Pellet Fueling of Helium-3 Enclosed in Li and Be Shells

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ABSTRACT

The proposed design of a fuel pellet containing liquid ^{3}He enclosed in a spherical Be shell of 300 µm thickness and overcoated with D_2 solid appears to be adequate for fueling large size d/^{3}He tokamaks. Smaller pellets of this design could be used for near-term experiments. The pellet fabrication should be simple and the components are non-radioactive.

INTRODUCTION

Conceptual design studies of d/^{3}He fueled tokamak fusion reactors, such as Apollo [1], are being pursued as an alternative to d/t fueled tokamaks. The d/^{3}He reactor designs indicate improved safety during accidents, much lower radioactivity at end-of-life, and lower cost-of-electricity than for d/t reactors. Special fueling techniques need to be developed for these d/^{3}He power reactors and early experimental devices because of the high plasma electron temperatures, T_e ~55 keV, more than 25 times present experiments. For this reason, several fueling concepts for tokamaks were previously reviewed and evaluated [2] as follows:

(1) Advanced techniques, such as plasma guns, accelerated plasmas from compact toroids and laser ablation of pellets are in very early stages of development and the results of their development cannot be predicted.

(2) Gas puffing which was useful for low energy experiments will be inadequate for high temperature devices.

(3) Pellet injection of frozen hydrogenic pellets has been successfully used for fueling many experimental tokamaks and is based upon reliable hardware development and an evolving theoretical understanding of the physical phenomenon involved.

For these reasons, pellet fueling concepts were considered for this study. The pellet fueling of ^{3}He is a challenge because it has the lowest critical temperature of any substance, 3.2 K. Upon further cooling it does not solidify but transforms to several superfluid phases. The liquid can be solidified only with the application of 3 MPa pressure; therefore, a solid pellet formed at this temperature would reliquify before it could be delivered to the plasma. Alternative methods for the fabrication of ^{3}He pellets were considered:

(a) The acceleration of liquid ^{3}He droplets is deemed inadequate because H_2 droplets were found to disintegrate at velocities above 2 km/s.

(b) Liquid deuterium dissolves some helium at high pressure, e.g., 0.024 mole fraction at 30 K and 2 MPa but decreases with temperature. Consequently, the concentration of ^{3}He in a frozen pellet of D_2 would be negligible.

(c) The entrapment of ^{3}He from the gas phase during the condensation of D_2 "ice" was considered; however, experimental evidence indicates that the D_2/He ratio must be $> 10^5$ before a significant fraction of the He is deposited. The concentration of ^{3}He in the D_2 ice would, therefore, be too dilute.

(d) My previous publication [2] proposed that ^{3}He droplets enclosed in thin polymeric shells could be fabricated remotely by simple procedures. With an overcoating of D_2 ice, acting as an insulator, Fig. 1, the fuel pellet could be delivered and launched in a gas gun.

After a review of the alternative concepts, the preconceptual design of a fuel pellet containing liquid ^{3}He enclosed in a thin shell was continued because it appeared to be the most near-term concept for development.

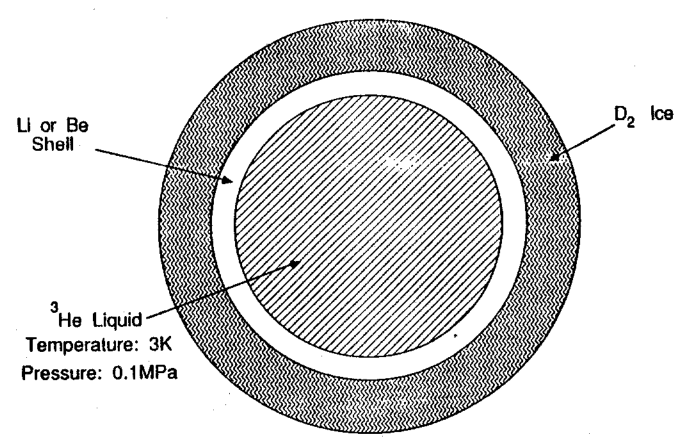

Fig. 1. Proposed ^{3}He fuel pellet.

CONCEPTUAL DESIGN OF A METALLIC SHELL FUEL PELLET

For the design of a ^{3}He fuel pellet enclosed in a shell, it is necessary to evaluate the following: (a) how much impurities will the shell contribute to the plasma, and (b) how far will the shell penetrate into the plasma. Regarding the introduction of impurities, the polymeric shell is a carbon (Z=6) and hydrogen (Z=1) compound. Carbon is the principal impurity in present-day large tokamaks, chiefly from erosion of the walls. Hydrogenic pellet fueling of these tokamaks indicates that improved performance is obtained at low carbon content; consequently, the introduction of polymeric material into the plasma should be avoided.

Materials with lower Z numbers which might be fabricated into shells are the metallic elements Li (Z=3) and Be (Z=4). Fortunately, both of these metallic elements exist in commercial quantities. Lithium foils are routinely manufactured for use in electrical batteries and experimental foils of only 75 μm thickness have been prepared. The Li metal is soft and easily fabricated. In addition, in the d-^{3}He reactor, the fusion reaction ^{6}Li/d would provide additional power. Regarding Be, it can be machined or fabricated to special shapes by powder metallurgical techniques. Unfortunately, the present commercially available powders contain oxygen and metallic impurities which would contribute high Z materials to the plasma. Recently, electrofined Be has been produced [3] with total metallic impurities < 500 ppm. Pellet production with this Be could be explored. Additionally, it has been reported [4] that very clean plasmas have been obtained in JET after the walls were coated with a thin layer of Be deposited by sputtering techniques; consequently, Be impurities in the plasma may not be undesirable.

SURVIVABILITY OF FUEL PELLETS IN PLASMA

The distance that a pellet can penetrate into the plasma is related to the ablation rate caused by the plasma and the velocity of the pellet. Presently available gas guns have been developed which launch D_2 ice pellets at velocities in the range of 2 to 4 km/s. Although higher velocity gas guns are being developed [5], such as two-stage guns, indications are that D_2 ice pellets may disintegrate at velocities > 4 km/s. On the other hand, metallic pellets have been launched from these advanced guns at velocities up to 10 km/s. For this study, I have assumed that Li and Be shell pellets can be launched at this high velocity.

Experimental observations of the pellet fueling of tokamaks and model studies proposed to explain these phenomena have indicated that the ablation process proceeds in three phases, namely;

(a) An initial ablation cloud of neutral gas particles is evolved from the pellet. The evolution of this spherical cloud is described by gas hydrodynamic principles. This gas cloud absorbs plasma electrons as a result of ionization and, thereby, shields the pellet from the high electron flux.

(b) When a significant number (~10%) of the gas particles have been ionized, the gas cloud does not remain spherical but becomes more cylindrical as the ionized particles become trapped along the magnetic flux lines. Because the plasma electrons are also confined to the magnetic lines, the ablated ions provide additional shielding to the pellet. Additional heating of the pellet could be caused by plasma ions because their gyroradii are much larger than for the electrons; consequently, the plasma ions or the plasma ash particles could bombard the pellet from directions unshielded by the pellet cloud. Most studies indicate, however, that this additional heating is a minor effect compared to the electronic heating.

(c) As the fraction of ionized gas particles surrounding the pellet increase, these ions form a cylindrical plasmoid surrounding the pellet. This plasmoid causes a large, local disruption in the magnetic flux field, affecting the electron flux along these field lines. Rediffusion of the magnetic field into the plasmoid requires a significant time.

The neutral and plasma shielding model has been reviewed and updated by Houlberg [6], et al. Lengyel [7] has proposed a model to calculate the dimensions of the plasmoid surrounding the pellet and determine the magnetic rediffusion time. Lengyel coupled his model with that of Houlberg, et al., and obtained good correlations with experimental observations of hydrogenic pellet fueling of present-day tokamaks. Several authors at a recent international symposium regarding pellet fueling [8] caution that this present agreement between experimental and computational results should not be extrapolated to higher power tokamaks in which the plasma temperatures and the magnetic field strengths will be much higher. Based upon this caution, I will only present a scoping study for the survival of Li and Be pellets, i.e. non-hydrogenic pellets, in very high temperature plasmas.

DESIGN CONSIDERATION

In order to gain an appreciation of the neutral cloud shielding, the early model of Milora and Foster [9] was used which yielded the following relationship for the rate of change of the pellet radius, r_o, as a function of time, t;

$$\frac{dr}{dt} = -A \int_{E_o}^{E_\infty} L(E)\, dE \,, \qquad (1)$$

where A = a series of physical parameters

L(E) = the stopping cross-section for electrons

E_∞ = the electron energy of the thermalized plasma

E_o = the degraded electron energy at the surface of the pellet.

The electronic cross-section for Li neutral atoms and ions was determined from reference data [10] as a function of electron energy and presented graphically in Fig. 2. The electronic cross-section for Be is similar to Li, except for the +4 ionization reaction at very high electron energy; consequently, the L(E) values for Li were used for Be, as an initial approximation.

Based on these values of L(E), the rate of ablation of the pellet, dr/dt, was determined by Eq. (1) for the shielded pellet and plotted as a function of the electron energy at the pellet, E_o, see Fig. 3. As can be seen the ablation rates for Li and Be are very high but decrease as E_o approaches E_∞ where the rate of ablation is "bottled-up" by the limiting rate at which atoms can evaporate from the pellet.

The rate of ablation for shielded pellets must be compared to the rate of evaporation of an unshielded pellet. When these values are plotted on Fig. 3, one notices that the values for the bare pellet intersect the shielded model at nearly the "bottled-up" limit, which is much different than for hydrogenic pellets. This difference is due to the fact that the heat of sublimation of Li and Be are ~680 and 1400 times greater, respectively, than for hydrogen. Because of the high energy of E_o at the pellet surface for Li and Be the shielded neutral cloud model is violated since it assumes that all the thermal energy absorbed in the molecular cloud results in thermalized sublimation of molecules from the pellet surface; consequently, the neutral cloud shielding model would need to be radically modified.

Instead of modifying the neutral cloud-plasma shield model, I suggest the use of a model proposed by Parks, et al. [11] to determine the ablation of solid pellets of Li, Be and carbon in tokamaks. Such pellets have been used for plasma diagnostic

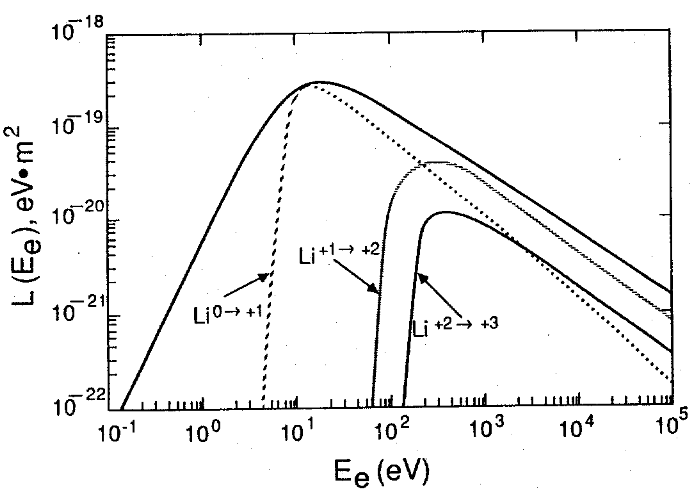

Fig. 2. Energy loss function for monoenergetic electrons in Li.

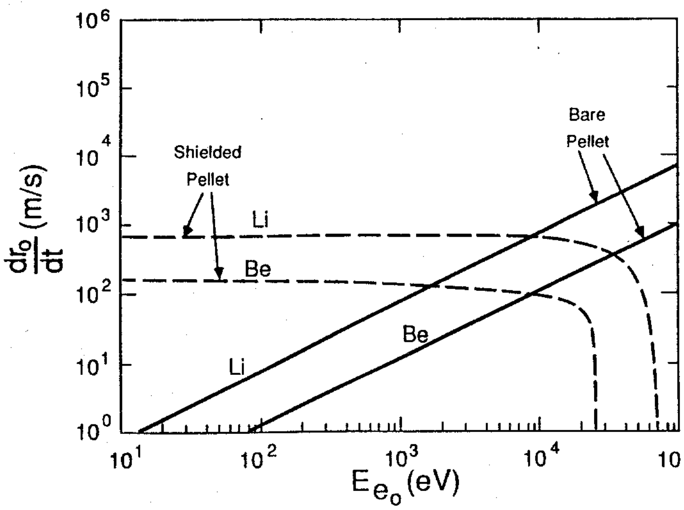

Fig. 3. Pellet ablation rates for the shielded pellet and the bare pellet as functions of the electron energy at the pellet surface.

purposes and the technique has been reviewed at a recent symposium [12]. Park's model examines the phenomenon associated with the absorption of massive energy fluxes deposited on the surface of a pellet, such as occurs during the fuel ignition phase of inertial confinement fusion devices. This high energy flux instantly vaporizes surface molecules, forming a cloud of pressure, p^x. This cloud reflects a pressure at the surface of the pellet, p_s. Based upon the pressure-temperature phase diagram of the solid, a surface temperature, T_s, is calculated by use of the relationship,

$$p_s = A \exp(- B/T_s),$$

where the constants A and B are given [11] for Li and Be.

Based upon the values calculated for p_s and T_s, the particle flux, $v_o n_o$, is determined by the relationship,

$$v_o n_o = (2\ mT_s)^{-1/2}(p_s(T_s) - p_o)$$

where m is the molecular weight of the ablatant and p_o is a background pressure.

Parks', et al., analysis determined that unique values exist for the ratio p_s/p^x. This ratio is ~3.5 for the full shielding limit and ~5.9 in the non-shielding limit. They have estimated that for a partially shielded pellet this ratio is ~4.8. Additionally, they calculate that for an advanced experimental tokamak, such as CIT, p^x is ~10 MPa. This value has been used for the present case because the previous analysis of the neutral and plasma shield indicated that the electron energy at the pellet surface would be degraded to ~10 keV and the magnetic flux in the plasmoid would also be weakened.

Based upon these assumptions, the thickness of the shell, t_d, has been calculated so that the shell will survive for a distance of 1 m in the plasma at a velocity of 10^4 m/s. The calculated values indicate that for a Li shell t_d would need to be ~2 mm which is unreasonable for a pellet with r = 5 mm. For a Be shell, however, t_d needs to be only 300 μm.

PLASMA FUELING-EXHAUST RATE AND PLASMA CONTAMINATION

A d/^{3}He fueled tokamak [1] operating at a fusion power of 3034 MW generates ~ 1 x 10^{21}/s of α and proton particles which must be exhausted at this same rate in order to maintain each of these ash particles at a concentration of ~4.5% of the total ions in the plasma. Based upon the total number of α−particles in the plasma, 8.6 x 10^{21}, the fraction of α-particles exhausted is 0.12/s, for a mean residence time of 8 s. All of the ions in the plasma will have this same mean residence time unless a technique is discovered which can selectively exhaust only the ash particles. The ash accumulation in tokamaks with high current and high field strength causes an additional concern because the energy confinement time scale is ~18 s. Consequently, some technique is needed to permit the exhausting of ash at 2 times this rate without losing the energy confinement.

If the exhaust non-selectively removes plasma particles, then, 9.4 x 10^{21}/s of ^{3}He ions are removed; consequently, the fueling rate required for ^{3}He is this exhaust rate plus the burn rate, 1 x 10^{21}/s for a total of 1.04 x 10^{22}/s of ^{3}He atoms. This number of atoms can be supplied by liquid ^{3}He at 3 K enclosed in a sphere with a radius ~5 mm. The proposed shell of this sphere will be Be at a thickness of 300 μm; however, the Be will accumulate as an impurity in the plasma. In present-day tokamak experiments the plasmas are contaminated with a few percent of carbon impurities. As previously noted, experiments at JET indicate that the carbon impurity is significantly reduced when the vacuum vessel is covered with a thin coating of Be. This information suggests that Be does not sputter as readily as carbon due to plasma ion bombardment and that Be does not readily recycle from the walls. If Be recycle is significantly less than for the fuel particles, then deposition of the Be atoms on the walls and/or limiters represents an additional mechanism to remove Be from the plasma. Studies of power reactor tokamaks have indicated that hydrogenic fuel may recycle from the walls as much as 40-50 times before being exhausted. If the recycle of Be is decreased by a factor of 10, then the amount of Be in the plasma would represent ~5% of the ions. If the Be recycle is decreased by a factor of 50, then Be would constitute only 1% of the plasma ions. Such values for the Be impurity with a low Z number may not seriously impair the operation of a power reactor.

CONCLUSIONS

The design of a pellet containing liquid ^{3}He enclosed within a spherical Be shell of radius 5 mm and wall thickness of 300 μm appears viable for the fueling of large d/^{3}He tokamaks. Smaller versions of this pellet could be used for fueling studies in near-term tokamaks. Validation of this fuel pellet design will come as more experimental and model studies are continued in the fueling of tokamaks with solid hydrogenic pellets and from experiments involving the launching of Li, Be and C pellets into plasmas for diagnostic purposes. The experimental development of the proposed fuel pellet should be straightforward because it is a simple design and all of the components are non-radioactive.

ACKNOWLEDGMENT

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