Air liquide cryogenic system for the KSTAR device

Briend P., Dauget P., Delcayre F., Abe I., Fauve E., Fossen A., Fuenzalida P., Lee L.A., Gistau G.[(*)], Kim Y.S.[(**)], Cho K.W.[(**)], Chang H.S.[(**)]

Air Liquide, Advanced Technology Division, B.P. 5, 38360 Sassenage, France
[(*)] Consultant, 44 chemin de la Buisse, 38330 Biviers, France
[(**)] Korean Basic Science Institute, Yeoeun-Dong, Yusung-Gu, Taejeon, 305-333, Korea

The cold components of the KSTAR tokamak require forced flow of supercritical helium for magnets/structure, boiling liquid helium for current leads, and gaseous helium for thermal shields. The cryogenic system should provide stable operation and full automatic control. A three-pressure helium cycle composed of six turbines has been simulated. A design operating mode defined by an exergy approach results with a system composed of a 7 kW refrigerator, using gas and liquid storages for mass balancing. During Shot/Standby mode, the heat loads are highly time-dependent. A thermal damper is used to smooth these variations and will allow stable operation.

INTRODUCTION

The tokamak developed in the KSTAR (Korean Superconducting Tokamak Advanced Research) project makes intensive use of superconducting magnets operated at 4.5K. The purpose of this discussion is to give a brief overview of the proposed cryogenic system for the KSTAR tokamak. This paper begins by quantifying the thermal loads of the refrigerator in the normal modes of operation and by describing the thermo-dynamical and process approach leading to the refrigerator design power. Also included is a discussion of the main results of the process calculations in the two main modes (Idle and Shot/Standby). An explanation of the main process control principle of the refrigerator follows.

DUTIES OF THE REFRIGERATOR AND DESIGN MODE

The cryogenic system will provide safe and stable operation and full automatic control to accommodate both normal operating modes and abnormal events. Normal operating modes occur in 24-hour cycles and involve the annual cooling/warming of 250 tons coils and structures. Ramp, Shot, Standby, De-Ramp, and Idle are examples of operating modes. Abnormal events include quenching, plasma disruption, and vacuum disclosure.

The dedicated VINCENTA code [1], [2] details the heat loads and liquid helium consumption related to the various tokamak operations. Table 1 summarizes these results. The Isothermal Refrigeration power @ 4.4K includes the heat loads due to both the supercritical helium circulation and the components of the DVB (distribution valves box). These heat loads are estimated from the preliminary design of the system. The equivalent refrigeration power varies between a maximum value of 9 kW in Shot/Standby mode and a minimum value of 5 kW in Idle mode. Designing the refrigerator regarding only the maximum case would lead to an oversized system. Therefore, a mean value of refrigeration power, approximately 7 kW, is selected as the design operating mode.

Table 1 Cryogenic System Duties in Normal Operation

Heat Loads	**Operating Modes**		
	Shot / Standby 8hrs/day	Idle 14 hrs/day	Ramp / De-Ramp 2 hrs/day
Thermal Shields @ 55K-75K	18 kW	18 kW	18 kW
Isothermal Refrigeration @ 4.4K	5.4 kW	2.6 kW	4.8 kW
LHe to current leads	23 $g.s^{-1}$	19 $g.s^{-1}$	20 $g.s^{-1}$
Total Refrigeration Power equivalent @ 4.5K	**9 kW**	**5.7 kW**	**8 kW**

The excess refrigeration power in Idle mode is used to produce liquid helium (LHe). LHe production is routed to a rising-level storage. In Shot/Standby mode, the lack of refrigeration power is balanced by liquid helium withdrawal. At the same time, the equivalent amount of gaseous helium fills gas cylinders at ambient temperature.

Table 2 gives the helium mass balance of the two main modes: Shot/Standby and Idle. In Shot/Standby mode, the process is close to that of a pure refrigerator whereas in Idle mode, the process is 50% liquefaction. Therefore, a careful study of the refrigeration system design is necessary to determine the optimal component that will be capable of satisfying a wide range of operations.

Table 2 Helium Mass Balance

Balance Components	**Operating Modes**	
	Shot/Standby	Idle
Total Refrigeration Power	7 kW	7 kW
LHe to current leads	23 $g.s^{-1}$	19 $g.s^{-1}$
Liquid Helium production	2 $g.s^{-1}$	32 $g.s^{-1}$
% Refrigeration	97 %	54%
Liquid Helium storage	-21 $g.s^{-1}$	+13g. s^{-1}

HELIUM CYCLE DESCRIPTION

The following description is related to the Shot/Standby mode and is illustrated by Figure 1. To simplify this discussion, the letters HX and T refer to a heat exchanger and a turbine, respectively. The convention used for referring to Figure 1 during this description employs **(1)** for corresponding to (1) on Figure 1 and so on. The HP (high pressure) helium (995 g/s) is cooled down to 188K in the counter-current heat exchanger HX1. At the outlet of HX1, the flow rate is divided into two flow: one to the turbines T1/T2 (148 g/s) and the other dedicated to the colder turbines **(1)**. At the cold end of HX6, the helium HP flow is at 55K, part of which (220g/s) is dedicated to the thermal shields**(2)**. Flow from the thermal shields is expanded in T3. Through HX7 / HX8 / T4, the helium gas is cooled down to 21.7K**(3)**. The next exchanger section (HX9 / HX10 / T5) cools HP helium gas from 21.7K to 12.8K**(4)**.

At about 20K, neon and hydrogen impurities are trapped in an adsorber. The expanded flow rate (634 g/s) at medium pressure in T2, T3, T4 and T5 is warmed in MP (medium pressure) circuits (HX1 to HX10) and sent to the MP compressor suction. Most of the remaining flow (291g/s) is expanded to 2.6 bar through T6, cooled down to 4.55K through HX12, and poured in LHe storage at 1.3bar[5].

The remaining HP flow is sent to the SC (superconducting) bus lines[6]. LHe storage feeds the current leads circuit and the thermal damper in the DVB (distribution valves box)[7]. The TD (thermal damper) is dedicated to absorb 4.4K refrigeration loads (5346W). The low pressure helium vapor at 1.19 bar is warmed and sent to the low pressure suction of compression station[8]. In Idle mode, the circulators in the DVB are stopped. The required tokamak supercritical helium flow rate is taken at 3 bars at the T6 outlet.

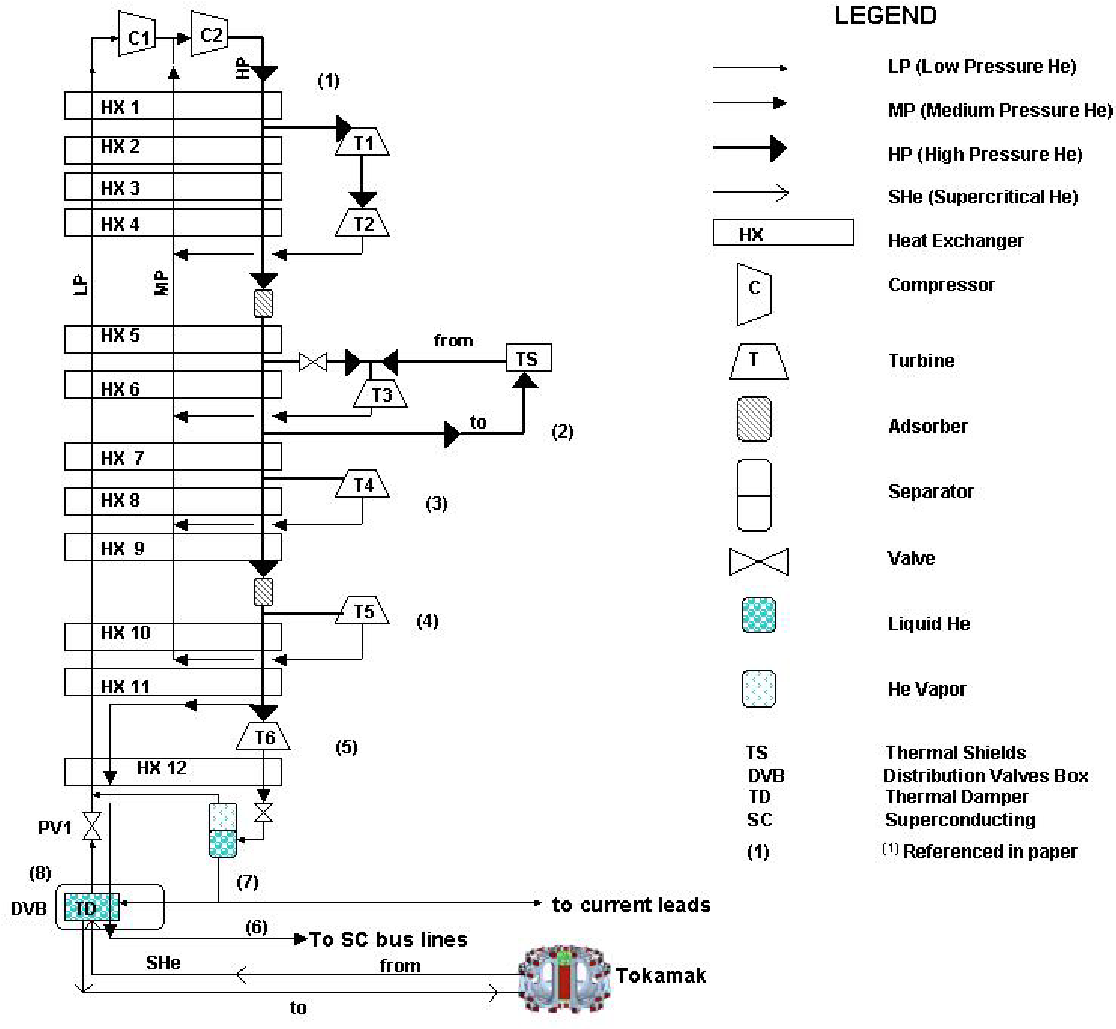

Figure 1 KSTAR Helium Cycle Process Flow Diagram

PROCESS CONTROL

One of the key control points of the refrigeration unit is the stable operation of the refrigerator coupled with the time-dependent heat load. The time-dependent heat load shown in Figure 2 is a result of the periodic and unsteady Shot/Standby operation mode of the tokamak. The main target of the control procedure is to keep the cold vapor flow rate constant when returning to the cold box. Using the PV1 control valve to maintain a given set point of the LP pressure will provide a constant mass flow rate to the volumetric LP compressor. The heat balance in the damper is the sum of the energy deposit from thermal loads minus the exhausted energy from both the vaporization and evacuation towards the cold box. The flow control will allow either the storage or the release of energy in the thermal damper and will thus ensure the stability of the refrigeration system.

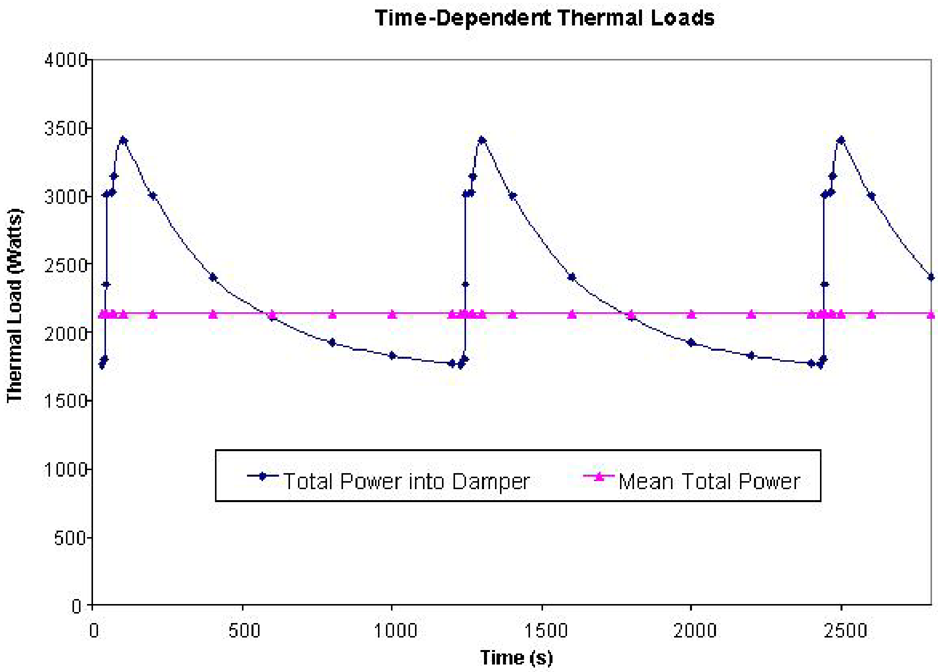

Figure 2 Shot/Stand-by Mode: Total Transferred Power into the Damper vs. Time

CONCLUSION

A helium cycle consisting of three pressure settings and six turbines has been simulated for the KSTAR cooling requirements. A design operating mode has been selected using an exergy approach. The result is a 7 kW constant power refrigerator and the use of gas and liquid storages for mass balance. The time-dependent heat load deposit from the tokamak during Shot/Standby mode is buffered into a thermal damper. A flow control method is proposed and will allow a very stable operation of the refrigerator.

REFERENCES

1. Kim Y.S. et al, Design of the Cryogenic System for the KSTAR Device, Proceedings of the Twentieth International Cryogenic Engineering Conference Beijing, China (2004) 20

2. Chang H. S. et al., Design Issues in the Distribution Valve Box of the KSTAR Helium Refrigerator, Proceedings of the Twentieth International Cryogenic Engineering Conference Beijing, China (2004) 20

3. Alekseev A., SINTEZ Final Report Review on Structural and Thermal Stability of The KSTAR Magnet System , Saint Petersbourg , Russia (2002)