ReNeW White Paper

Taming the Plasma-Material Interface and an Energy Sustainment Mission

D. Whyte, Feb. 20, 2009

The summary White Paper on an *Energy Sustainment Mission* stated that much of its motivation comes from the necessity to explore the coupled core plasma – wall science in the parameter regimes relevant to DEMO and/or CTF missions, namely: arbitrary long pulse length, reactor level P/S ~ 1 MW/m^2 and elevated ambient wall temperatures (T>1000 K). A preliminary feasibility study has indicated that a small (R~1 m, a ~ 0.25 m) tokamak, 'Vulcan', with super-conducting coils (B < 7 T), sustained non-inductively with RF current drive (~ 15-20 MW) could meet this mission. In the spirit of ReNeW we do not regard Vulcan as a definitive proposal for a device. However it is useful to use this as a starting point in the discussion of science and design challenges required to meet the energy sustainment mission. The purpose of this White Paper is to examine in more detail those challenges and opportunities from the PWI point of view.

<u>Attaining plasma-wall equilibrium</u> The scientific goal of Vulcan is to obtain states of equilibrium between the core/edge plasma, fuel cycle, plasma-wall interactions and material evolution, at reactor-relevant power fluxes and ambient wall temperature. The motivation for this goal is twofold. First a DEMO or CTF will access these equilibrium states and it is necessary to attain and study these states beforehand. This must be accomplished with the proper power exhaust level and ambient temperature, since it is the combination of these that predominately set the equilibrium states and timescales. Because the wall's physical chemistry follows Arrenhius relationships the equilibrium is hyper-sensitive to operating material temperature under plasma loading. The second motivation is that attaining these states, which means that the plasma-wall interaction is effectively stationary ($\partial/\partial t \rightarrow 0$), provides an enormously powerful analysis tool to understand the underlying PWI science, one that has been essentially lacking to date due to inertially cooled walls with constantly evolving temperature and pulsed devices – which makes for an incomparably more difficult situation to interpret. One can in fact estimate that the wall-plasma system will go through various phases of quasi-equilibrium; the timescales for these range from ~ seconds (recycling), hours to days (erosion/deposition, changing PFC thickness affecting surface temperatures, flaking/dusts) to several days to weeks (fuel permeation, displacement damage in PFCs). Moreover these timescales will again be hypersensitive to ambient temperature and material choices. Given its exploratory nature, Vulcan's scientific goal therefore requires arbitrarily long pulse lengths.

Both ITER and the upcoming Asian "long pulse" tokamaks still have very short pulses, 100 - 1000 s, times which are far shorter than a number of critical PWI equilibration times. Nor can high annual duty cycles compensate for short individual plasma pulses, since the equilibrium state is highly perturbed by pulsing the plasma bombardment and material temperatures, mostly due again to the hypersensitive relationship between physical chemistry rates and temperature. Take for example a study of fuel retention and permeation in a hot-wall pulsed device. If one chooses to drop the temperature between shots to "freeze" in the fuel, then one must accept the highly perturbing nature of thermal cycling to materials and plasma-deposited films, not to mention the transient nature of the plasma startup and shutdown which will change the wall temperature non-uniformly. Conversely if the wall is kept hot then in the absence of the implanting plasma flux the fuel will be thermally released out of the PFCs. We note that if we accept that the tokamak device should be able to operate non-inductively for reasons of advancing steady-state scenario development (Theme II) then arbitrary pulse length is simply a matter of choosing appropriate steady-state heating/current drive technology. In this sense Vulcan would properly and inextricably link the high performance core and PWI equilibrium missions.

Exploring boundary physics and extrapolating boundary plasma solutions

A successful energy sustainment mission necessitates that Vulcan is capable of attaining solutions to heat exhaust compatible with the actively-cooled PFC limit ~10-15 MW/m^2; without a viable power exhaust solution arbitrary pulse lengths will obviously not be possible! At the same time, Vulcan must provide a science bridge to CTF/DEMO with respect to boundary physics; i.e. as much as possible one desires that the edge problems **and** solutions are as similar as possible to those foreseen. Therefore it is imperative to place issues like boundary power exhaust in the proper context in order to have confidence in our extrapolation to CTF/DEMO. It seems likely that our present deficiencies in physics are too large to truly predict boundary plasmas, therefore a comprehensive strategy is required to meet these dual goals through empirical and similarity scaling.

Towards the power exhaust solution in Vulcan a two-pronged approach is appropriate. First, use off-line plasma or beam facilities to fully develop and test the helium cooled high-temperature PFC and wall, in order to assure that maximum peak loading is achievable and reliable on the scale of Vulcan (several m^2 of high heat flux components). Secondly, use existing pulsed confinement devices, coupled with a vigorous program to improve heat flux characterization, in order to provide the best possible starting point in Vulcan. This seems feasible for extrapolation to Vulcan: for example C-Mod has P/S approaching 0.8 MW/m^2. The initial phases of Vulcan would be performed in pulsed H plasmas to avoid activation and allow access to in-vessel components to fully explore the options for reducing peak heat loading to acceptable levels.

Boundary plasma similarity arguments provide a way to frame the issues of extrapolation beyond Vulcan, much as it does for the core plasma. (It should be noted that exact similarity is not possible across size scales, so one must choose the parameters of most importance.) The zeroth-order similarities are geometry and B topology: aspect ratio, safety factor, elongation, which set underlying critical aspects of the SOL such as field inclination, flux expansion, B ratios from inner to outer divertor, etc. Vulcan uses R/a=4 as required in CTF/ARIES-class devices for inner-column shielding. This also has the benefit of reducing plasma surface area at fixed R~1 m thus decreasing heating requirement and wall area (S ~ 15 m^2). Additionally, with R/a=4 the same B field as CTF/DEMO is allowed given the same SC technology. Power throughput is set by P/S~1 MW/m2 which is dictated by neutron wall loading requirements in a reactor or CTF; for the upstream SOL the power width is found to be $\sim R^1$, which means that upstream parallel heat flux, $q_{//}$, is therefore matched. Matching $q_{//}$ is also important in the "engineering" scaling sense; the required PFC alignments, peak heat loads, etc. are

locally set by only $q_{//}$. Taking the divertor alignment limit as 1 degree, this means that the acceptable $q_{//}$ ~ 10 MW/m^2 / sin(1^o) ~ 600 MW/m^2; a level of $q_{//}$ which has been measured in the C-Mod divertor which is encouraging for using the compact high field approach for similarity. Analysis indicates that with matching $q_{//}$ in a Vulcan R~1m device that other scaling similarities up to CTF/DEMO (R ~3-6 m) can be exactly or closely matched. The upstream SOL temperature $T_u \sim (P/R)^{2/7}$ has a very weak size dependence through the non-linearity of heat conduction with T. More importantly the divertor parameters, which are obviously most critical to the heat exhaust problem, can be manipulated through their extreme sensitivity to upstream density, n_u. For example using the Stangeby two-point model with matched $q_{//}$ that divertor target (T, n) plasma matching occurs between $n_u \cdot R^{0.28-0.33}$ held constant. Similar analysis using SOL collisionality based on T_u shows that $n_u \cdot R^{3/7}$ held constant provides similarity. Thus a modest scaling in n_u (2x larger in Vulcan than CTF/Demo) provides relevant divertor conditions but is simultaneously compatible with Vulcan RF current drive requirements at P/S~1 MW/m^2, due to the fact that most of the plasma heating can be dedicated to CD in Vulcan. Also, if one further allows the divertor to increase in size relative to the core, the matched $q_{//}$/B allows for extremely close divertor plasma similarity in size scale up[2]. This clearly motivates the ability to also study an "expanded volume" divertor in Vulcan, a feature which seems reasonable with respect to losing confined plasma volume given its small size.
In summary through operational and design considerations we can expect every reasonable opportunity to provide a reliable empirical scaling of the boundary physics solutions from Vulcan up to a non-inductive CTF or DEMO D-T burning device.

Exploring the Frontiers of PWI science

The Vulcan mission would certainly push the boundaries of our present PWI knowledge in both the technology and science sense, opening windows to solving vexing PWI issues. We list some areas where the Vulcan mission would make a large impact:
- Fuel retention. Present devices, including one with high-Z metal walls, remain orders of magnitude from demonstrating the requirements for a closed fuel cycle in a D-T reactor. Adjustable ambient temperatures > 700 C present probably the only realistic solution to guaranteeing low in-vessel fuel inventories for any PFC. Importantly Vulcan would be able to probe the exact sensitivity of the fuel recovery and permeation through attaining steady-state through arbitrary long pulses, achieving for the first time energy and particle throughput found in a CTF/DEMO.
- Controlling erosion. High-Z refractory metals hold the hope of a nearly erosion-free wall due to their high physical sputter threshold with H fuel ions. However the reality is that present devices find that the metals are not erosion free due to the presence of uncontrollable levels of low-Z impurities (C, O) from vacuum contamination; low-Z impurities which recycle in the plasma and cause erosion due to their higher masses. With ambient temperature in excess of 700 C, and thermal removal of all such volatiles, we may expect to realize the dream of an effectively erosion-free divertor; or if low-Z radiators must be introduced they will at least be under external control.
- H plasma studies Hydrogen plasmas are convenient to explore plasma physics without invoking activation in the wall from D-D neutrons. However, H plasma studies for PWI

are highly confused by the large presence of background H from water contamination. Vulcan would eliminate this issue with the strong thermal desorption at high temperature.
- Intermediate nuclear damage mission A high-field D-D device with arbitrary pulse length will begin to affect the PFC properties (e.g. thermal conductivity) after several weeks of operation. This will provide a unique insight into the coupled problem of evolving irradiation PFC damage and healing, and effects on PWI, in a material temperature environment consistent with a CTF/DEMO.
- Advanced PSI diagnostics We are exploring a wide range of innovative PSI diagnostic tools for Vulcan to advance the state-of-art in PWI knowledge. Chief among these are a real-time accelerator-based diagnostic which would probe the surface properties of the divertor and wall during steady-state plasma operations, and real-time global measurements of wall fuel content through neutron scattering methods. We note that such diagnostic development for the high T environment would be an important step to designing CTF/DEMO edge diagnostics.
- Expanded boundary plasma As mentioned above there is a similarity argument to explore expanded divertor volumes. Such studies would also point to innovative geometry solutions for the heat exhaust problem.

[1] Kallenbach et al. J. Nucl. Mater. **337-339** (2005) 381.
[2] Hutchinson & Vlases, Nucl. Fusion **36** (1996) 783.