ON THE AVAILABLITY, SUPPLY AND USE OF CRITICAL NATURAL RESOURCE FOR THE REALISATION OF THE FUSION INDUSTRY

R. J. PEARSON
Kyoto Fusioneering Ltd.
Reading, United Kingdom
Email: r.pearson@kyotofusioneering.com

Various developments in several nations, in both the public and private sector, have moved us towards a power-producing fusion reaction. The fusion sector is entering into a period of industrialisation. In addition to solving remaining physics and engineering challenges to realise fusion, consideration of industrial challenges rather than experimental R&D is required. A key challenge is the availability and supply of critical natural resources required for fusion reactors.

Fusion is often described as having widespread and abundant fuels and would be able to provide a virtually unlimited renewable energy source. Looking at the two primary fuels, deuterium and lithium (not tritium, which is not a naturally occurring isotope, and must be produced in the reactor), resources are indeed abundant and widespread; both are present in seawater. However, in the same way that a wind turbine does not depend only on the materials and manufacture of its turbine blades but also on materials for the gearbox, power conversion systems etc, a fusion reactor does not depend only on the above two primary fuels. Instead, its overall function depends on other systems within the reactor, which require novel or special materials, including for the structure, for components in the fuel cycle (including those that are tritium-compatible), for magnets, laser, or drive systems, to name just a few. Indeed, it is here argued that a fusion reactor contains one of the most complex and wide-ranging set of resources and materials than any other energy technology currently in use or under development today. As such, a dedicated focus on the topic of resource availability, supply and expected fusion use is paramount for the success of the fledgling fusion industry.

Several studies have explored the concept of sustainability of fusion [1–3]. Previous research by the author has explored key issues associated with the primary fusion fuels and blankets [4]. That research found that for several resources, there are issues associated with availability (whether a resource is abundant on Earth) as well as supply chain maturity and/or capacity (whether it is possible to mine or produce it in significant quantities). At current, resources for fusion reactors are in very small quantities only. Any costs associated with resources for fusion technologies now are thus predominantly for R&D. This is necessary to cover experimental equipment, development and qualification of new materials, computer modelling etc. However, later, in the latter stages of the fusion innovation process [5] – i.e. production – raw materials and manufacturing are likely to significantly impact commercial viability [6]. Commercial challenges extend beyond the cost of resource, however.

Several new energy technologies, including solar and battery technologies, have seen similar demand for new natural resources. Interestingly, these are in areas that have traditionally seen less demand [7]. However, for fusion, the resource availability and supply problem has the potential to be rather different, mainly due to the wide range and quantities of specific natural resource that currently have limited supply chain maturity or, in some cases, a limited or geographically concentrated resource base. Often, the materials for the wide range of fusion applications are used out of necessity, due to nuclear or other special materials characteristics; they cannot be substituted. In many cases, therefore, there are limited alternative material options for a given application or component. A key example of this is the tritium breeding blanket, which is one of the most important systems in a fusion power plant, as it is required for both closing the fuel cycle (so-called tritium self-sufficiency) and for transferring the fusion power as heat to be used for power generation. It also requires several natural resources that are critical to its function. Noting that because tritium is not a commodity that can be produced in quantities sufficient to support a fusion industry (see [8,9]), one part of the two fuels for the D-T fusion reaction is actually lithium, which produces tritium under neutron interaction. However, for several reasons, using lithium for tritium breeding in a blanket alone may not be plausible. Many fusion reactor designs depend on an additional material for neutron multiplication to increase the tritium breeding ratio. Most blanket designs depend on either beryllium or lead as a multiplier. The latter (lead) is abundant, cheap, and geographically widespread; the former (beryllium) is not. Some blanket designs require enrichment in the lithium-6 isotope due to the neutronic properties of particular blanket designs [10]. However, lithium-6 constitutes only 7.4% of naturally occurring lithium. Moreover, lithium-6 is an export-controlled commodity and worldwide production is effectively zero. Finally, helium is regarded as one of the potential coolant options for fusion reactors (not only for the blanket but also for magnet cooling and for cooling other high temperature systems such as the plasma exhaust). However, helium is becomingly increasingly expensive and is expected to be in relatively short supply, amongst a host of other problems, within the coming decades [11,12].

Elsewhere in the reactor, there is a large range of materials used for specialist applications. Equipment in a fusion reactor that requires novel materials includes, for example, diagnostics for plasma measurements or diagnostics for gyrotrons (high frequency microwave emitting devices) for plasma heating depend on diamond windows. The magnets in a tokamak or stellarator, as well as the magnet required in other systems such as gyrotrons, may be made from a range of superconducting materials, including HTS (YBCO) or LTS (e.g. Nb3Sn or NbTi). These would require significant quantities of elements, including yttrium or niobium, for which the supply chains are not currently equipped for the expected level of demand. Beryllium or tungsten are likely to be required for first wall plates or tiles. Similarly, tungsten is likely to be used as a neutron shield to protect outer systems, including the magnets in magnetically confined concepts such has the tokamak. Tritium technologies, be it pumping systems or tritium separation technologies, may require palladium membranes or catalysts. More generally, there is a need for development of reduced activation materials. Perhaps most pertinent is developing structural materials that do not contain certain isotopes, to avoid the production of long-lived or high-level waste. Most pertinently is the need to develop reduced activation ferritic martensitic (RAFM) steels, which sees isotopes like niobium removed (due to the fact that even if present only in very small quantities results in long-lived, high-level waste) and replaced with tantalum, which is rare and expensive, with a limited and geopolitically problematic supply chain. In addition to the natural resource availability and physical supply, and whilst progress has been made in the development of RAFM steels, its availability as a fabricated product (i.e. the RAFM supply chain) is limited with only quantities in the order of several tons of each type of RAFM developed having been manufactured to date [13,14]. Other potentially suitable structural materials, such as vanadium alloys, ODS steels or silicon carbide composites (SiCf/SiC) are also not without issue, given that the supply chain for these materials are still not firmly established. As a final example, which demonstrates an obvious overlap with the nuclear industry in that many materials in a fusion reactor must withstand a harsh nuclear environment, often more extreme than for fission, materials like depleted uranium may be required for tritium storage.

In summary, it is likely that a significant scale-up of existing supply chains would be needed to support even a prototype reactor; a statement that may hold true for several key resources. A high-level assessment of key challenges with regards to specific natural resource availability, supply, and use, is presented. The issues associated with critical natural resources, including aspects such as export control, geopolitics associated with geographical concentration or production of specific resources, as well as other aspects such as non-proliferation. Commercial challenges such as the concept of a fusion-created monopsony, whereby a particular market or industry supplies for just one source of demand (here, the fusion industry), and the risks associated, is also detailed. A view of the potential pathway(s) forward to resolve these problems will be outlined. Importantly, it is emphasised that collective understanding and action is needed to avoid a significant bottleneck or, in extremis, a resource availability or supply-induced showstopper, that hinders the future rollout of commercial fusion reactors. Accordingly, it is addressed that in determining a route forward, the required solution must be supported by and, indeed, created by multiple stakeholders from across the fusion sector, with subsequent significant investment of capital and time.

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