RESULTS AND FINAL CONCLUSIONS

Results of the experimental and analytical work conducted during the program now ending have shown all of the conclusions necessary to support and define the next step to full-scale net fusion power demonstration. These include:

1. No closed box machine can ever yield net fusion power; open recirculating MG machines and systems are required. This is an immutable result of the determination of losses of electrons in experiments, that show that losses to surfaces that are NOT magnetically shielded must be kept to less than 1E-5 or so of the cusp axis flow of electrons in the WB effect at beta = one. This is impossible for two reasons: (a) it is not practically possible to cover all but 1E-5 of the entire surface of a box containing the interior plasma, with magnetic oils that protect all of this surface, and (b) even if this were possible, it is not possible to protect against losses directly along the cusp axes to the end plates that bound each cusp. These intrinsic losses are inherent in the magnetic topology of a closed box system and forever prevent this from operating at small losses.

2. The inescapable conclusion is that all polyhedral Polywell® machines must operate as open recirculating devices, and that all such systems must have essentially no B-field-unshielded surface area available to electrons in the machine, itself. This means that all structure containing B field-generating coils must be conformal to the fields so produced, thus coil containers must have elliptical or circular cross-sections. If not, there will be large regions in which B fields go into the metal surfaces at an angle rather than circulate around such surfaces. And electrons will simply drive along these intersecting B fields, directly into the metal, to yield excessive losses.

3. Because of this, it is also evident that – no matter their individual plan form shape (i.e. circles, squares, triangles, polygons etc.) – magnet coils must not touch at their adjacent corners, but must be spaced sufficiently far apart to ensure that no B fields intersect their containers. In this way, electrons can recirculate freely around all parts of each coil, and thus operate with minimal losses. These corner spacing line-like-cusps give local current flows that reduce the effective e- trapping factor (Gmj) in the machine interior from that for pure WB behaviour alone. However, the reduction is not sufficient to prevent ready attainment of the e- density ratios inside/outside, required for avoidance of external arcing (see below, in Conclusions 4, 7, 8)).

4. Operating as recirculating (MaGrid) machines means that there will be an external region between the machine and its containing exterior wall, in which Paschen arc breakdown can occur, unless both external electron and neutral gas density can be kept below some critical level. To do so requires large scale vacuum pumping in this exterior region. However, this level is so low that it can not produce significant fusion rates inside the machine, if the densities are allowed to be the same across the system. Thus, some means must be found to ensure large electron density within the machine, while maintaining it at small levels outside.

5. This requires that the ionization (of neutral gas) density within the machine be very large relative to that outside; and this can be attained only by neutral gas injection directly into the machine, followed by subsequent very rapid ionization of this gas, before it can escape into the exterior region. In small machines this is difficult, as time scales for neutral transport to the exterior are measured in fractions of a millisecond, and dimensions within the machines are not sufficient to allow rapid ionization at the limited electron currents and densities attainable. In large machines, such as power reactors (typically 2-3 m in diameter) with high power electron drives (e.g. 100-500 Amps at 15-30 kV for DD and 180-220 kV for pB11), it is easy to show that almost total ionization of inflowing neutral gas can be achieved in a few cm of electron path length at the system edge, but small devices can not reach this condition.

6. Thus, in small systems there is a big incentive to attempt to fuel the machine with ions injected from ion guns placed on cusp axes. This, however, poses the problem that the ion guns must be at machine voltage, thus constitute very visible and attractive potential sinks for electrons, as they can *not* be fully magnetically shielded, as can the magnets themselves. In this situation, it appears that the only way to test these principles in small machines is to try to use capacitor discharge drives, timed precisely so that neutral gas injection is started with the cap drives, and the electron well drives are also started simultaneously. This requires very precise timing, which is difficult but has been achieved in such tests, however, this entire problem goes away in machine sizes for net power production. This conclusion echoes that of previous years. If it were possible to provide ion injection surfaces on the inside faces of the magnets (but no such sources exist), this might solve the problem in small test devices, however, ions injected at low energy at such positions will, themselves, be trapped in the magnet surface B fields, and have to cross into the potential well gradient by ExB drift forces, which may not be practicable. In reactor-size systems, ions formed within the interior field surface boundary will fall to the center naturally, under the effect of the high radial potential gradient that makes the deep well of the system.

7. Finally, in terms of practical limitations it was noted that the basic physics concept presumes magnet coils of near-zero physical cross-section, which touch at acute to right angles at the corners of the polyhedral-vertex boundaries on which they are supposed to lie. This has always given a “funny cusp” at such touching corners, which has been noted as having essentially zero tangential radius, although it also has zero B field. However, with realistic coils of *finite* dimensions (i.e. the coil cross-sections are a not insignificant fraction of the machine or coil major radius) this “funny cusp” expands to involve a rectangular region bounded by the dimensions/size of the coil containers. This rectangular region will have competing fields at 90 degree intervals, thus will act as an unshielded area for electron losses from the machine drive. The fractional size of this unshielded area is always found (from magnet design studies using real conductors) to be in the range of 0.01-0.1 of the total surface area of the coil containers. Since unshielded fractional areas above 1E-5 to 1E-4 are untenable, this effect gives losses that are ca. 1000x too large for useful fusion output.

8. The only way to avoid this, with coils of realistic finite size, using realistic conductors (e.g. superconductors) is to space the coils a distance from each other, as described in (3),

above, so that NO B fields intersect the coil container metal surfaces, but rather the field lines flow in parallel between the spacing at these corners. To achieve the ideal polyhedral trapping effect with proper coil magnetic insulation, the coil centerlines may also be offset so as to appear directly along the edge vertices,. although this is not an essential requirement. Thus, the only coil configuration that can work to best advantage is one in which the coils are contained in circular cross-section tubes, turning at each corner through a small straight section, which is spaced a distance away from its not-quite-touching adjacent neighbor coil. Analysis shows that this spacing should be at least 3-8 gyro radii of the electrons in the coil surface field. This will avoid all direct incident electron impact but, as noted previously, will result in increased electron flow between inside and outside due to the fact that the spaced regions act like small line cusps rather than point cusps. Greater coil spacing can be used but only at the price of lesser internal trapping. A balance must be struck between Paschen arcing exterior density, and interior density required for the desired fusion output. Fortunately, it has been found that a margin of about 1000x is available in design for these conditions.

9. These line cusp flow increases will operate in parallel with the cusp-confinement Gwb of the basic coil geometry, and will thus reduce the overall trapping factor to something less than Gwb. Calling the overall trapping factor Gmj, it is found that Gmj can be computed as the inverse sum of the two trapping factors for the machine; one being Gwb, the other being the line cusp factor Glc, weighted by the fractional area “seen” by electrons for each type of loss. Thus 1/Gmj = (1-flc)/Gwb + flc/Glc, where flc is the fractional line cusp area in the system. These loss mechanisms act as parallel flow channel factors. If the line cusp corner dimensions are only a few cm, the reduction in effective trapping from the basic Gwb may still be a factor of 2-5x.

10. This has the consequence that the maximum electron density ratio that can be sustained between inside and outside will be equally reduced, and the outside density must be that much larger for a given interior density (as required for useful fusion output). This requires greater vacuum pumping in the exterior, to reduce ionization from the higher background density, and limits the ability of small systems still further to be run (even for very short times) in the capacitor-drive pulsed mode. Since Gmj factors needed to avoid Paschen arcing are in the range of 1E3-1E4, while basic Gwb factors are one or two orders of magnitude larger than this, the avoidance of arcing at fusion conditions in the interior is easily attainable even with the spaced corner flow increases.

11. Once again, large machines will not suffer from these problems to any significant degree, but they will cost a great deal more. Costs tend to scale as the cube of the system size and the square of the B field. Thus, full-scale machines and their development will cost in the range of ca $ 180 – 200 M, depending on the fuel combination selected. These cost estimates closely reproduce those made throughout the USN program life, from its earliest work (1991) to its conclusion (mid-2006) including those made at interim reviews (1995, 1999). USNavy costs expended to date in this program have been approximately $ 18 M over about 10 years (2/3 in last 6 years).