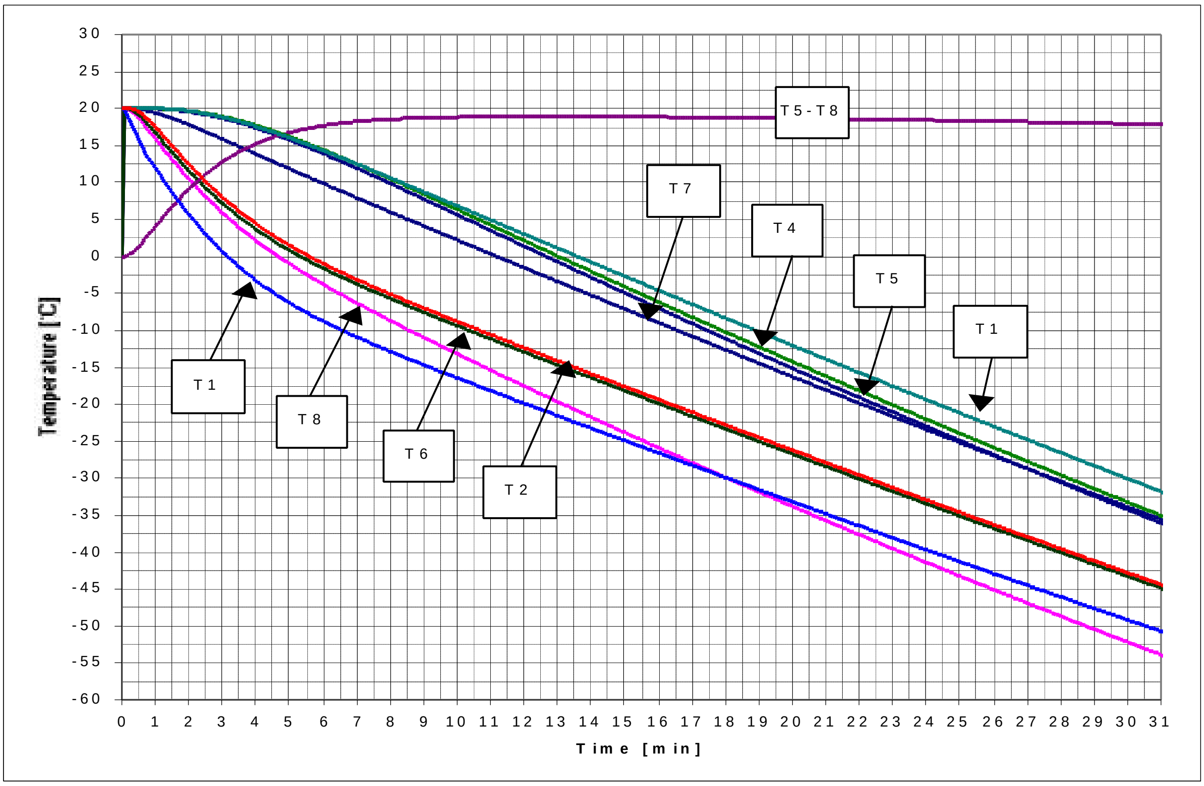

Figure 8.5-5: „Worst case“ temperature in lapped flange
(Breakdown of cooling circuit with reactor shut down)

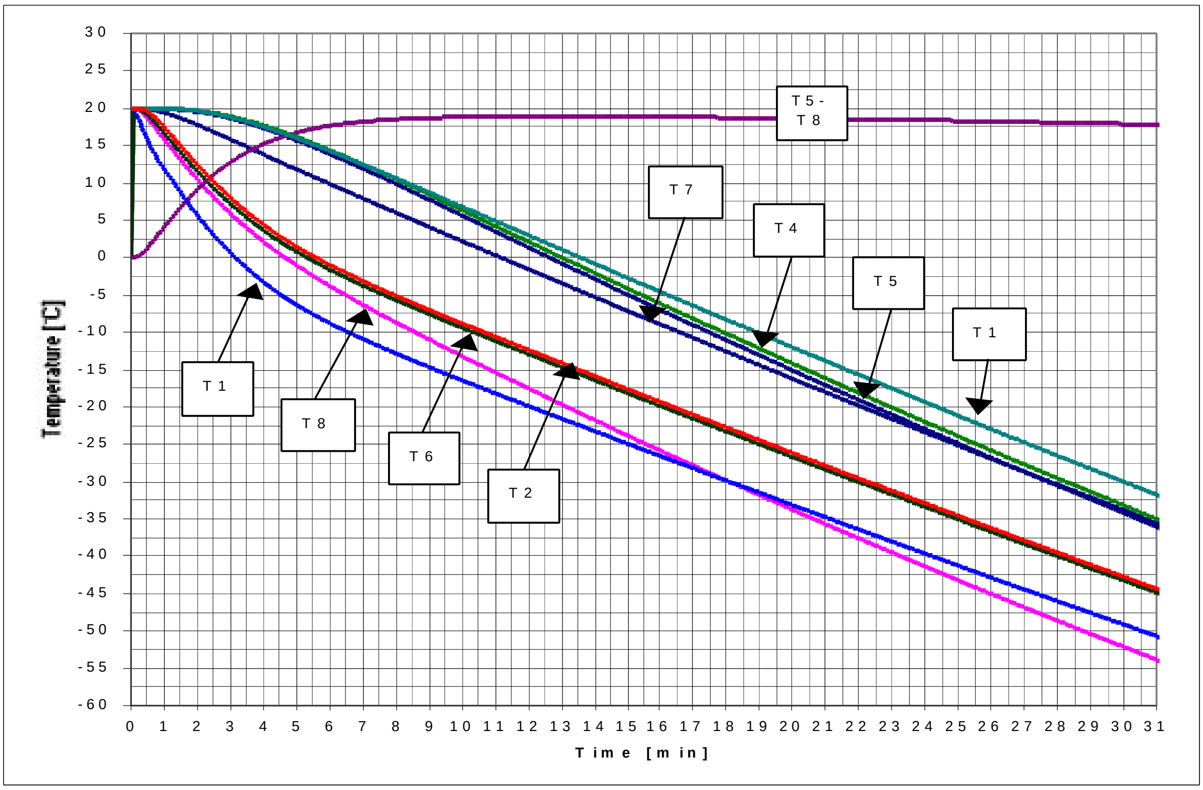

Figure 8.5-6: „Worst case“ temperature in lapped flange
(Constant mass flow of 1,344 g/s)

8.6 Result of temperature distribution the valves

The nodal configuration of a valve type in the piping line to the buffer tank are shown in figure 8.6-1.
The temperature distribution in the area of the valve seat sealing is show in figure 8.6-2 for a constant mass flow of 1,344 g/s and for 19 g/s (see mass flow figure 5-1).

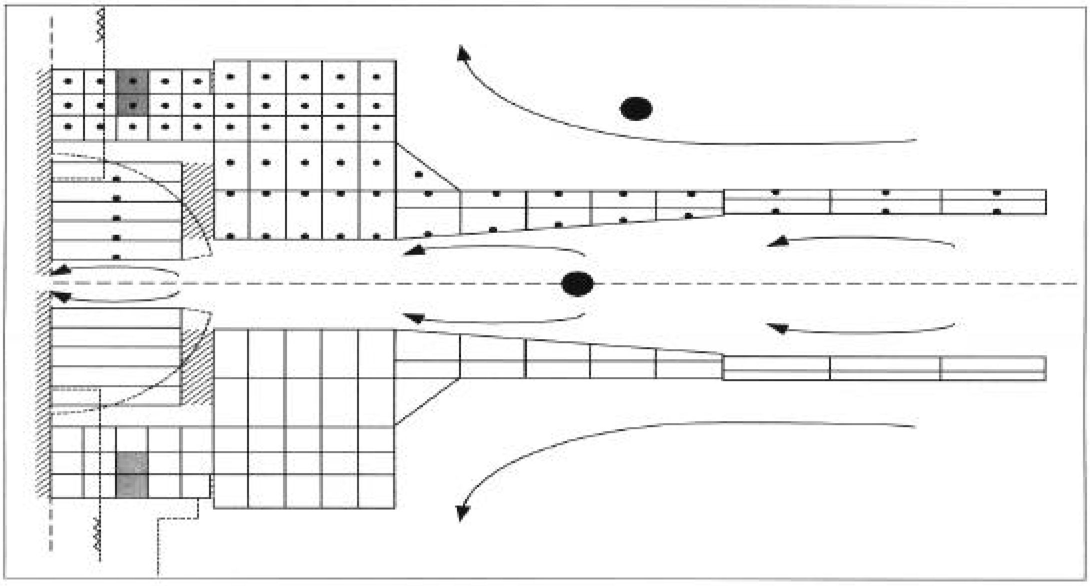

Figure 8.6.1: Nodal configuration of the valve JBB10AA102

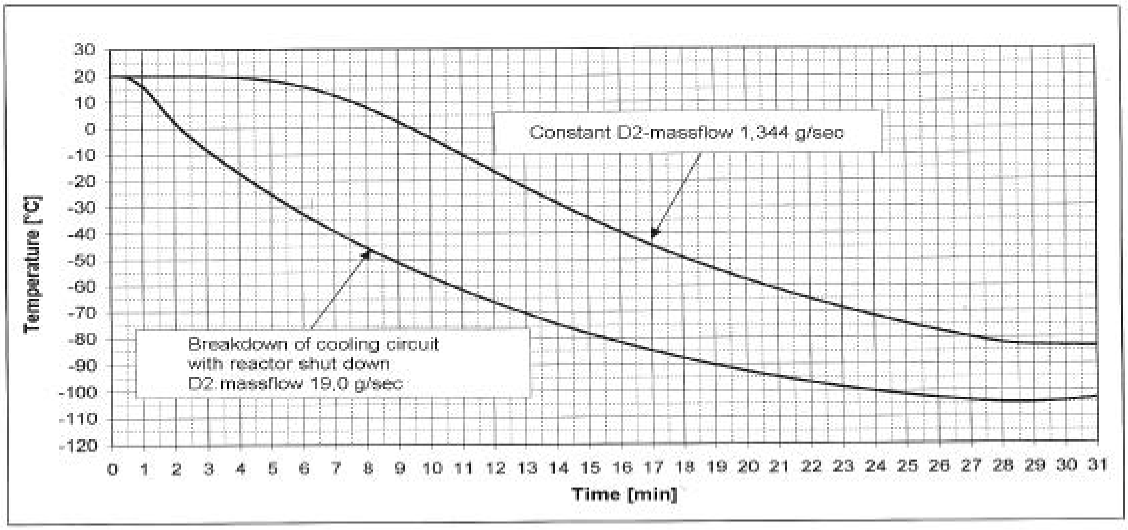

Figure 8.6.2: Temperature distribution of the ball valve in the region of the valve shaft sealing

9. Design of the components

9.1 Result of the stress analysis in the inpile part

The results of the stress analysis with respect to the choiced transient are listed up in table 4.

Table 4

Moderator vessel	**Primary stresses**		**Secondary stresses**	
	σ_{rises} / MPa	$\sigma_{allow.}$ / MPa	σ_{rises} / MPa	$\sigma_{allow.}$ / MPa
Weld upper cone to cylinder part	25	50	27,5	150
Base material bottom part	48	78	59,5	234
Weld in cylinder	33,3	50	38,1	150
Vaccum vessel	7,1	129	12,2	387

9.2 Design of the rigid piping system in the SG-2

For the design temperature of the rigid piping system with the supports in the Vessel SG-2 a temperature of –196 °C was take into account.

9.3 Design of the flange parts in the D_2-line from inpile part to the butter tank

The design data of the flanges in the D_2-line from inpile part to the buffer-tank are shown in table 5.

Table 5: Design data

			SG2 to SG3	**Inpile to SG2**
D_2-Pipeline	Design Pressure	Inner pipe	3,0 bar / 13,0 bar	3 bar / 13 bar
	Design Temperature		60 °C	80 °C
	Design Temperature		-191 °C	-191 °C
	Test Pressure		20,0 bar	20,0 bar
	Working Pressure		0,5 bar	0,5 bar
	Working Temperature during transients see Fig.	Flange Bolts	-40 °C 20 °C	-30 °C 20 °C
Protection Gas Pipeline	Design Pressure	Outer Pipe	13,0 bar	13,0 bar
	Design Temperature		60 °C	80 °C
	Test Pressure		20,0 bar	20,0 bar

With the results of the transient analysis we have chosen for the design temperature differences between the flange and the bolts of 60 °C or 50 °C.
The flanges were calculated on base of the German nuclear rules KTA 3211. For the flange calculation the TUEV flange calculation program "FLABOL" was used, which calculated the following steps:

- Design and Testing Conditions Level O, P
- Design of operation Level A, B
- Design to the temperature transients Level A, B

including the pressure, external forces and the sealing parameter. The important point in the design of the flange connection is beside the mechanical design the leak tightness for all load cases.

In the parameter study, which can be done with the computer program very quickly, the optimization of the sealing parameters were calculated; so the leak tightness can be guaranteed (see table 6).

Table 6

Sealing flanges between SG2 to SG3					
		Assembly condition	**Operation A/B**	**Testing P**	**Transient DT 60 °C**
Min.	N/mm²	37,2	33,7	34,2	22,4
Max.	N/mm²	62	58,2	58,9	47,4
Min. required	N/mm²	15	15	15	15

9.4 Design of the valve

For the design of the valves body a design temperature of –196 °C was used. For the leak tightness in the stuffing box special cold test were done. The results shows that the leak tightness can be guarantee up to temperature of –150 °C, which covers the expected lowest temperature of –110 °C, see figure 8.6-2.

10. Temperature measurements during first operation and validation of the transient analysis

For the first operation of the CNS temporary temperature measurement points were installed (see figure 10-1).

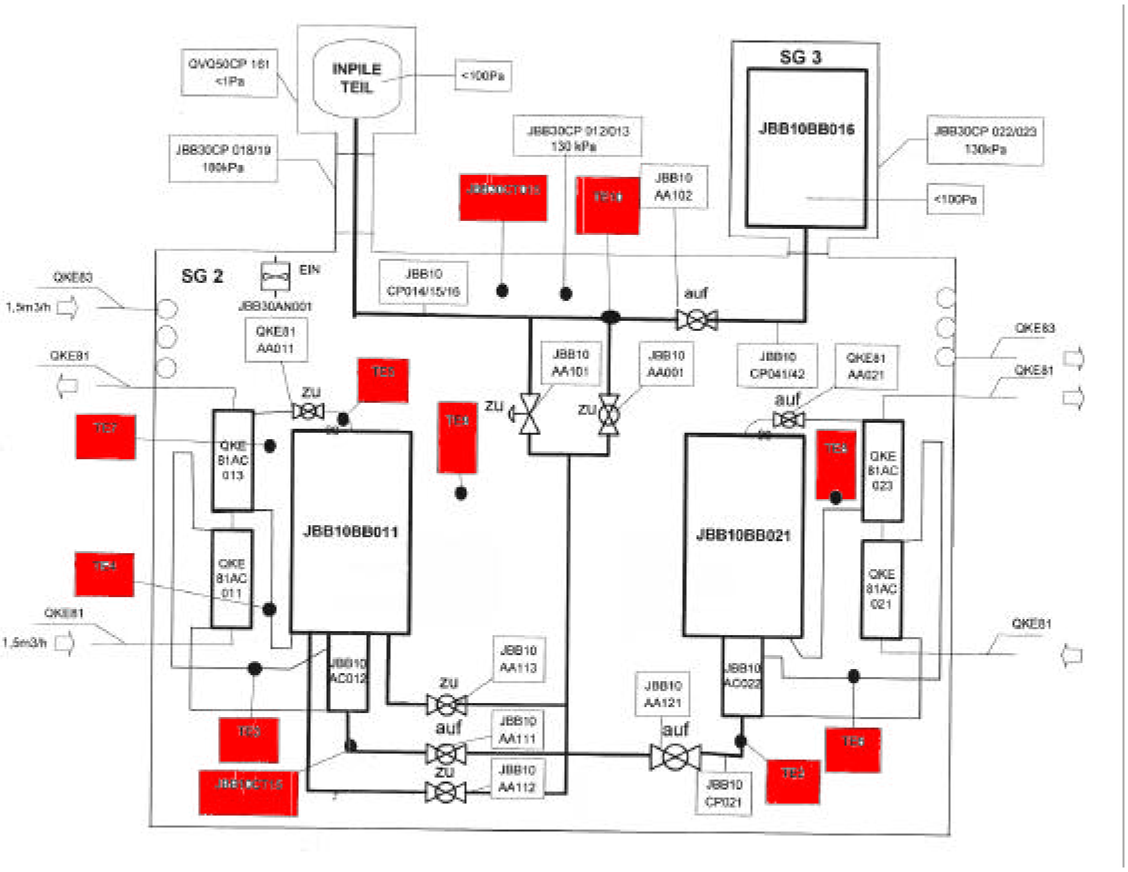

Figure 10-1: Cold Neutron Source
Temporary temperature measuring points during first operation

At time there are no temperature measurements available because the relevant tests wasn't done at time. The results will be presented at IGORR 9 meeting.

11. Summary and Conclusions

The transients of the CNS were analysed. The results of the analysis shows the timely temperature variations in the systems and in the walls of the components and give information of the lowest expecting temperatures and temperature differences. These results were taken over to the design phase. With temporary measurements temperature during the first operation of the CNS a validation of the calculation shall be examined

The results of the mechanical design of the inpile part and the connecting systems and components and experimental test of the valves shows a fulfilment of the specification requirements.

The conclusion is that a transient analysis of CNS with cold mass flows must be analysed in conceptual design phase to give a good base for the detailed design.

12. Documents

/1/ Cold Neutron Source Specification
Nr. KS D 8100.0010

/2/ Design Data Sheets Cold Neutron Source 6/1-6/6
Transient analysis

/3/ KTA 3211.2 Issue 06.1992
Pressure- and activity retaining components connecting to primary circuit
Part 2: Design, Construction and Calculation

/4/ AD-Merkblatt B7 Issue 06.1986 Bolts
AD-Merkblatt B8 Issue 02.1998 Flanges

/5/ DIN EN ISO 3506-1 Issue 03.1998
Mechanical Properties of corrosion resistant stainless steel fasteners
Part 1: Bolts

/6/ VDI 2230 Part 1 Issue 07.1986 and Issue 11.1998 Draft
Systematic calculation of high duty bolted joints
Joints with one cylindrical bolt

/7/ EM-ESATAN-056
Engineering Manual

/8/ TÜV Rheinland
Flange Calculation Program “FLABOL”

/9/ ADINAT / ADINA 7.3.1
ADINA R & D, Inc.