JUN 5 1989

Professor Weston M. Stacey
Nuclear Engineering and Health
Physics Programs
Georgia Institute of Technology
Atlanta, GA 30332

Dear Professor Stacey:

Thank you for your letter of May 12, 1989.

The idea of cold fusion being catalyzed by cosmic muons has been dealt a severe blow as a result of the experiments by Nakamine et al., as reported at the Santa Fe workshop. As you may by now know, these researchers have exposed deuterized palladium to a muon beam at the Japanese KEK facility. No effect was registered.

Should future experiments (some of which are in progress at Brookhaven) indicate otherwise, your concept would clearly deserve a careful look.

Thanks for sharing your thoughts, and your preprint!

Sincerely,

Original signed by:
Ryszard Gajewski

Ryszard Gajewski, Director
Division of Advanced Energy Projects
Office of Basic Energy Sciences, ER-16

ER-16:RGajewski:sad:3-5995:6-5-89:c:Gajewski:Stacey

ER-16
RGajewski
6/ /89

Georgia Institute of Technology
A UNIT OF THE UNIVERSITY SYSTEM OF GEORGIA
NUCLEAR ENGINEERING AND HEALTH PHYSICS PROGRAMS
SCHOOL OF MECHANICAL ENGINEERING

Please reply to:
NUCLEAR ENGINEERING AND HEALTH PHYSICS PROGRAMS
ENGINEERING SCIENCE AND MECHANICS BUILDING
GEORGIA INST. OF TECHNOLOGY
ATLANTA, GEORGIA 30332 U.S.A.

May 12, 1989

Dr. Ryszard Gajewski, Director
Division of Advanced Energy Projects
ER-16, GTN
U.S. Department of Energy
Washington, DC 20545

Dear Sir:

Although "cold fusion" has faded as a media event and the continuing failure of any major research lab to confirm the Fleischmann-Pons claims casts growing doubt upon their validity, there may yet be some significant results that emerge from all of this activity.

Several people have conjectured that the 2.5 MeV neutrons observed by Jones, et al. (Nature) emanating from D_2O electrolysis cells with palladium and titanium cathodes are due to cosmic muon-catalyzed D-D fusion taking place within the cathodes. Such an interpretation requires that the fusion chain length (average number of fusions catalyzed by a single muon) be several hundred. The fusion chain length in dense D_2 gas is less than one, and in D_2O much less than one. Thus, if the Jones, et al. neutrons are due to cosmic muon-catalyzed fusion, then the D-D fusion chain length can be increased by more than two orders of magnitude relative to D_2 gas by concentrating the deuterium in a transition metal. I believe that there are experiments ongoing at Livermore and Cal Tech (and probably elsewhere) to check this cosmic muon catalyzed D-D fusion conjecture.

If the ongoing experiments confirm the cosmic muon-catalyzed D-D fusion conjecture, then the burning question becomes, does the same thing happen for D-T fusion? Fusion chain lengths of about 150 have already been achieved in dense DT gas. If a one-to-two orders of magnitude increase in the D-T fusion chain length can be achieved by concentrating the DT in a transition metal (e.g. palladium), then a new path for fusion R & D is in the offing. Obviously, an experimental determination of the D-T fusion chain length in a transition metal concentrated in D,T would be of the utmost significance, if the muon-catalyzed fusion conjecture for D-D is confirmed.

Telephone: 404-894-3720 Telex: 542507 GTRIOCAATL Fax: 404-894-3120 (Verify: 404-894-6951)

With a little help from my colleagues, I have speculated on the reactor prospects that would follow from a one-to-two order of magnitude increase in the D-T fusion chain length by concentrating DT in a transition metal fusion core and using an accelerator to produce the muons. The intent of this speculation was to identify the scientific and engineering feasibility issues, hence the most crucial research areas, and to get some rough idea of the magnitudes involved. A preprint of a paper containing these speculations and arguments supporting a cosmic muon-catalyzed fusion explanation of the Jones, et al. results is enclosed.

If the increased D-D and D-T fusion chain lengths conjectured above for D,D and D,T concentrated in a transition metal are confirmed by experiment, then a "reactor study" to identify the feasibility issues and scope the potential would be of great value in guiding an expanded research program. The speculations in the enclosed preprint could be a starting point. Several people at Georgia Tech are interested in being involved in such a study. I personally have experience in organizing and technically directing multi-institutional fusion reactor studies (enclosed reprint). If you decide that such a study should be done, I would be willing to assist you in any way that I can.

Sincerely,

Weston M. Stacey

Weston M. Stacey, Chairman
Nuclear Engineering and Health
Physics Programs

WMS:cv

Enclosures: Preprint "Reactor Prospects of Muon-Catalyzed Fusion of Deuterium and Tritium Concentrated in Transition Metals"

Reprint "The INTOR Workshop: A Unique International Collaboration in Fusion"

REACTOR PROSPECTS OF MUON-CATALYZED FUSION OF DEUTERIUM AND TRITIUM CONCENTRATED IN TRANSITION METALS

W. M. Stacey, Jr.

Fusion Research Center & Nuclear Engineering Program
Georgia Institute of Technology

April, 1989

Preprint of paper submitted to FUSION TECHNOLOGY.

ABSTRACT

It is conjectured that the number of fusion events catalyzed by a single muon is orders of magnitude greater for deuterium and tritium concentrated in a transition metal than in gaseous form and that the recent observation of 2.5 MeV neutrons from a D_2O electrolytic cell with palladium and titanium cathodes can thereby be interpreted in terms of cosmic muon-catalyzed D-D fusion. This suggests a new fusion reactor concept consisting of deuterium and tritium concentrated in transition metal fuel elements in a fusion core that surrounds an accelerator-produced muon source. The feasibility of net energy production in such a reactor is established in terms of requirements on the number of fusion events catalyzed per muon. The technological implications for a power reactor based on this concept are examined. Finally, the potential of such a concept as a neutron source for materials testing and tritium and plutonium production is briefly discussed.

I. INTRODUCTION

"Cold fusion" has been very much in the public eye and a topic of discussion in the scientific community recently, as a result of the massive press coverage of the Fleischmann-Pons (F-P) announcement of electrochemically induced fusion of deuterium concentrated in a transition metal cathode and the subsequent circulation of their paper [1] on the subject. While the F-P results have not yet been confirmed, they may nevertheless suggest an alternative line of research towards fusion power.

Overshadowed by the sensationalism of the press coverage of the F-P announcement and subsequent releases is a paper [2] by S. E. Jones, *et al.* reporting the detection of neutrons (presumably from fusion) in an electrochemical (electrolysis) experiment similar to that of F-P. Jones *et al.* measured neutron levels several orders of magnitude smaller than those reported by F-P. We believe that the neutron levels measured by Jones, *et al.* can be explained by the cosmic muon-catalyzed fusion of deuterium that has been electrochemically concentrated in a transition metal cathode, and this conjecture is discussed in Section II.

If the number of fusions catalyzed per muon is orders of magnitude greater for deuterium and tritium concentrated in a transition metal than in a gas, then a reactor consisting of transition metal fuel elements saturated with D and T in a fusion core surrounding an accelerator-produced source of muons may be possible. This would introduce a third possible path to fusion power--the two paths presently being developed are magnetic confinement and inertial confinement. In this paper, we take a first glimpse down this new path suggested by the recent "cold fusion" experiments. In Section III, the feasibility of net energy production is established in terms of requirements on the number of fusion events catalyzed per muon. The technological implications for a power reactor based on this concept are examined in Section IV, and the potential of such a concept for a neutron source is briefly discussed in Section V. A summary and the principal conclusions are given in Section VI.

II. INTERPRETATION OF COLD FUSION NEUTRON DATA

Jones, et al. [2] report the observation of ~2.5 Mev neutrons emitted during low voltage electrolytic infusion of deuterons into metallic titanium or palladium electrodes at room temperature. The neutron detector was a liquid organic (BC-505) scintillator contained in a glass cylinder 12.5 cm in diameter, in which three Li-6 doped glass scintillator plates were embedded. The detector was calibrated using 2.9 and 5.2 Mev neutrons produced by a deuteron beam from a Van de Graaff accelerator. Background count rates were approximately 10^{-3}/s.

The observed neutron count rate over 13 different runs varied from ~1 to ~3 times background, or from ~0 to ~2 X 10^{-3}/s neutron counts above background. The average 2.5 MeV neutron count rate was about 1 x 10^{-3}/s above background.

Efforts to generate fake neutron signals by switching the Van de Graaff and auxiliary equipment on and off were negative. The neutron counts persisted as shielding was removed and as electronics was tuned or replaced. Similar runs with D_2O replaced by H_2O in the electrochemical cells were without neutron count rates above background. No neutron count rates were recorded when the current was turned off.

Thus, it seems that Jones, et al. have credible evidence for fusion neutrons from the reaction

$$D + D \rightarrow {}^3He\ (.82\ MeV) + n\ (2.45\ Mev). \qquad (1)$$

We conjecture that this reaction was catalyzed by cosmic ray μ-mesons (muons) in the deuterium that had been concentrated in the palladium and titanium electrodes by electrolysis. (We learned during the course of this work of the same conjecture by Guinan, Chapline and Moir [3].)

From Ref. [4], we estimate an intensity of cosmic ray muons $I \simeq 10^{-5}/g.s$, so that the muon source intensity in the $M \simeq 35g$ palladium electrodes used by Jones, et al. is $S_\mu \simeq 5.5 \times 10^{-4}/s$, calculated from

$$S_\mu = \frac{\pi}{2} I M, \qquad (2)$$

where $\pi/2$ is a geometric factor obtained by assuming the incident muons have a $\cos^3\theta$ distribution, where θ is the angle with respect to the perpendicular. The fusion rate, F_μ, in the palladium electrodes is

$$F_\mu = S_\mu f_\mu \qquad (3)$$

where f_μ is the number of fusion events per muon (discussed later). Since about half of the D-D fusion events proceed by reaction channel (1) and the other half proceed by

$$D + D \rightarrow H\ (3\ MeV) + T\ (1\ MeV), \qquad (4)$$

the fusion neutron detection rate is

$$d_\mu = 1/2\ \epsilon\ F_\mu = 1/2\ \epsilon\ S_\mu\ f_\mu, \qquad (5)$$

where ϵ is the neutron detector efficiency.

(There are measurements [5] which indicate that the branching ratio of channels (1) and (4) may be more like 1.4 than 1.0 in muon-catalyzed fusion.)

Taking $d_\mu = 10^{-3}$ n/s, as discussed above, and using the calculated (Monte-Carlo) neutron detector efficiency of 1%, a fusion chain length

$$f_\mu = \frac{2\ d_\mu}{\epsilon S_\mu} = \frac{(2)\ (10^{-3})}{(10^{-2})\ (5.5 \times 10^{-4})} \simeq 360 \text{ fusions}/\mu$$

is required in order to account for the 2.5 MeV neutron count levels measured by Jones, et al. [2] by the cosmic ray muon-catalyzed fusion of deuterium concentrated in the palladium electrodes.

The fusion chain length, f_μ, depends on:

(1) the rate of formation of μDD molecules in which the proximity of the two deuterons is such that the spontaneous fusion rate is quite large ($\gtrsim 10^9$/s);

(2) the probability that the muon released by the fusion event is not trapped by the ^3He ion produced in fusion reaction (1);

(3) the probability that the muon is not trapped by the ions in the metal;

(4) the proximity of other deuterons to form a subsequent μDD molecule and so continue the chain of fusion reactions; and

(5) the muon lifetime of 2.2×10^{-6} s.

The most rapid formation of μDD molecules in a gas proceeds by a resonance reaction [6,7] according to the scheme

$$\mu D + D_2 \rightarrow [\,(DD\mu)\ D2e]_\nu^* \qquad (6)$$

in which a μD atom joins a D_2 molecule to form a peculiar [(DDμ) D2e] muonic molecule which includes a $(DD\mu)^+$ and a D^+ as nuclei. Such a resonance process is possible in a gas state only if the energy released as the muonic molecule forms (DDμ binding energy, E_b, plus initial kinetic energy of the Dμ atom, E_κ) is approximately equal to one of the quantized excited rotational-vibrational states of the muonic molecule; i.e.

$$E_\nu^* = E_b + E_\kappa \qquad (7)$$

where E_ν^* is the excitation energy of the νth vibrational-rotational state of the muonic molecule. Calculations [8] indicate that there is an excited state of the $DD\mu$ molecule which has a binding energy of 1.9 eV, which is small enough to be absorbed in one of the rotational-vibrational states of the $[(DD\mu)\ D2e]_\nu^*$ molecule without breaking it apart. Another constraint on the μDD formation rate is the requirement of angular momentum conservation. Calculations based on this resonant mechanism indicate that in a D_2 gas the formation time for μDD molecules is longer than the muon lifetime of $2.2X10^{-6}$s, and no fusion chain will occur.

We conjecture that for D concentrated in a transition metal lattice the constraints upon the formation rate of the μDD are relaxed, relative to the gas state, and the formation rate is much greater. In the metal there are many lattice excitation modes to absorb excess energy $\Delta E = E_b + E_k - E_\nu^*$ and excess angular momentum, so that the constraint of Eq. (7) and of angular momentum conservation are effectively eliminated. (We note that because D most likely exists as D^+ in the metal lattice, the formation reaction is probably $\mu D + D^+ \rightarrow \mu DD$.)

The probability that upon fusion the muon would be captured by the fusion alpha particle has been calculated [8] to be as large as $W_s^o = 0.012$. However, as the $\alpha\mu$ atom moves through the surrounding medium there is a large probability of the muon being stripped by interactions with deuterons [3], so that the effective trapping probability, $W_s = W_s^o\ (1-R)$, where R is the stripping probability, can be much smaller. Moreover, there are other calculations [8] which suggest a lower value of W_s^o, and there are measurements [8] of W_s for a dense D-T gas which are considerably lower than the theoretical prediction. Muon capture is cumulative, so that the maximum fusion chain length is limited by W_s^{-1}. $W_s^{-1} = 360$ with $W_s^o = 0.012$ requires $R > .77$; the processes discussed in Ref. [3] could possibly lead to such a large stripping probability.

The trapping of a muon by the metal lattice depends upon the availability of unoccupied electronic states, particularly low-lying states beneath the conduction band. The electrons added to the metal lattice with the deuterons in a saturated transition metal should fill all the low-lying states up through the equivalent of the d-shell in a fuel atom. Thus, the muons should be almost completely shielded from the metal atoms in saturated transition metal deuterides (hydrides), and the muon trapping into unoccupied states beneath the conduction band should be very small. This would suggest that the muon-metal trapping probability decreases, hence the fusion chain length increases, as the deuterium concentration in the metal increases, and that there could be a dramatic change in both as the saturation concentration is approached. This could explain an "incubation period" before neutrons are observed in the experiments [1, 2].

The maximum theoretical density of octahedrally sited D^+ ions in a metal lattice is equal to the metal atom density. However, if the metal has vacancies, more than six D^+ ions can be located at each vacancy [9], so that the D^+ density could exceed the metal density. Furthermore, the deuterium is highly mobile in transition metals, with residence times of $\sim 10^{-11} - 10^{-10}$ s at room temperature [10]. Thus, the proximity of other deuterons with which a muon liberated in a fusion event can form subsequent μDD molecules to continue the fusion chain is much greater for deuterium in a saturated lattice than for D_2 gas.

Taking all of these factors into account, it seems plausible that a fusion chain length of several hundred fusions per muon could be obtained in a transition metal lattice saturated with deuterium. Thus, we are led to conclude that the value $f_\mu \simeq 360$ fusions/μ required to explain the Jones, et al. [2] neutron count level is plausible and that cosmic muon-catalyzed D-D fusion is a plausible explanation for the measured neutron count rates.

An explanation in terms of cosmic muon-catalyzed D-D fusion of the 4×10^4/s fusion neutron rate reported by Fleishmann-Pons (F-P) [1] for a similar experiment would require a fusion chain length of f_μ ~$O(10^8)$, which is clearly implausible. However, one may question the F-P neutron rate on several counts. An effective detector efficiency of about 10^{-6} was used to convert count rate to total fusion neutron rate. They did not report any checks of the sensitivity of their measurements to other experimental or environmental factors that could have introduced spurious counts. They took their background in a different room.

III. FEASIBILITY OF NET ENERGY PRODUCTION

The implication of the previous section is that substantially increased fusion chain lengths for muon-catalyzed fusion of D-D (or D-T) can be achieved by concentrating deuterium (or deuterium plus tritium) at saturation levels in transition metals. This suggests that concentrating D (or D+T) at saturation levels in transition metals would be more efficient than using these materials in gaseous form in a muon-catalyzed fusion reactor.

It would be glorious indeed if we could speculate on such reactors being catalyzed solely by cosmic muons. Unfortunately, a simple calculation quickly dispels that speculation. The fusion power output of a reactor operating on cosmic muon-catalyzed fusion can be written

$$P_f = Q_f \, f_\mu S_\mu = Q_f \, f_\mu \, \frac{\pi}{2} \, I \, M, \qquad (8)$$

where Q_f is the energy release per fusion. Taking P_f = 100 MW, Q_f^{DD} = 4 MeV and Q_f^{DT} = 23 MeV, we find that the product $f_\mu M(g)$ must be ~10^{25} for D-D fusion and ~10^{24} for D-T fusion.

So, nature has not served us a free lunch, and we need to consider an accelerator-based μ-meson source (accelerators produce pi-mesons which decay into μ-mesons in 2.5 X 10^{-8}s) combined with a "fusion core" consisting of a transition metal saturated with deuterium or deuterium plus tritium. The electrical power produced by muon-catalyzed fusion in such a reactor may be written

$$P_{el} = \eta_t S_\mu f_\mu Q_f \eta_{th}, \tag{9}$$

where S_μ (s^{-1}) is the rate of μ-meson (pion) production, η_t is the efficiency with which the muons are delivered from the point of (pion) production to the deuterium (tritium) in the fusion core, η_{th} is the efficiency of converting the fusion power to electrical power, and f_μ and Q_f were defined above.

The power required to produce the μ-mesons may be written

$$P_\mu = \frac{Q_\mu}{\eta_\mu} S_\mu, \tag{10}$$

where Q_μ is the energy required to produce a muon, η_μ is the efficiency of converting electrical energy to muon production energy, and S_μ is the muon production rate.

A figure of merit is the energy amplification factor

$$Q = \frac{P_{el}}{P_\mu} = \frac{(f_\mu Q_f)\eta_t \eta_{th}}{(Q_\mu/\eta_\mu)} \tag{11}$$

The parameters $(f_\mu Q_f)$ characterize the fusion core. The parameters (Q_μ/η_μ) characterize the muon production system. The parameter η_t characterizes the system for delivering the muons to the fusion core. The parameter η_{th} characterizes the fusion-to-electrical energy conversion system. Each parameter will be discussed in turn.

If the analysis of the previous section is correct, muon-catalyzed fusion chains of $f_\mu^{DD} \simeq 360 \pm 100\%$ have been observed in a transition metal lattice saturated with deuterium at room temperature. The formation rate of the μDD molecule in D_2 gas has been observed [7] to increase with temperature up to about 400°K, after which it is predicted [7] to slowly increase up to about 540°K, then slowly decrease. Based upon this observation, one could expect ~30% increase in f_μ^{DD} for a D_2 gas if the temperature were increased from room temperature to reactor temperatures. However, the μDD formation mechanism is probably different for D^+ in a metal than for a D_2 gas, and there is no information on the temperature dependence in a metal.

It does not seem unreasonable to anticipate that the fusion chain length could be increased above the value apparently obtained in the Jones, et al. experiment [2] by temperature or other factors, so that $400 \lesssim f_\mu^{DD} \lesssim 1000$ might be achieved in a D-D fusion reactor.

Muon-catalyzed fusion chain lengths $f_\mu^{DT} = 150$ have been observed [8] in equimolar D-T gas mixtures at a density of 5×10^{22}/cc and at temperatures less than 100°K. The measurements showed a roughly linear density dependence, which, in itself, would cause f_μ^{DT} to scale up 30-50% at densities ($6 - 8 \times 10^{22}$/cc) expected in saturated transition metal lattices.

The μDT molecule formation rate should also be increased in a transition metal relative to a gas, due to the relaxation of energy and angular momentum constraints that lead to a resonant condition for formation, as discussed in the previous section. The key question is how much of an increase. If the situation is similar to what appears to be the case for D-D, we could expect at least a hundred-fold increase in f_μ^{DT}.

The energy released per fusion by reaction (1) is

$$Q_f^{DD} = .82 + 2.45\,(1 + \gamma^{DD}) \text{ MeV}$$

and by reaction (4) is

$$Q_f^{DD} = 4.0 \text{ MeV},$$

where γ^{DD} is the additional energy liberated by exoergic neutron reactions with the materials in and surrounding the fusion core. If reactions (1) and (4) occur with equal probability, the average is

$$\langle Q_f^{DD} \rangle = 2.41 + 1.23\ (1+\gamma^{DD})\ \text{MeV}$$

The D-T fusion reaction

$$D + T \rightarrow {}^3He\ (3.5\ \text{Mev}) + n\ (14.1\ \text{Mev}) \qquad (12)$$

releases

$$Q^{DT} = 3.5 + 14.1\ (1 + \gamma^{DT})\ \text{MeV.}$$

The quantity $\gamma^{DT} \simeq 1/4 - 1/2$, unless fissionable material is present, in which case it can become quite large [11]. The quantity γ^{DD} is smaller because the cross sections for exoergic reactions increase strongly with neutron energy. For our estimates, we will use $Q_f^{DD} = 4$ Mev and $Q_f^{DT} = 23$ MeV.

Muons can be produced by accelerating tritons to several GeV energy and delivering them to a D-T target (gaseous or solid). It is estimated [8] that $Q_\mu/\eta_\mu \simeq 5$ GeV is required to produce a muon by advanced techniques. Another estimate [12], based on accelerating tritons to 2700 MeV and estimating that two-thirds of the collisions in the target lead to muons, yields $Q_\mu = 3/2 \times 2700 = 4050$ MeV. The grid-to-triton beam power energy conversion efficiency is estimated [8] to be 60% in such a triton accelerator. Assuming some beam energy recovery and the conversion of the energy of the neutrons and protons produced in the target, we estimate an effective $\eta_\mu = .8$, which reconciles the two estimates [8, 12]. We note that two colliding beams of 600 MeV tritons would produce a muon for $Q_\mu = 2 \times 3/2 \times 600 = 1800$ MeV [12], but we consider this a much more speculative muon source. Thus, we take $Q_\mu = 4000$ MeV and $\eta_\mu = .8$ for our purposes.

The quantity η_t is the product of: 1) the probability η_{t1} that a pion produced at the accelerator target escapes capture and is not lost from the system before it decays into a muon (mean lifetime 2.5×10^{-8}s); 2) the probability η_{t2} that the muon escapes capture and is not otherwise lost from the system before it enters the fusion core; and 3) the probability η_{t3} that the muon escapes capture within the fusion core and forms a μDD (μDT) molecule to initiate a fusion chain. A magnetic confinement system is described in Ref. [5] for which $\eta_{t1} \times \eta_{t2} \simeq .8$. We propose (Section IV.D) placing the accelerator target in the center of the fusion core to achieve $\eta_{t1} \times \eta_{t2} \simeq .8$. Achieving a high value of η_{t3} is an engineering design feasibility issue. We will take $\eta_t = \eta_{t1} \times \eta_{t2} \times \eta_{t3} \simeq .8$ for our purposes.

An energy conversion efficiency $\eta_{th}=.4$ is plausible with existing technology, provided that a fusion core can be operated with sufficiently high coolant outlet temperature.

Using these estimates we are in a position to estimate energy amplification factors for muon-catalyzed D-D and D-T reactors from Eq. (11), which we rewrite as

$$Q_{DD} = \frac{((f_\mu^{DT})\ (4))}{((4000)/(.8))}\ (.8)\ (.4) = .025\ (f_\mu^{DT}/100)$$

and (13-a)

$$Q_{DT} = \frac{((f_\mu^{DT})\ (23))}{((4000)/(.8))}\ (.8)\ (.4) = .15\ (f_\mu^{DT}/100).$$

If we interpret the Jones, et al. experiment [2] as an experimental determination of $f_\mu^{DD} = 360$ fusions/μ and take the LAMPF experimental value [8] of $f_\mu^{DT} = 150$ fusions/μ, then based on values of f_μ already achieved experimentally, we would estimate $Q_{DD} \simeq$ and $Q_{DT} \simeq 0.2$ as lower bounds. As discussed above, there are reasons to anticipate that f_μ^{DD} could increase by 2-3, which would still yield $Q_{DD} < 1$. On the other hand, there is some justification for hoping that f_μ^{DT} might increase by two orders of magnitude or more, as discussed by two orders of magnitude or more, as discussed above, which would lead to $Q_{DT} \gg 1$. An increase over already achieved values of f_μ^{DT} by roughly a factor of X 4.5 to 675 would yield $Q_{DT} \simeq 1$, and an increase X 45 would yield $Q_{DT} > 10$. Recalling that f_μ^{DD} increased by more than two orders of magnitude in going from D_2 gas to D^+ in a transition metal lattice, such increases in f_μ^{DT} do not seem impossible.

The achievable values of f_μ for D-T and D-D are clearly the major scientific feasibility issue for muon-catalyzed fusion energy production. The various factors upon which f_μ depends for D-D and D-T fusion in a transition metal were discussed above. Highest priority should be given to experimental and theoretical investigation of these factors.

If the fusion core is surrounded by a blanket containing fissionable material, the multiplication of the fusion neutron energy in the blanket can become a factor of ~ 10; i.e. $\gamma^{DT} \simeq \gamma^{DD} \simeq 10$. In this case, $Q_f^{DD} \simeq 16$ and $Q_f^{DT} \simeq 160$, and Eqs. (13-a) become

$$Q_{DD} \simeq 0.1(f_\mu^{DD}/100)$$
and
$$Q_{DT} \simeq 1.0\ (f_\mu^{DT}/100). \tag{13-b}$$

In this case, the Jones, et al. [2] value $f_\mu^{DD} \simeq 360$ fusions/μ leads to $Q_{DD} \simeq .4$. A factor of approximately x 3 improvement is required for $Q_{DD} > 1$, and a factor x 30 improvement is required for $Q_{DD} > 10$. For D-T fusion, the experimentally achieved value [8] $f_\mu^{DT} = 150$ fusions/μ leads to $Q_{DT} = 1.5$, and only a x 7 improvement is needed for $Q_{DT} > 10$.

The definition of Q used here does not include the electrical power requirements for auxiliary reactor systems and the balance of plant. Assuming that these power requirements are about half the power required to operate the accelerator, $Q \gtrsim 1.5$ would be required for net electrical power production for a plant. A commercially viable plant must produce substantially more power than it consumes. Let us take $Q \gtrsim 5$ as a threshold for commercial viability, and estimate the required fusion chain lengths in an accelerator muon-catalyzed fusion reactor with the deuterium (and tritium) concentrated in transition metal fuel elements. For D-D fusion, $f_\mu^{DD} \gtrsim 20{,}000$ would be required for a commercially viable, pure fusion reactor; and $f_\mu^{DD} \gtrsim 5{,}000$ would be required for a commercially viable, fission-enhanced reactor. Fusion chains of these lengths do not seem plausible, based on the information available today. For D-T fusion, $f_\mu^{DT} \gtrsim 3300$ would be required for a commercially viable, pure fusion reactor; and $f_\mu^{DT} \gtrsim 500$ would be required for a commercially viable, fission-enhanced reactor. This latter fusion chain length should be achievable; and the former fusion chain length is plausible provided that an order of magnitude enhancement in the fusion chain length is achieved for D-T in a transition metal relative to D-T gas, as appears to have been the case for D-D.

IV. REACTOR IMPLICATIONS

A reactor would consist of a fusion core, a surrounding blanket, an accelerator-based pion source, a pion-muon conversion system, and auxiliary systems.

A. Fusion Core

The fusion core would consist of the transition metal "fuel elements" within which the D (D and T) was concentrated, a coolant to remove the heat into which the fusion energy is converted, structural material, and possibly other materials as discussed below. The criteria that would determine the configuration of these materials are: 1) achievement of a high probability, η_{t3}, that a muon entering the fusion core survives capture to initiate a fusion chain, or achievement of a high value of η_t if the accelerator target is placed within the fusion core; 2) achievement of long fusion chains per muon, $f\mu$; 3) achievement of acceptable operating temperatures in the transition metal; 4) achievement of high coolant outlet temperatures; and 5) achievement of high power density or neutron flux objectives.

The energy released by the fusion event will be in the form of kinetic energy of charged particles and neutrons. The former will be converted to heat by collisions with the lattice atoms within a small region about the fusion site. The neutron energy will be converted to heat over a larger region (~ 10's of cm) about the fusion site. Thus, the geometric fine structure of the fusion core will be determined in large part by the requirement to remove that fraction of the fusion energy carried by charged particles (66% for D-D, 20% for D-T) as heat from the transition metal "fuel elements". Most of the neutron energy can be converted to heat outside of the transition metal fuel element, perhaps directly in the coolant.

By comparison with nuclear fission reactor fuel elements, the transition metal "fuel elements" of a fusion core would seem to have some thermal advantages. Firstly, the thermal conductivity and heat capacity of palladium are larger than those of stainless steel or zirconium (and much larger than the thermal conductivity of uranium oxide). However, the thermal conductivity may be altered by hydride formation. Secondly, the fraction of the nuclear energy deposited within the fuel element by charged fusion products is smaller for fusion (66% for DD, 20% for DT) than for fission (85%). Thus, one might expect that fusion reactor fuel elements could tolerate a higher power density or be larger than fission reactor fuel elements. Dimensions as large as a few centimeters might characterize the fine structure.

Consider the extension of the "electrolytic cell" concept used in the recent experiments [1, 2] to a reactor. One could envision an array of concentric annuli cells, with a 1-2 cm radius cylindrical palladium cathode at the center surrounded by D_2O

(DTO), and then an annular anode which formed the outer boundary of the cell with radius 5-10 cm. In such a configuration, the D_2O (DTO) would also act as the coolant to remove the heat generated within the cathode by fusion, provided that the flow velocity (~ 20 ft/s), high pressure and fluid temperature required for sensible heat removal are compatible with the maintenance of the chemical electrode potential that is necessary to galvanostatically concentrate D^+ (D^+ and T^+) into the cathode. Alternatively, the cathode could be cooled internally, if the palladium was separated from the coolant by a diffusion barrier to prevent excessive loss of D^+ (D^+ and T^+) to the coolant.

Thermodynamic efficiency (η_{th}) would be improved by operating the cathode at high temperatures (many hundred °C). However, the solubility of D (D and T) in palladium decreases with increasing temperature [13]. Whether or not a cathode design can be found that allows an operating temperature compatible with both high η_{th} and high D (D and T) concentration in the cathode is an engineering feasibility issue.

A fusion core consisting of an array of electolytic cells would provide for continuous "refueling"--i.e. replenishment of the D (D and T) fusion fuel. In fact, the achievable concentration could conceivably increase with time because of radiation damage--at least 6 D (D or T) will be attracted to a single lattice vacancy [9]. However, the accumulation of the He fusion product in the cathode could reduce the fusion chain length by increasing the muon trapping rate. Moreover, the electrode potential that is needed to concentrate the D (D and T) into the cathode is very sensitive to the state of activation of the surface with regard to its ability to equilibrate with the D_2O (DTO) molecules dissolved in the electrolyte [13], and the termination of heat and neutron production in the recent experiments [1, 2] seems to have been associated with a change in surface conditions. Maintenance of appropriate surface conditions may be another major engineering feasibility issue for the electrolytic cell fusion core concept.

An alternative to the electrolytic cell fusion core concept is the clad fuel element concept. D (D and T) would be concentrated in a palladium fuel element--by electrolysis, baking in a D (D and T) atmosphere, or other means--then the fuel element would be clad with a material that formed a barrier to the diffusion of D (and T). Arrays of these clad fuel elements could then be configured similarly to the configuration of fuel elements in nuclear fission reactors, with the fusion heat being removed by coolant flowing over or within the clad fuel elements. The D (or D and T) density in such a clad fuel element might be 5×10^{22}/cc, so that a 10% burnup corresponds to .12 MW.days/cc or 10^4 MW.days/ton Pd, for D-T fusion.

Palladium was used in the above discussion because it: 1) can concentrate a large amount of D (D and T); 2) has an electronic structure such that when it is fully loaded with D (D and T) the low-lying electronic states beneath the conduction band are almost completely occupied and the electrical charge of the nucleus is almost completely shielded, thus minimizing muon capture; 3) has acceptable thermal and strength properties. Any other metal which satisfies these three criteria could also be considered.

The fusion process could be terminated within $\sim 10^{-6}$ s by turning off the accelerator source of muons, and the temperature dependence of the D (D and T) solubility would provide a stabilizing negative feedback on the slow time scale. So, control of the fusion process would not appear to be a safety concern. The major safety concerns for the fusion core would seem to be the possibility of a hydrogen explosion and the large tritium inventory in the transition metals.

B. Blanket

In addition to being a heat source, the fusion core would be a copious neutron source. The fusion core could be surrounded by a blanket designed to utilize the neutrons escaping from the core. The energy of these neutrons could be enhanced by exoergic (n, 2n), (n, p) etc. reactions in the blanket, and could be multiplied many times over by fission reactions. The blanket could also be used for breeding tritium by neutron capture in Li or for breeding fissile material by neutron capture in U-238 or Th-232. Such blankets should be very similar to those which have been conceptualized for plasma fusion applications [14, 15].

C. Accelerator Muon Source

Equation (9) can be rewritten to determine the muon source rate, S_μ (μ/s), needed to produce a given amount of electrical power

$$S_\mu\ (\mu/s) = \frac{P_{el}}{\eta_t \eta_{th} f_\mu Q_f} \simeq \frac{1.9 \times 10^{21}\ P_{el}(100 MW_e)}{f_\mu Q_f(MeV)} \qquad (14)$$

An efficiency η_t = .8 of delivering muons from the accelerator to the fusion core [5] and a thermal-to-electrical conversion efficiency η_{th} = .4 were used in Eq. (14).

It may be possible [8] to build triton accelerators, based on extensions of the rf quaddrupole technology developed over the past decade, that would deliver $\simeq$ 200 mA ($\simeq 1.3 \times 10^{18}$ tritons/s) beams of $\simeq$3 GeV tritons at a grid-to-beam power efficiency of $\eta_\mu \simeq$ .6. (We note that 200mA of 3 GeV tritons is a beam power of 650 MW corresponding at η_μ = .6 to $\simeq$ 1.1 GW of power to the grid. Such a beam could probably vaporize any solid target.) About 2/3 of the tritons incident on a D-T target will produce negative pions [12], which decay into negative muons. Thus, it is plausible to anticipate an accelerator-based muon source of $S_\mu \simeq$ 8-9X10^{17} μ/s. A colliding-triton beam muon source based on two lower energy triton accelerators [12] could produce a similar muon source rate with lower energy tritons and a greater energy efficiency, but at the added expense of a second accelerator.

Using $S_\mu = 9 \times 10^{17} \mu/s$, Eq. (14) yields the minimum fusion chain length required to produce a given amount of electricity.

$$\bar{f}_\mu \simeq \frac{1.9 \times 10^{21} P_{el}(100\ MW_e)}{S_\mu Q_f(MeV)} \simeq \frac{2 \times 10^3 P_{el}(100\ MW_e)}{Q_f(MeV)} \qquad (15)$$

Using $Q_f^{DD} = 4$ MeV and $Q_f^{DT} = 23$ MeV for "pure" fusion,

$\bar{f}_\mu^{DD} \simeq 500\ P_{el}(100\ MW_e)$
and
$\bar{f}_\mu^{DT} \simeq 87\ P_{el}(100\ MW_e)$.

From this calculation and the previous estimates of achievable values of f_μ, we tentatively conclude that a single accelerator would support a D-T reactor up to any desired power output, but that a single accelerator would support a D-D reactor only up to the $\simeq$ 100 MW_e power output level.

Looking at this another way, for a given fusion chain length and electrical power output, Eq. (14) gives the muon source required for a pure fusion reactor. A commercially viable, pure fusion, DT reactor was estimated to require $f_\mu^{DT} \gtrsim 3300$, which would require $S_\mu \simeq 2.5 \times 10^{17}\ \mu/s$ for a 1000 MW_e output. For a fission-enhanced, DT reactor, the required S_μ can be estimated from Eq. (14) if P_{el} is understood to be the fusion contribution to the electrical power output, which is about 15% for $\gamma^{DT} \simeq 10$. A commercially viable, fission-enhanced, DT reactor was estimated to require $f_\mu^{DT} \gtrsim 500$, which would also require $S_\mu \simeq 2.5 \times 10^{17}$ μ/s. The required S_μ scales linearly with the electric power output, so the value $S_\mu \simeq 9 \times 10^{17}\ \mu/s$, which was estimated to be the maximum achievable from a single accelerator, could support commercially viable DT reactors up to about 3500 MW_e.

D. Pion-Muon Conversion

High energy tritons impinging on a solid D-T target produce copious quantities of pi-mesons (pions), neutrons, protons, and alpha particles. In principle, it is possible to recover and directly convert to electricity the protons and alpha particles and to recover the energy of the neutrons as heat in a surrounding material, thus improving the efficiency of producing the muons. The pions must be confined until they decay into muons (lifetime 2.5×10^{-8}s), and then the muons must be delivered to the fusion core.

Previous concepts (e.g. [5]) for such a pion-muon conversion system involve magnetic confinement of the pions and an electric field to accelerate the muons out of the pion confinement region into the fusion core. The dimensions, magnetic fields and vacuum requirements for such systems are comparable to those envisioned for the confinement of plasmas in conceptual designs of magnetic fusion reactors. An efficiency $\eta_t \simeq .8$ has been estimated [5] for confinement and conversion of pions to muons and delivery of muons to the fusion core.

The flux of muons emerging from the pion-muon conversion system must be delivered to the D (DT) saturated transition metal in the fusion core. This may impose certain constraints on the geometrical configuration and materials of the fusion core. For example, it may be necessary for the muon flux to be incident directly on the transition metal.

A pion-muon conversion system of this type (e.g. [5]), which is comparable in technological complexity with a magnetic plasma confinement system, combined with a large accelerator and a fusion core and blanket, would almost certainly be more complex technologically than a magnetic fusion plasma confinement system (which is also the "fusion core") plus a similar blanket, which are the principal ingredients of a magnetically-confined plasma fusion reactor. There is no possibility of eliminating either the accelerator or the fusion core, so we will consider briefly an idea for eliminating the pion-muon conversion system.

If the accelerator target were to be located in the center of the fusion core, and the dimensions of the surrounding fusion core were large enough to insure that the pion decayed to a muon before it traversed the fusion core, then no separate magnetic pion storage system is required.

Pions lose energy by ionization in passing through matter. We estimate from range-energy relationships [16] that a 1 GeV pion has a range of ~ 1m in a 50-50 mixture of D_2O (DTO) and palladium. Pions also interact strongly with atomic nuclei in scattering and absorption collisions. A scattering event would cause an energy loss, hence reducing the range estimated above on the basis of ionization. The mean free path for nuclear collisions is about 80 g/cm^2 for light elements and about 150 g/cm^2 for heavy elements [16], which corresponds to about 15 cm in a 50-50 D_2O (DTO)/Pd mixture. When a pion is captured in an atomic nucleus, practically all of the rest mass energy (140 MeV) of the captured pion is transmitted to the nucleus and is usually expended in the disruption of the nucleus into fragments with considerable kinetic energy. For example, π^-capture by D produces two neutrons. This energy production would partly compensate, in the overall energy balance, for the loss of a pion via nuclear capture and the consequent loss of a fusion chain producing $f_\mu Q_f$ energy.

Pion capture by atomic nuclei could be a significant loss mechanism and is, perhaps, the principal scientific issue associated with this concept of surrounding the accelerator target with the fusion core. It may be possible to choose materials with large nuclear scattering and small nuclear capture cross sections for the part of the fusion core facing the target chamber. It may be necessary to magnetically retard the pions in the target chamber to enhance the likelihood of pion decay prior to capture. The magnetic rigidity of highly energetic pions is $RB = mv\gamma/e \simeq .45\gamma$. Allowing $\gamma \equiv (1-v^2/c^2)^{-1/2} \lesssim 10$ for relativistic effects, $RB \lesssim 5$. A roughly spherical magnetic mirror configuration with B=10T and R=0.5m should suffice to retard the pions until they decay.

A negative muon, emitted in the decay of a negative pion, loses energy by ionization, but does not have nuclear interactions. The range of the muon formed in pion decay depends upon the kinetic energy of the muon, and hence upon the kinetic energy of the decaying pion. If it is necessary to magnetically retard the pion in the target chamber, then the muon kinetic energy is on the order of a GeV. The range-energy relations for muons are very similar to those for pions, so ~ 1m of a 50-50 mixture of D_2O (DTO) and palladium is sufficient to bring the muon to rest because of ionization energy loss. If, on the other hand, the pion is free to traverse the fusion core, loosing energy by ionization in the process, then the muon will be created with kinetic energy much less than a GeV. The range decreases dramatically with energy. For example, we estimate from the range-energy relationships [16] that the range of a 10 MeV muon in a 50-50 D_2O (DTO)/Pd mixture is $\lesssim$ 10 cm. Once a negative muon comes to rest in matter, muonic molecule formation or nuclear capture is virtually certain.

Thus, we envision a roughly spherical fusion core of thickness > 1m surrounding a solid or gas D-T target upon which the high energy tritons from the accelerator are incident. (A gaseous D-T target would have the advantage of eliminating the requirement for access for target replacement.)

E. Fusion Core Size and Power Density

The minimum dimensions of the fusion core would be set by the range of the energetic pions, which is estimated to be ≃ 1m.

Thus, the minimum size fusion core might be a spherical shell of thickness 1m surrounding a spherical target chamber of radius ≃ 0.5m, which would have a volume of ~ $15m^3$. A larger volume is probably needed to obtain a reasonable power density. For example, the core average power density is about 10 MW/m^3 in fossil fuel plants, gas-cooled and CANDU-type D_2O-cooled nuclear reactors; and about 100 MW/m^3 for pressurized water nuclear reactors. For an electrical output of 1000 MW_e and $\eta_{th} = .4$, volumes of 250 and $25m^3$ would lead to thermal power densities of 10 and 100 MW/m^3, respectively. These volumes correspond to spherical shells of ~ 3.9m and ~ 1.8m, respectively, surrounding a spherical target chamber of radius 0.5m.

F. Engineering Issues

In addition to the issues discussed above, which are unique to muon-catalyzed fusion in a transition metal fusion core type reactor, there are a host of engineering issues such as radiation damage, hydrogen embrittlement, tritium containment, etc. too numerous to even enumerate here. Reviews of the engineering issues for magnetic confinement fusion reactors [17] (excluding the plasma heating and confinement issues) and for muon-catalyzed fusion reactors with gaseous fusion cores [18] provide a good starting point for examination of these additional engineering issues.

V. NEUTRON SOURCE IMPLICATIONS

The fusion neutron source rate may be written

$$S_n \text{ (n/s)} = \beta f_\mu S_\mu \eta_t, \tag{16}$$

where β = 1/2 for D-D and β = 1 for D-T. Using $S_\mu = 9 \times 10^{17}$ μ/s and $\eta_t = .8$, Eq. (16) yields

$$S_n^{DD} \text{ (n/s)} = 3.6 \times 10^{17} f_\mu^{DD}, \qquad S_n^{DT} \text{ (n/s)} = 7.2 \times 10^{17} f_\mu^{DT}.$$

Using the value f_μ^{DD} = 360 fusions/μ inferred from the Jones, et al. experiment [2] and the measured value f_μ^{DT} from the LAMPF experiments [8], a lower bound on the neutron source rate is $\simeq 10^{20}$ n/s for D-D or D-T fusion. The potential for increasing f_μ^{DT} by ~ 2 orders of magnitude translates into the potential for a neutron source rate of $\simeq 10^{22}$ n/s. This large neutron source could be exploited for materials testing, tritium production and fissile fuel production.

VI. SUMMARY AND CONCLUSIONS

It is conjectured that the observation of 2.5 MeV neutrons coming from a D_2O electrolytic cell with palladium and titanium cathodes is due to D-D fusions catalyzed by cosmic ray muons. If this conjecture is correct, then the experiment demonstrated that the number of fusion events catalyzed per fusion event is orders of magnitude greater for deuterium concentrated in a transition metal than for D_2 gas.

We find that the implication of increasing the muon-catalyzed D-T fusion rate by 1-2 orders of magnitude relative to what has been achieved experimentally in a D-T gas is that a net power producing reactor consisting of a transition metal core, saturated with D and T, combined with an accelerator-produced muon source becomes feasible from the power balance standpoint. Specifically, ~ 3300 fusions per muon for a pure D-T fusion reactor, or ~ 500 fusions per muon for a fission-enhanced D-T fusion reactor, are required for practical feasibility. Fusion reactors based on D-D do not appear to be capable of achieving net electrical power production.

The main scientific feasibility issue is the achievable number of fusions catalyzed by a muon in a transition metal saturated with D and T. Experiments presently ongoing should confirm or discredit the conjecture that the neutron observations reported in Ref. [2] are due to cosmic ray muon-catalyzed D-D fusion. If the result is confirmatory, the experimental determination of the number of fusion events per muon that can be achieved in D-D and in D-T concentrated in transition metals and the complementary theoretical analysis should be pursued with high priority.

In the reactor concept presented in this paper, an accelerator produces pions, which decay into muons, at a target surrounded by the fusion core. This concept depends upon the feasibility of achieving a low pion nuclear capture probability in the fusion core and has the great advantage of eliminating the separate complex pion storage and muon production system that has been a feature of gas-core, muon-catalyzed fusion reactor concepts in the past. The fusion core is surrounded, in turn, by a blanket to utilize the copious fusion neutron source for tritium and/or fissile breeding and possibly for fission enhancement of the energy output.

An accelerator that produces ~ 3 GeV tritons is required. The power required to run such an accelerator to produce the required muon source is ≃ 1/4 - 1 GW, and the power in the beam is about half of this amount, depending on the power output of the reactor. Construction of such an accelerator is a major technological feasibility issue.

Two fusion core concepts were proposed. One is an adaptation of the electrolytic cell concept in which the D and T in the cathode are constantly replenished. The technical feasibility issues with this concept are: 1) achieving a cathode temperature that is compatible with sensible heat production and with D,T solubility in the cathode; and 2) maintaining acceptable cathode surface conditions. An alternate concept is based on transition metal fuel elements in which the D,T is concentrated (by electrolysis, baking, etc.) and which are then clad with a material that serves as a D,T diffusion barrier.

Like any fusion reactor, the concept discussed in this paper would be a copious source of neutrons which could be exploited for materials testing, tritium production and plutonium production.

We find the technological implications for a reactor based on accelerator-produced muon-catalyzed fusion of D,T concentrated in a transition metal core imposing, even under relatively optimistic assumptions. We certainly cannot make any judgements about its complexity vis-a-vis other approaches to fusion at this early stage, but we can conclude that it definitely is not the long-awaited panacea of a simple approach to fusion.

ACKNOWLEDGEMENT

The author wishes to express his appreciation for stimulating discussions during the course of this work with many of his colleagues at Georgia Tech, in particular with S. Abdel-Khalik, M. Hayes, U. Landman, A. Schneider and C. Thomas.

REFERENCES

1. M. Fleischmann, S. Pons, J. Electroanal. Chem., 261 (1989) 301.

2. S.E. Jones, et al., "Observation of Cold Nuclear Fusion in Condensed Matter", Nature, submitted.

3. M.W. Guinan, G.F. Chapline, R.W. Moir, "Catalysis of Deuterium Fusion in Metal Hydrides by Cosmic Ray Muons", LLNL report UCRL-100881 (1989); submitted to Phys. Rev. Lett.

4. G.N. Fowler, W. Wolfendale, "The Hard Component of μ-Mesons" in Handbuck der Physik, Cosmic Rays 1, ed. K. Sitte, Springer-Verlag, New York (1967) 292.

5. L. Bracci, G. Fiorentini, Fusion Techn., 8 (1985) 2646.

6. E.A. Vesman, Sov. Phys. JETP Lett., 5 (1967) 91.

7. S. Gerstein, L. Ponomarev, Phys. Lett., 72B (1977) 80.

8. S.E. Jones, Nature, 321 (1986) 127.

9. P. Nordlander, J. Norskov, F. Besenbacher, "Multiple Deuterium Occupancy of Vacancies in Pd and Related Metals", Phys. Rev. Lett., submitted.

10. J. Volkl, G. Alefeld, in Recent Development in Diffusion in Solids, ed. A. Nowick, J. Burton, Academic Press, New York (1975).

11. W.M. Stacey, Fusion, Sect. 10.5, Wiley-Interscience, New York (1984).

12. G. Chapline, R. Moir, J. Fusion Energy, 5 (1986) 191.

13. F.A. Lewis, The Palladium Hydrogen System, Academic Press, London (1967).

14. D.L. Smith, ed. in Fusion Techn., 8 (1) (1986).

15. S.I. Abdel-Khalik, Nucl. Techn./Fusion, 3 (1983) 53.

16. R.B. Leighton, "Principles of Modern Physics", McGraw-Hill, New York (1959).

17. W.M. Stacey, et al., Nucl. Techn./Fusion, 5 (1984) 266.

18. S.E. Jones, Fusion Techn., 8 (1985) 1511.