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A Modular Approach to the Design of Cold Moderators

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Abstract

Cold moderators are usually designed to the specific requirements of the parent neutron source. However since all cryogenic moderators within a broad design envelope require certain common parameters, it should be possible to create a central core design served by smaller packages designed, or selected to satisfy a wide range of individual requirements. This paper describes a modular design philosophy that has been applied to two very different cold sources with only minor changes to two of the modules in the system. Both of the systems and the basic differences between them are described in detail.

Applications

Two major projects are under way at the Oak Ridge National Laboratory. One is an upgrade program for the High Flux Isotope Reactor (HFIR) and the other, with the collaboration of four other 'U.S Department of Energy' national laboratories, is the design, and planned, construction of a Spallation Neutron Source (SNS). Both will require cryogenic moderators to provide high fluxes of cold and very cold neutrons. In each case hydrogen at supercritical pressure was chosen for the moderator material to avoid two phase flow problems normally associated with a lower pressure. A typical flow diagram (HFIR system) is shown in figure 1.

The HFIR moderator is situated in a very high radiation area, close to the reactor core which produces a heat load in the cryogenic hydrogen and the aluminum alloy moderator vessel. The total heat load is about 2.2 kW and has to be removed by the supercritical cryogenic hydrogen, (@15 bars,17K) which is circulated at a flow rate of 1 L/s. A 3-dimensional thermal-hydraulic 'CFD' analysis of the moderator vessel was carried out to determine the flow requirements and the vessel configuration to provide the necessary energy removal. A thorough stress analysis was also carried out to optimize the vessel design for minimum material mass. In addition, a potential manufacturer of the vessel was consulted for input on machining and fabrication considerations in order to achieve an overall optimal design.

The 'SNS' spallation source has two cryogenic moderators each of which represents a heat load of 1 kW. These moderators are coupled together in a series configuration requiring one moderator to have a mean temperature about 1.5 K lower than the other. However, the series configuration gives better flow control than a parallel arrangement, allowing full flow to both moderators without a complicated balancing valve system.
Since the HFIR & SNS systems represent a very similar overall heat load, the basic hydrogen loops and automatic control systems are of similar design. Although each system has very different basic design characteristics and installation requirements it was found possible to use an identical basic cryogenic design with identical major component modules. It is not implied that a common design philosophy can be applied to all cold moderator requirements, but careful design can result in a modular system encompassing a broad operating spectrum which is scaleable to function in other similar systems. The majority of successful cold moderator systems use the passive thermo-siphon principle thereby eliminating an active pumping system. This is classically simple in operation and is, to some extent self regulating. However such a system requires careful planning of transfer line routes which usually tend to be larger than those needed for mechanically circulated systems. On the other hand active systems normally operate best with a single phase fluid (vapor or liquid). This requires the hydrogen to be pressurized, to allow it to be circulated as sub-cooled liquid, or in a supercritical phase. Operation under this scenario requires that all hydrogen in the loop has to be of high density and safety considerations dictate a careful consideration of the overall hydrogen inventory. However, there is an over-riding requirement for the cooling of the moderator vessel walls. Unless this is independently provided by a separate cryogenic loop, cooling will depend totally on the neutron moderating hydrogen flow. Future cold moderator systems are likely to be required to operate in higher radiation fluxes (therefore energy) that will require fluid flows not easily achievable with a thermo-siphon system. Also shielding demands are likely to become more challenging, making remote handling of active components more difficult. This will tend to make the more compact active circulated system a more natural choice for most applications. The availability of more reliable circulators, installed redundancy and the ability to replace a failed circulator on line will help eliminate safety and operational concerns.

What is modular

In the present context, modular is defined as a complete cryogenic system designed around a system of core units (modules) that contains those basic components that are common to a wide range of cold moderator applications. An example is the pump module. Supporting sub-systems which could differ with the application, are grouped into smaller modules: the gas handling module, purge module, vacuum stations, and standby module. Each module and its function are described later and table 'A' lists individual components. The extent of modular breakdown is a question of judgment and could vary with development, but in addition to the obvious advantage of flexibility it improves maintenance operations. It should be relatively easy to localize system problems to a specific module and to effect servicing without the need to spoil the entire vacuum

system.
Other items, such as transfer lines and even the refrigerator, could also be referred to as modules since they operate as functional packages whose purpose can be identified and redesigned. The refrigerator in this case can be switched into a standby mode to function passively at a level sufficient to keep the temperature of the moderator vessel within safe limits. Transfer lines could suit other applications with a change in length only.
The moderator vessel assembly is very specific to the particular application, but can also be described as a module.

Specific Applications

The HFIR upgrade and the SNS projects are different applications, but both have been satisfied by using a basically identical cold moderator system and modifying only two of the modules. For safety reasons a secondary inert blanket surrounds all hydrogen bearing regions over the entire system providing double containment of ambient temperature areas and triple containment of cold vacuum insulated areas.

The HFIR Reactor Cold source

The HFIR cold moderator will produce a continuous flux of cold neutrons are least equal equal in brightness to any currently available sources. The moderator is situated very close to the reactor core and a heat load of 2.2 kW is generated in it, 75% of this being deposited in the aluminum alloy material. Ref. figure 2. A design flow of 1 L/s is needed to provide vessel cooling. This flow-rate is provided by a high density cryogenic circulator. To ensure continuous operability, this system module contains an identical backup (or redundant) spare circulator. This spare is under automatic control to be activated if circulation failure is detected. Both circulators are independently electrically driven centrifugal cryogenic pumps. They have no rotating seals as the motor operates in ambient temperature hydrogen gas that is directly connected to the cold loop. Either one can be isolated from the loop, blown down to atmospheric pressure, evacuated and filled with dry helium gas through a purging system. It is then possible to replace a faulty circulator without breaking the double containment philosophy.

The moderator vessel is cylindrical with a hemispherical end and a flow smoothing inlet and outlet flared section. A roughly elliptical shape between the flow and return ways is the cold neutron viewing area that illuminates three divergent beam guides providing cold neutrons to the scattering instruments. The vessel shape is designed to optimize the conflicting requirements of good coolant flow characteristics, low mass and acceptable stress levels, while providing good neutron moderation and minimal beam interference.

The critical pressure of hydrogen is approximately 13 bar abs and the system includes gas handling equipment designed to maintain a higher pressure than that at all times. For safety reasons the system can be operated in a standby state to allow the reactor to continue at full power (but without cold neutron production) in the event of a cold source failure. This is achieved by cooling a lower density hydrogen gas with liquid nitrogen and increasing the circulation rate to 2.25 L/s. A separate lower power circulator provides enough hydrogen flow to hold the aluminum moderator vessel in a safe condition.

The main hydrogen loop and all enclosed systems (including vacuum and inert blankets) are protected against positive pressure excursions by rupture discs and relief valves that are vented to a nitrogen purged manifold before being released to the atmosphere through an elevated stack .

The SNS Spallation source cold moderators

The spallation source will require two cold moderators placed above the mercury target. These are coupled together in a series configuration to allow a single refrigerator and hydrogen loop. This means that the first moderator in line has an average temperature about 1.5 K cooler than the other; however, full flow through each ensures adequate cooling. The total heat load is 2kW which is very close to that of the HFIR system but the installation geometry is very different. However, the main cryogenic systems are similar in most aspects as described below. Ref. figure 3.

Individual modules

i) Pump Module

(High Flux Isotope Reactor - HIFR)

This module is the heart of the system and incorporates the heat exchanger that interfaces the hydrogen loop with the refrigerant, all three circulators, double valving for the circulators, three pressure and temperature sensor systems and the loop pressure interface vessel. The stainless steel containment housing is about 8 feet in diameter and 4 feet tall and is double walled to incorporate part of the inert gas blanket. A flow diagram is shown in figure 4.

(Spallation Source - SNS)

This is virtually identical to that for the HFIR but the appendage that contains the low density (standby state) circulator has been removed and blanked off. Instead it is planned to develop a variable geometry circulator (in which the effective thickness of the impeller can be changed by a stepper motor that axially moves the entire rotor and shaft assembly). Together with speed adjustment this allows a single circulator to cover both normal and standby operational requirements. It also allows infinite adjustment of the flow during cool-down by causing the power drawn by the main electric motor to remain constant as fluid density increases. This should result in greatly improved stability and smoother transitions between normal and standby states.

ii) Refrigerator (HFIR & SNS)

The refrigerator selected is an 'off-the-shelf' design (which uses helium as the refrigerant with liquid nitrogen pre-cooling), up to five screw compressors and four reciprocating expander engines provide a maximum power of 3.5 kW at 20K. It will operate at the maximum power required for normal operation (approximately 2.5 kW) plus a small contingency which will be finely controlled by an electrically powered control heater. A special feature allows the helium refrigerant to bypass the expanders and cool the hydrogen directly using the liquid nitrogen pre-cooler, this is termed the standby state. No compressors are required in that condition as helium flow will be provided by an auxiliary gas circulator. No temperature control is required since temperatures would be limited by the liquid nitrogen. This makes the standby state available over a wide range of system failures. Since the refrigerator is considered an independent module, alternative refrigerator choices would be workable.

iii) Transfer lines (HFIR & SNS)

The transfer line design will be similar for both applications, differing only in length. The transfer lines are made from spirally convoluted stainless steel tubes. A concentric pipe configuration is used, which minimizes heat loss and transfer line footprint. This transfer line design is easily transported in long lengths and expansion/contraction of the cold inner tubes, due to temperature differences, are self compensating. The main line is a five-concentric-tube design for flow-vacuum-return-vacuum (with multi-layer insulation) -inert gas blanket (the two vacuums are interconnected). A second transfer line connects the refrigerator to the pump module. This is similar in design, but since the transport fluid is helium gas it does not require the outer helium tube. The concentric pipe arrangement is shown in figure 5.

iv) Gas handling system (HFIR & SNS)

The gas handling system is in three parts and is shown schematically in figure 6:

- A large double walled hydrogen storage vessel which allows the system to reside at a uniform pressure of 4 bar abs under total shutdown conditions.
- A hydrogen gas transfer pump that raises the main loop pressure to 14 bar abs at the start of a cool-down and maintains this pressure by adding gas from the storage tank.
- A vacuum vessel that contains the hydrogen feed vessel and all valves associated with the ambient temperature gas handling system.

At the start of a cool-down, gas is drawn from the storage vessel to raise the loop pressures to 14 bar abs. As the gas cools and its density increases, the loop supercritical pressure is maintained. Under operating conditions the storage vessel is reduced in pressure to a partial vacuum. The loop pressure is controlled thereafter by opening the inlet valve from the feed vessel, or the return valve to the storage vessel in response to the hydrogen loop automatic control system. The inert blanket for the gas handling system is low vacuum rather than helium gas. This is a safety measure since the main storage vessel operates at partial vacuum under normal conditions. It also provides insulation when cold gas is admitted to the storage vessel during system shut-down. This mode of operation reduces the overall hydrogen inventory since the majority of it is utilized in the loop. If an application did not require such a mode of operation it could be replaced by a more appropriate system.

v) Purge module (HFIR and SNS)

The purge module comprises a helium gas vessel containing the purge pump and valves. This module allows either of the high density circulators to be isolated, blown down, evacuated and filled with dry helium for replacement. The module also includes relief systems to protect sections of piping that could be isolated by the closure of two valves at the same time. The module will also allow initial purging of whole hydrogen system. The circuitry of this module could be changed considerably to suit specific requirements. The outer housing comprises an integral part of the inert blanket system.

vi) Vacuum modules (HFIR & SNS)

The HFIR system has three (3) separate vacuum systems and the Spallation Source two (2). These provide insulation for the following sections of the loop:

- The moderator assembly – this is separated from the rest of the loop to limit contamination in the event of a failure.
- The pump module, heat exchanger and transfer line

The HFIR has the following additional vacuum system:

- The transfer line between the point of entry through the wall of the reactor building and the moderator vessel assembly.

Each vacuum system is maintained by a vacuum station which comprises a helium housing that containing isolation valves, a turbo pump and a backing pumps. The housing comprises a part of the inert blanket system but is designed to allow quick replacement in the event of failure, without breaking the double containment philosophy. Each vacuum system is equipped with a gas analyzer to monitor for leaks of hydrogen or helium and a pressure relief system to protect the vessel from overpressure. Ref. figure 7.

vii) Vent system (HFIR & SNS)

Although the hydrogen operates in a closed loop, it is pressure protected by relief valves and rupture discs in the event of a pressure excursion. The vacuum and inert blanket systems are also protected from pressure excursions above 3 bar abs. More vulnerable components are housed in a safe room that is constantly ventilated. A hydrogen sensor in the ventilation system initiates a rise in flow rate to the equivalent of one air change/min. All rupture discs, relief valves and vacuum pump exhausts are fed to a common vent manifold that is maintained at 1.5 bar abs with a nitrogen gas purge. In the event of the operation of a relief system the manifold exhausts into a dedicated elevated vent stack. Ref. figure 8.

viii) Control system (HFIR & SNS)
The control system is PC based using readily available software and hardware. It controls the gas handling system and cold moderator operating conditions. It also monitors the circulators and initiates changeover if an operating circulator malfunctions. In extreme cases it is capable of deriving a signals to initiate reactor scrams. The control system will have built-in redundancy and an automatic transition will be initiated in the event of a control system problem. The refrigerator is set up to operate at its maximum anticipated power requirement and a control heater in the helium line substitutes for the power of the reactor. When the reactor is started, power in the control heater is reduced until the system is in equilibrium. The temperature control is not required during standby operation since the minimum temperature is limited to 77K. The high flow (but lower density) circulator is used during cool-down and a control sensor in the heat exchanger limits the temperature of the heat exchanger to avoid freezing of the low density hydrogen. When the temperature reaches about 50K, the control system switches temperature control to a sensor in the main feed line. It is ultimately planned to allow the control system to transition the system into standby automatically in the event of a cold loop problem.

ix) Moderator Vessel Assembly
This will always be specific to the application, but in many cases its design will have an impact on the configuration of one or more of the other modules.

(HFIR)
This comprises the moderator vessel which is mounted inside a vacuum chamber. The complete assembly is shrink fitted into the beam tube and the cryogenic lines are passed through the rear beam collimator section.
The complete assembly is about 13'-0" long and replacement would be a major task. Ref.figure 9.

(SNS)
The two moderator units are mounted into a vertical circular plug, which is replaced as a complete unit. However the moderator assembly can be replaced in a hot cell though it is unlikely that it could be serviced and is regarded as dispensable. Ref. figure 10.

x) Standby service module (HFIR & SNS)
This is a single walled vacuum chamber that is outside of the inert blanket. It contains a helium circulator used for the standby state, isolation valves and bypass valve. It also contains the main loop temperature control heater.

Conclusion

By the substitution of one or more modules, the entire system can be reconfigured to operate over a wide range of requirements. Within the modules themselves specific components, such as circulators, could also be readily substituted without major design or structural changes. Overall, the modular philosophy could not only minimize design effort, but offers the advantage of using a proven system that has already undergone development and operating stages.

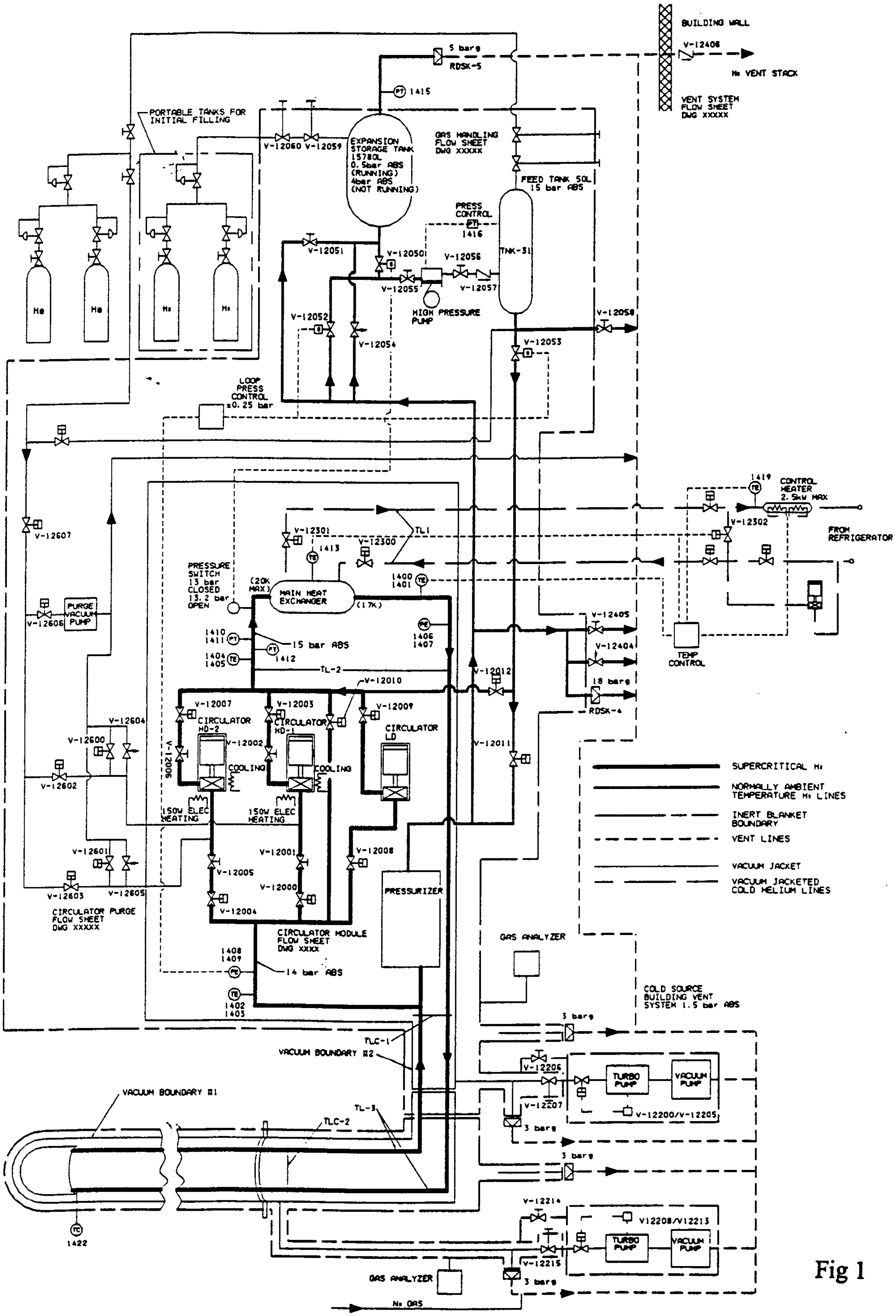

Fig 1

Flow Diagram of HFIR Cold Source system

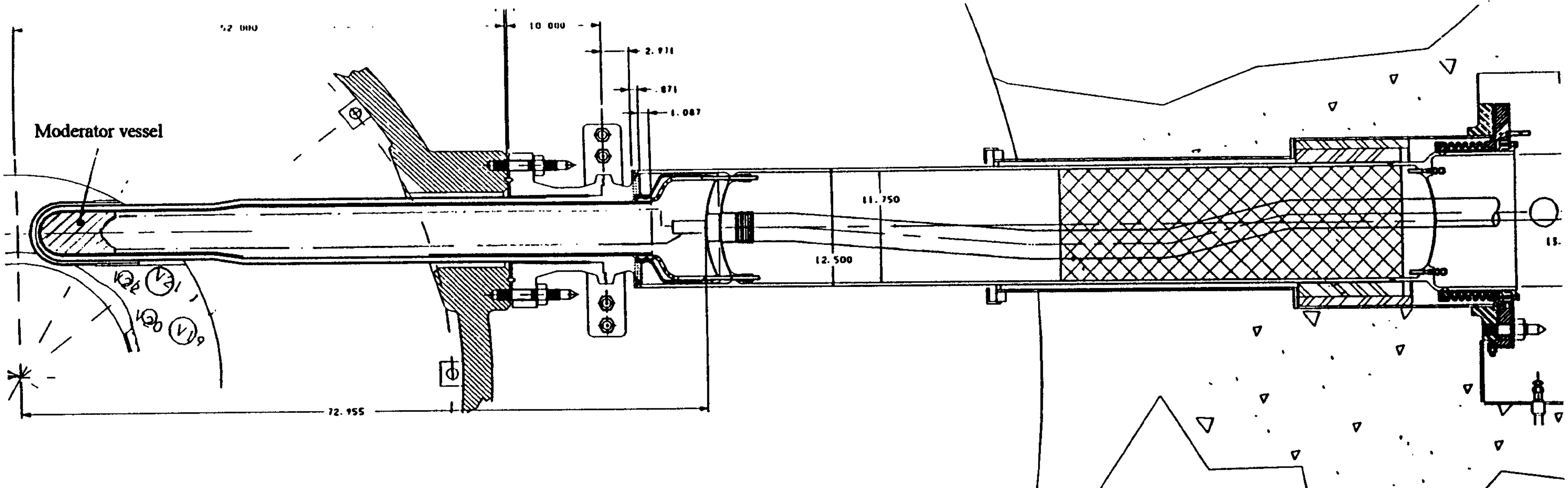

Fig 2

HFIR cold source installation

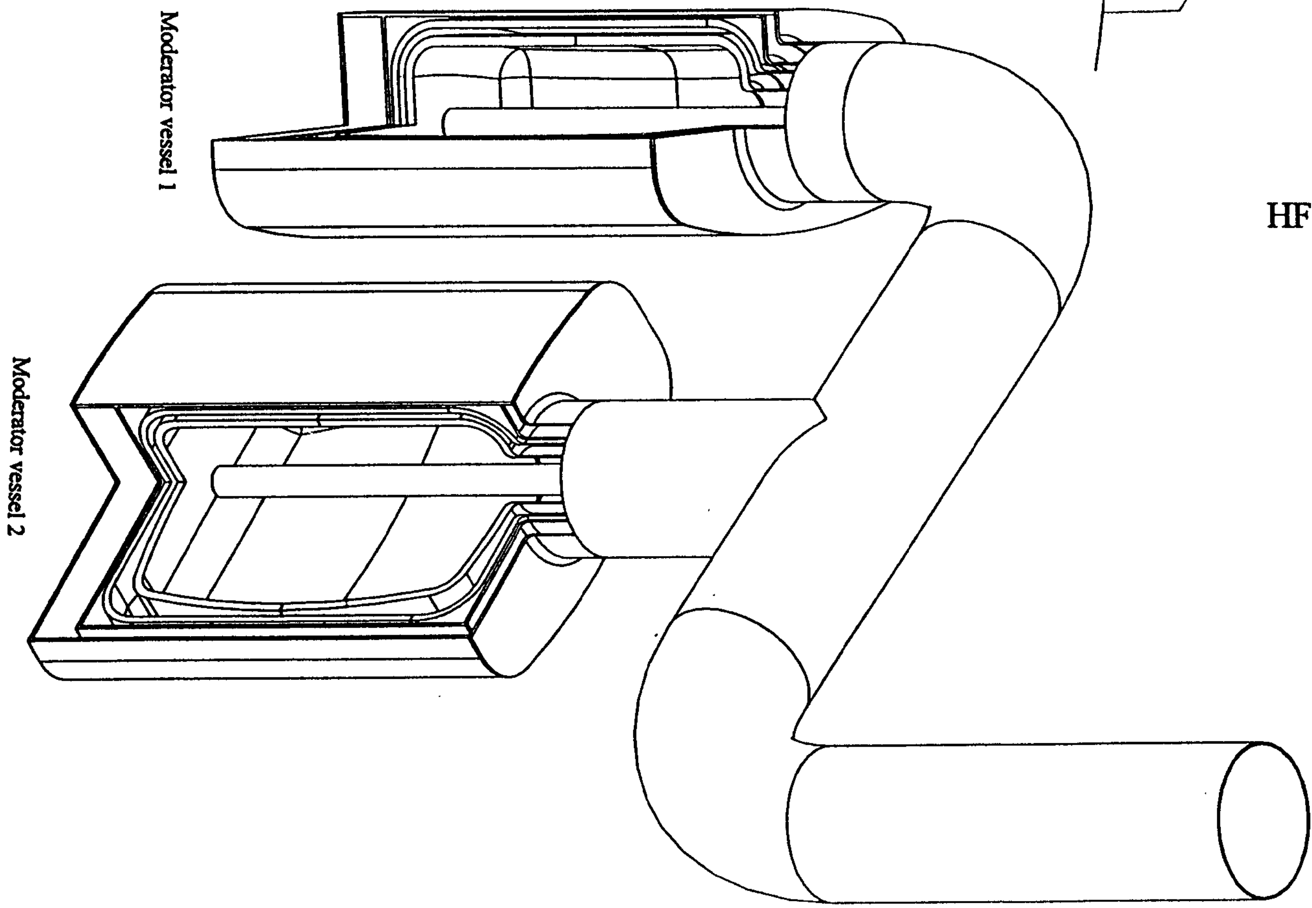

Fig 3

SNS moderator arrangement

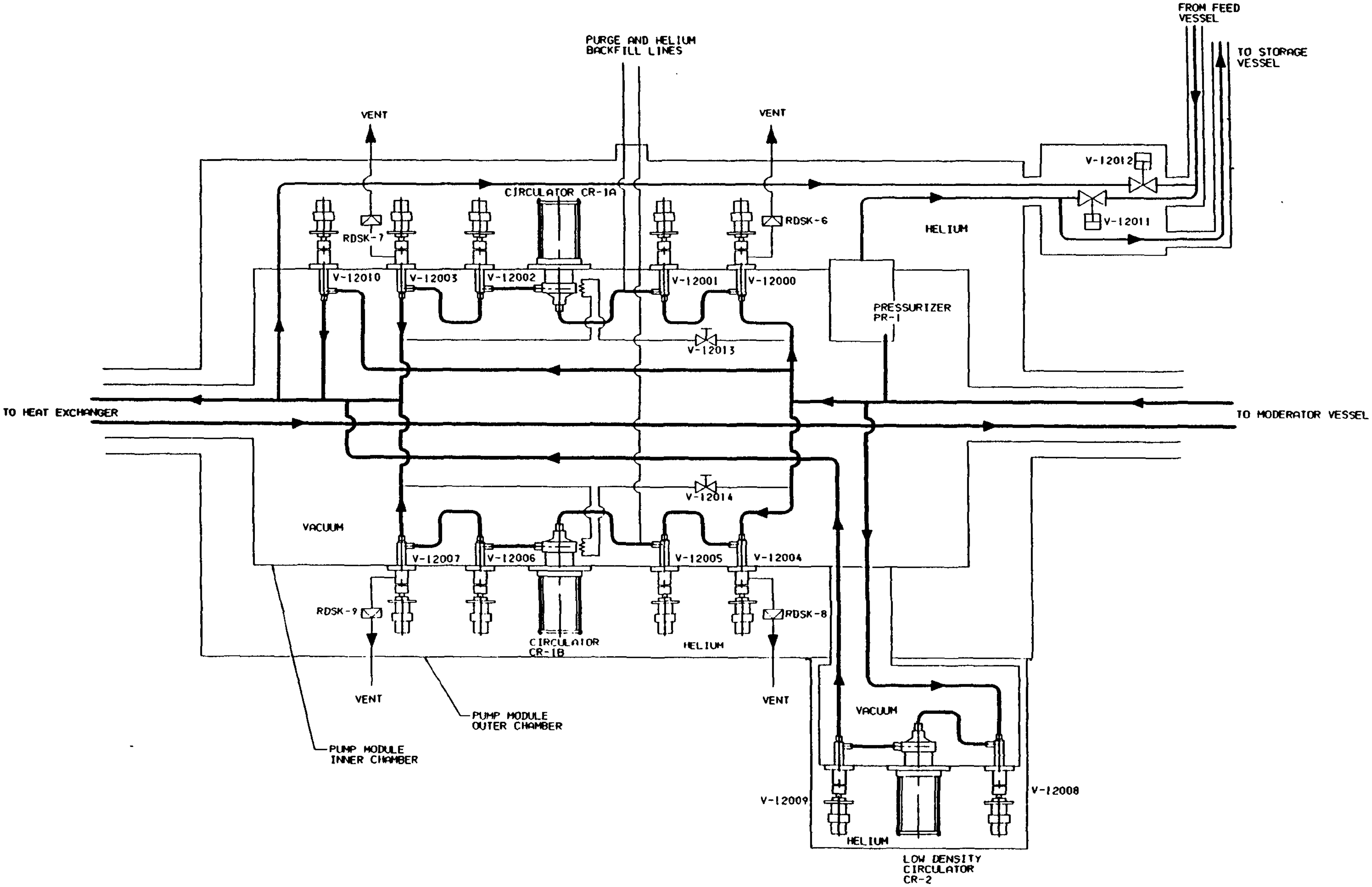

Fig 4

Schematic diagram of Gas Handling system

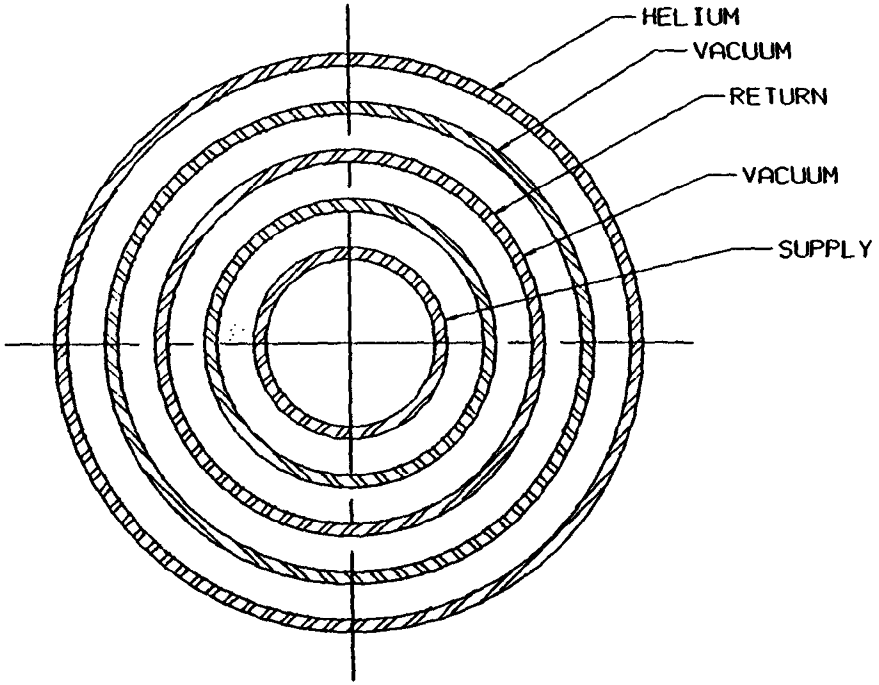

Fig 5
Transfer line pipe configuration

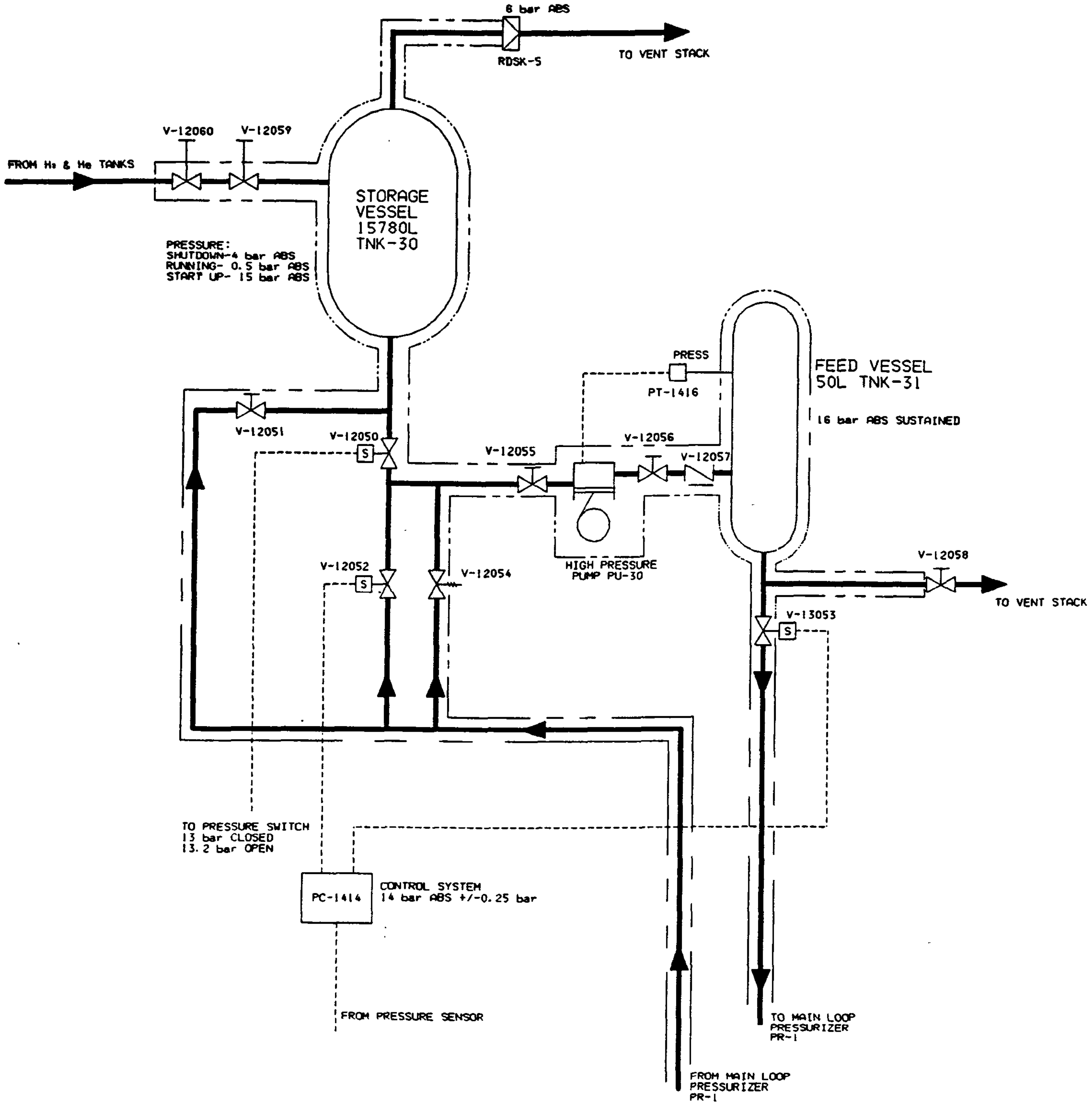

Fig 6
Gas handling arangement

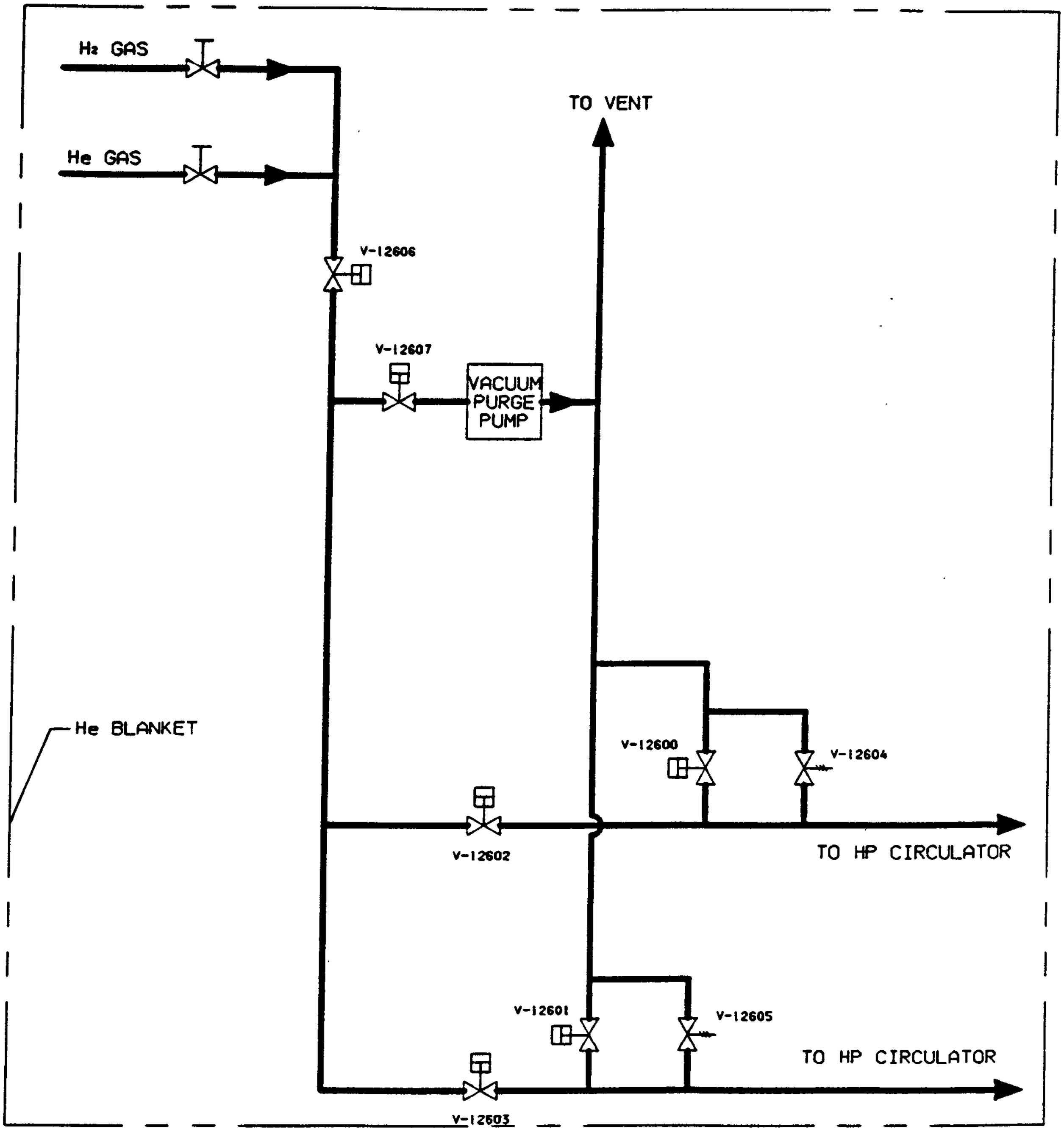

Fig 7
Purge module

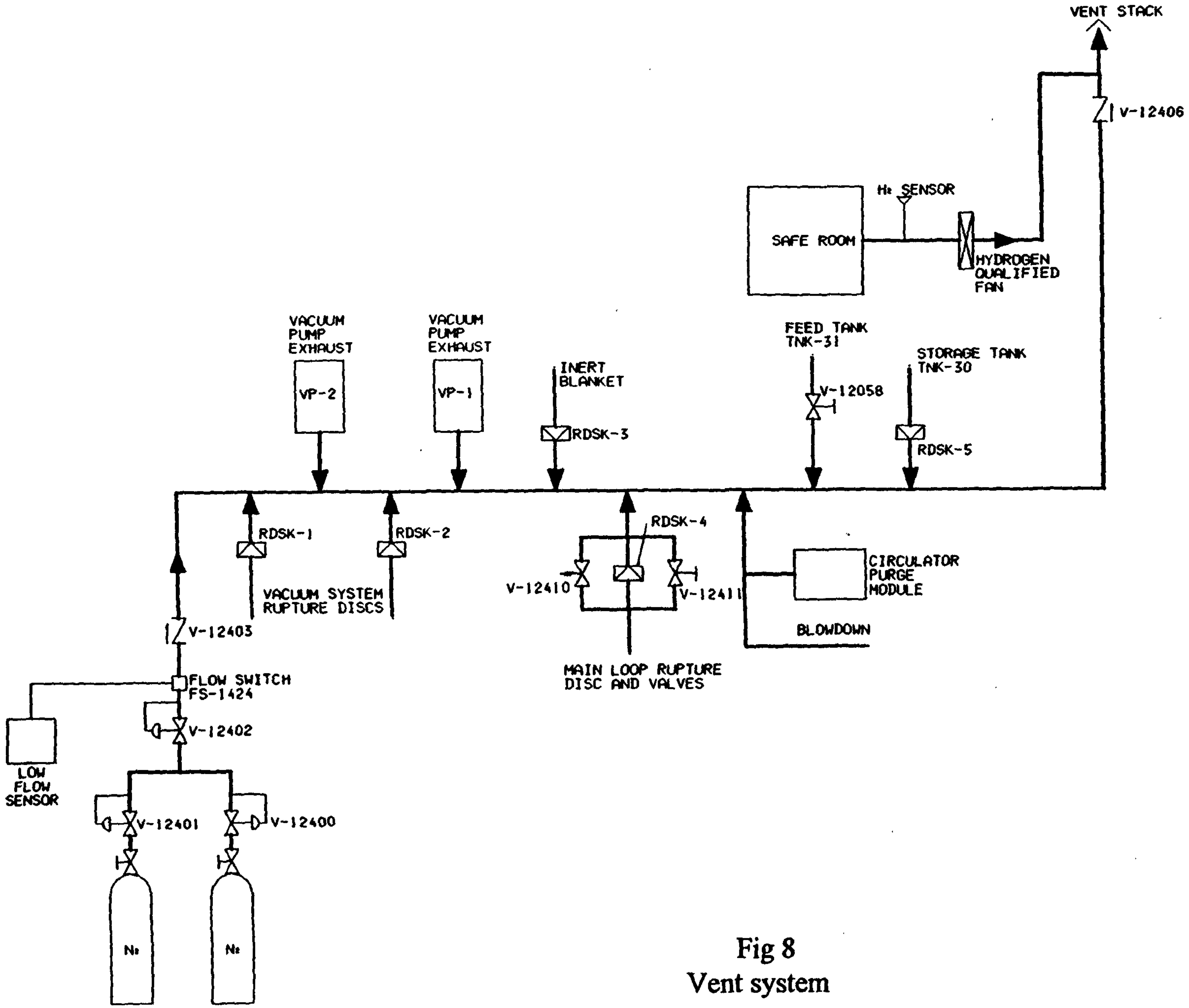

Fig 8
Vent system

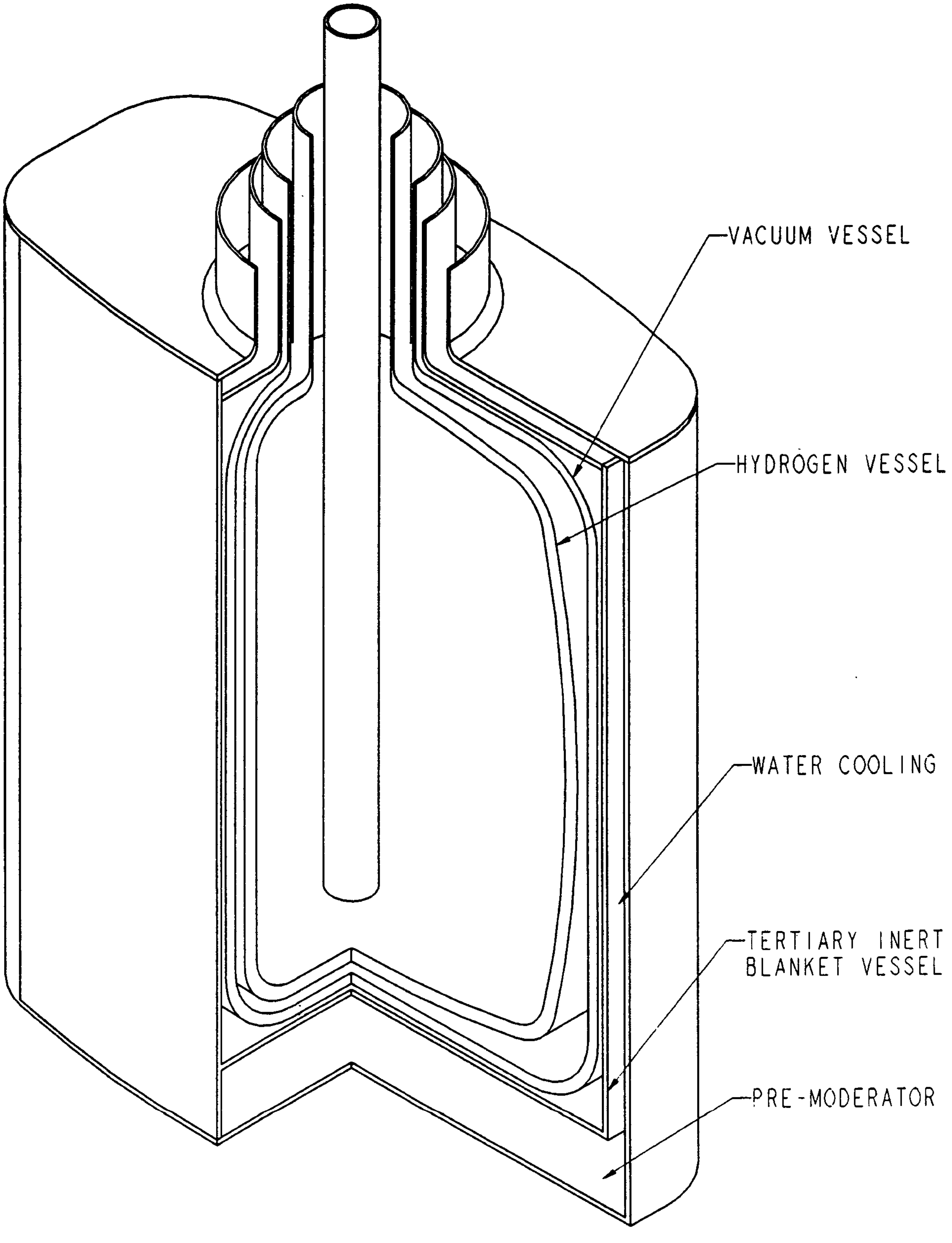

Fig 10
SNS Moderator vessel Assembly