Indirect hydrogen versus helium or nitrogen cooling for fusion cryogenic and magnet systems

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Capital cost reduction in fusion cryogenic and magnet systems may be possible through the use of 15-20 K cooling. This approach also enables the pre-separation of exhaust gases, increased fuel recycling and reduced refrigeration power. Resource concerns are causing helium's use in fusion to be scrutinised, although sometimes there is no substitute. By using an intermediate, leak-tight, pressurised helium loop the benefits of 15-20 K cooling can be harnessed without encountering the safety impacts of LH_2. Good thermal coupling between this 'iLH_2 loop' and cryogenic sub-systems may be constrained by pumping power limits. A novel 3-stage charcoal-coated cryopump may enhance thermal and fuel-cycle efficiency.

CRYOGENIC SYSTEMS IN FUSION

Cryogenic systems provide vital infrastructure in both inertial (ICF) and magnetically confined (MCF) fusion reactor concepts. In research MCF machines, such as the JET [1], JT-60S.A. [2] and ITER [3] tokamaks, cryogenic helium plants provide ~4.5 K and ~80 K services to key sub-systems as required:

- Cryopumping: the removal of species (^{4}He, ^{1}H, ^{2}H, ^{3}H etc) from tokamak-related spaces using cryocondensing or crysorbing surfaces to recover reactants (^{2}H and ^{3}H), remove 'ash' (^{4}He) and achieve high vacuum. Charcoal coating is essential for ^{4}He capture, as Day et al [4] show.
- Pellets: a fuelling strategy involving the manufacture of solid ^{2}H or ^{3}H pellets which are then projected into the plasma core or edge to provide fuel, increase plasma heating and stability.
- Cryodistillation: for large scale recovery of pure ^{2}H and ^{3}H which may be recycled within the fuel system many times before being burnt, with considerable emphasis on minimising ^{3}H inventory.
- Cryogenic turbopumping: as shown by Manzagol et al [5], turbopumps designed for 20K operation can increase the pumping capacity 15-fold. This could be used for removing pellet spallation gas.
- Magnets: huge, high field Nb_3Sn and NbTi superconducting toroidal and poloidal magnets define the ITER cryosystem and require the delivery of ~25 kW of ScHe cooling at 4.5 K, Kalinin et al [6].

MAGNETS – POTENTIAL MATERIALS FOR ~20K USE

Existing niobium superconducting magnet schemes all require helium refrigerators. The availability of 4.5 K coolant is also essential for the sorption pumping of helium 'ash', but for all the other sub-systems higher temperatures are possible e.g. the sorption of ^2H is ‘guaranteed’ up to ~15 K, state Dremel et al [7]. This prompts us to consider the potential for the use of HTS materials where coolant would be provided at 15-20 K, rather than 4.5 K or 65-77 K – currently the only options widely considered for fusion. If, for example, YBCO were to be used in the liquid hydrogen temperature range the following questions arise: are there forms of this alloy that would provide the required field; the current density; strength; reliability and, importantly, low cost? The target would be < $2/kA-m, given that the Nb-alloys are ~$1/kA-m but have to be driven with a most energy-intensive helium plant. YBCO is emerging as a highly promising material but it is expensive. One way to reduce costs is to produce thin film ribbon or tape.

DEMO, the generic name for the first fusion demonstration reactor, may have non-niobium magnets and require a B~5.9 T toroidal field (~14.4 T at conductor) and a non-copper conductor current density J_c of 150A/mm^2 Duchateau et al [8]. The copper section is significant. It has to absorb quenches and maintain the coil below 250 K while keeping the voltage below 4 kV. As a result, the non-copper conductor might only occupy 30% of the cross-section, with a similar area for the coolant (helium). This places demands on HTS materials which cannot be met by known forms of HTS at ~77 K. Figure 1 shows several materials to be acceptable at 4.2 K but, in the ~20 K range, only YBCO appears to comfortably meet the B and J_c criteria. Manufacturability, radiation resistance and quench behaviour are still being investigated.

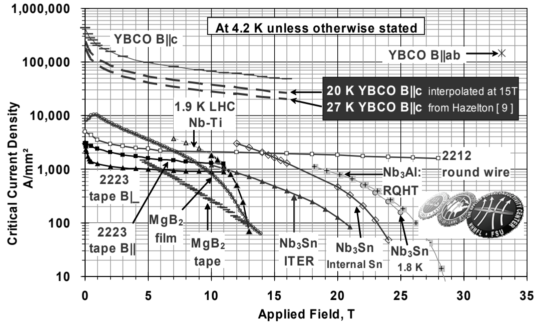

Figure 1. B-J_c for various candidate conductors for DEMO toroidal field magnets, US NHMFL [10]

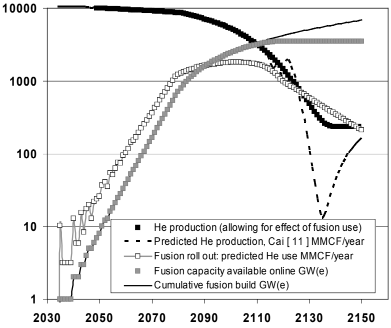

Figure 2. Possible evolution of fusion’s helium demand (MMCF/year) and capacity (GWe), Cai and Clarke [12]

HELIUM RESOURCES – THE IMPACT ON FUSION

The need to consider carefully fusion’s coolant strategy has emerged in the Helium Resources Project [11]. Natural gas sources of helium should be utilised as a ‘stepping stone’ towards a more sustainable situation where renewable helium supplies and fusion demand are more in balance. The use of ~20 K cooling is seen as a goal requiring thorough research before a move is made away from 4.5 K helium refrigerators etc.

Cai’s system dynamics model (Cai et al [11]) predicts global helium production will plateau around 2030, as price inelasticity finally offsets a strong, exogenous, high-technology helium demand growth rate. Thereafter, a production decline driven by the depletion of USGS-identified reserves is expected. Some of these reserves might now be questioned, given the upsurge in interest in unconventional (shale) gas production. This may reduce the demand for LNG plants, now emerging as the main source of helium.

If Cai's predictions are combined with a scenario of long-term fusion power plant roll-out it becomes evident that, after just 100 GW(e) of installations, fusion's demand for helium would exceed global supply if today's pattern of helium use in fusion research were to be extrapolated to large plants. Naturally, the roll-out assumptions are important; it is assumed that a 1 GW(e) unit goes on-line in 2035 and capacity follows a 1970's pattern of *fission* growth and then tends towards ⅓ world electricity supply by 2120 [12].

Cryogenics and high pressure helium cooling of the divertor and blankets represent the major uses in fusion, and all of them are intensely power consuming. Unless extremely leak-tight gas circulators are developed, the research efforts on warm-end equipment may need to be directed towards supercritical water cooling, molten Pb-Li blankets and, possibly, molten salt cooling and blankets. Based on JET [1] and ITER [3], helium cryogenics plant inventory is estimated to be proportional to (refrigeration power)$^{0.75}$[12].

It has been predicted by Cai and Clarke [12] that if fusion were to adopt a helium intensity-of-use reduction strategy rather less onerous than that needed to meet UK 2050 CO_2 targets then a sustainable usage pattern would emerge. For that to occur, it will be desirable to extract helium from air in dedicated side columns in large air separation units (ASUs) to produce a crude Ne-He gas mixture that would be sent in tube-trailers to central facilities for high purity refining using proven processes developed by Arkharov et al [13]. As an ASU's capital is funded from the primary products it makes, the cost of producing neon and helium from air derives mainly from the additional plant items and is thus expected to be competitive within just a few years. However, even if all ASUs were retro-fitted, helium production from air would amount to perhaps 1% of current global helium use. The helium 'ash' flow from fusion is negligible [11].

Allowing for the above assumptions, a pattern of helium use and production shown in Figure 2 might emerge. In the early years, the erratic helium consumption arises from the need to charge up new reactors with helium. Over time, the inventory and leak rate of new reactors would be expected to fall as reduction, substitution and re-use strategies would be put into effect to save cost and mitigate supply risks.

LIQUID HYDROGEN COOLING

Direct hydrogen cooling

Direct LH_2 cooling of HTS has been proposed [14] for highway concepts combining the delivery of high power and liquid hydrogen for zero-emission vehicle fill stations. In these applications there is a demand for both 20K and LH_2 but given the distances involved the HTS must be cheap, strongly favouring MgB_2. In fusion the situation is rather different. High B and high stresses limit the HTS choice and multiple hazards (electrical systems, tritium etc.) strongly discourage direct hydrogen cooling. Traditionally, this has polarised the coolant choice towards 4.5 K or 77 K, although liquid nitrogen itself is prohibited because high energy neutron interactions produce ozone (liquid nitrogen contains trace oxygen) and ^{14}C from ^{14}N. In ITER, a pressurised helium loop is designed to transfer heat to boiling nitrogen and, of course, such a concept can be used to transfer heat at any temperature. This is limited only at high temperature and pressure by creep, so we suggest that fusion's focus be mainly directed towards the use of helium loops.

Indirect hydrogen cooling (iLH_2)

The requirements of intermediate helium loops for liquid hydrogen cooling dictate that the system pressure should be as high as possible in order to minimise pressure drop and maximise heat transfer rates.

Mechanical constraints will limit the pressure but the ITER design point of 17 bar is a reasonable target. The delivered temperature would depend on the distance between the cooling and fusion plants. Liquefiers typically operate at ~1 bar (20.6 K) which may be too high for many of the fusion cryogenic applications. To reach 15 K a compressor suction pressure of <0.15 bar(a), or cycle modifications, will be required and that may increase the hydrogen plant capital and operating costs. A liquid hydrogen bath, preferably with minimised LH_2 inventory, could contain a reboiler, with suitably enhanced boiling surfaces and intense gas-side heat transfer surfaces, to provide the primary coupling to the intermediate helium loop. Or, to avoid dryout, a multi-stream gas-gas exchanger could be positioned ahead of the JT valve (Figure 3). Cryogenic fans or compressors would circulate the cold gas and distribute it to the multiple end users.

In the magnets and cryopumps, it is critical that stable and uniform temperature fields are established. This potentially creates a pressure drop and, therefore, a thermal challenge. Ideally, micro- or nano-channels will ensure near perfect gas distribution within the device structure. By considering the coolant geometry at the outset, as an integral part of the design process, a solution should be found where pressure drop is mostly consumed in heat transfer passages and not in the gas distribution networks. The added advantage is that this will help improve distribution.

For long magnet coils, the intensification of helium gas cooling is limited by pressure drop constraints. As YBCO's B and J_c performance is not substantially reduced at ~27 K (see Figure 1), a low inventory neon thermo-siphon system developed by Stautner et al [15] could be adapted to interface with an iLH_2 loop using a temperature-controlled bypass flow. As pure neon is a by-product of the helium refinery described earlier there could, if neon became cheaper, be a pumped 25 K LNe loop that extends back to a 3.5 bar(a) hydrogen liquefier. LNe would create intimate thermal contact with the coils, although quench relief units will be required. The choice of coolant will be largely decided by thermal-hydraulics and cost. Helium demand will mainly be determined by the 4.5 K thermal load and leak tightness of cryogenic sub-systems. However, the need to limit loop pumping power may constrain the location of the hydrogen liquefier.

For cryopumping, rather than operate the LH_2 liquefier at <1 bar(a), Figure 3 (inspired by McDonald et al's work [16]) shows how two liquefiers might be coupled to provide a thermal source for the ^{2}H and ^{3}H pumping cycle. During normal operation, a 3-way valve creates a controlled bypass path around a 4.5 K loop to achieve the required temperature. Charcoal's pumping characteristics led us to the concept of a *three-stage cryopump*, where only ^{4}He is sorbed on a 4.5 K charcoal coated surface, and ^{2}H and ^{3}H is sorbed at ~15 K on a second coated surface. The separate path leading to the 4.5 K cryopump is shown.

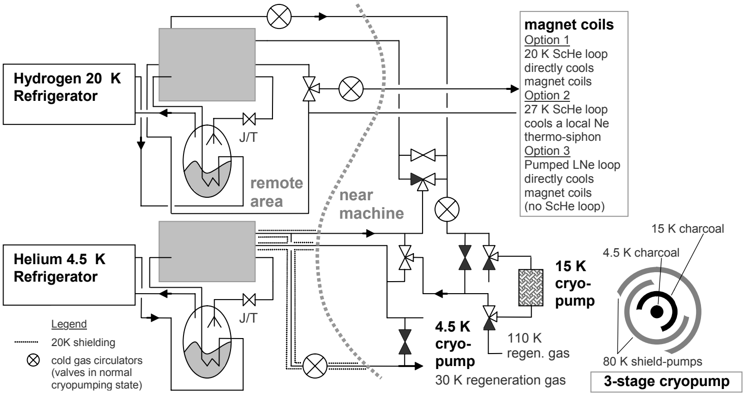

Figure 3. Combined use of hydrogen and helium refrigerators for three-stage cryopumps and HTS magnets

Significant low-temperature energy savings are possible during the cryopump regeneration sequence. Firstly, the 4.5 K pump is regenerated (releasing all of the ^{4}He at ~30 K [17]). Meanwhile, the long 4.5 K loop is put into recycle to be ready for the next cooldown. The 4.5 K lines would be shielded by a 20 K helium loop, significantly reducing the heat load on the helium liquefier. In the next regeneration step, deuterium and tritium are released from the second stage of the cryopump at ~110 K [17]. After the gas recovery, the second stage would be cooled down in two steps: 110 - 20 K and 20 - 15 K. The first step would use the 20 K helium loop, with the 4.5 K loop being re-opened to cool the pump back to 15 K. With lower regeneration and cryoline loads, refrigeration power (and hence helium inventory) will be less.

Apart from the thermal advantage, a three stage cryopump may enable helium 'ash' to be pre-separated from other species. This would benefit the downstream cryodistillation unit, by reducing the number of mass transfer stages required. The cryopump's second stage exhaust may contain virtually no helium, potentially enabling higher fuel recycling to be achieved per unit of cryogenic power expended.

CONCLUSIONS AND RECOMMENDATIONS

Cryogenics plays an essential role in fusion – in cryopumping, fuelling, fuel recycling and in magnet cooling. 4.5 K helium systems have been used because of the constraints of the Nb-alloy magnets. The HTS YBCO might meet fusion's magnet requirements in the range 20-27 K and, near 15 K, all other cryo-system components would work with the exception of ^{4}He 'ash' pumping. We suggest that a *three-stage cryopump* be investigated where ^{4}He is sorbed on a 4.5 K charcoal coated surface, with ^{2}H and ^{3}H sorbed at ~15 K on a second coated surface with 80 K shielding. This might enable more efficient fuel recycling. To reduce heat load on the 4.5 K loop during the regeneration steps, a coupling of refrigerators is proposed.

The Helium Resources Project [11] showed that an ongoing helium substitution, reduction and re-use programme, aided by the extraction of helium from air, is desirable if cryosystems are to be used in commercial fusion plants. Indirect hydrogen cooling (iLH_2) is one way to help achieve this.

A helium loop iLH_2 system needs to operate at high pressure and use enhanced-surface heat transfer at both the liquid hydrogen-helium and helium-cryosystem interfaces. Stable and uniform flow is essential and further studies might address the incorporation of nano-scale coolant channels within sub-system components. For long coil structures direct LNe cooling, or adaptation of a neon thermo-siphon system proposed by Stautner et al [15], might enable better thermal coupling with magnet coils to be achieved.

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