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BY

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INTERSTELLAR PROPULSION USING A PELLET STREAM FOR MOMENTUM TRANSFER

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ABSTRACT

A pellet-stream concept for interstellar propulsion is described. Small pellets are accelerated in the solar system and accurately guided to an interstellar probe where they are intercepted and transfer momentum. This propulsion system appears to offer orders-of-magnitude improvements in terms of engineering simplicity and power requirements over any other known feasible system for transport over interstellar distance in a time comparable to a human lifespan.

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to be submitted (without postscript) to *J. Brit. Interplaneta Soc.*

1 INTRODUCTION

1.1 On-board Propulsion

Interstellar transport using on-board rocket propulsion will require formidable technological advances, even for flights taking up to 100 years with velocities small compared to the speed of light. Exotic on-board propulsion systems such as antimatter annihilation [1], gravitational accretion onto small black holes, and collecting interstellar matter for a ramjet [2], present fundamental physical and technological problems to which there are at present no forseeable solutions [3,4]. It has therefore recently been concluded that the most practicable on-board system for interstellar propulsion is pulsed nuclear fusion. A pulsed fusion rocket would use small pellets of deuterium and He^3, which would be injected into the center of a large magnetically insulated chamber and ignited with relativistic electron beams. A comprehensive study of propulsion using such a pulsed fusion rocket, the Daedalus project [4], led to the conclusion that a solar-system-wide economy would be required for a one-way automated probe mission to cover the 6 light-years to Barnard's star with a flight time of 50 years. This conceptual design study considered construction and automated maintenance of the propulsion system, fuel sources, interactions with the interstellar medium, navigation, and data collection and transmission. This was the first serious attempt at an engineering analysis of these problems, and represents a milestone in the study of interstellar propulsion. Of the problems encountered, the use of large amounts of the rare isotope He^3 presented major difficulties in the design concept, but the most serious uncertainty in the feasibility of the design is undoubtedly the requirement for construction and automated remote maintenance of a power source with extremely high power density. Much of the analysis of such crucial issues as neutron damage, reaction chamber heating and stresses, and pellet burn performance, was necessarily limited to order of magnitude estimates of system performance, and a more detailed analysis may well reveal problems which seriously limit the performance of a pulsed fusion rocket. In particular, it is not even _yet_ clear that the plasma physics (such as limitations due to plasma instabilities) will even allow net energy gain in the relativistic electron beam approach to pulsed fusion.

1.2 Laser Propulsion

The limitations of on-board propulsion have led to the proposal of using momentum and/or energy transfer from a locally based laser [5,6,7]. In the simplest version of this propulsion system, a stream of photons is launched from a large laser situated in the solar system. The photons travel across interstellar space, _e.g._ to a mirror on the interstellar probe. Each arriving photon exerts a push on the mirror, thereby accelerating the probe. The ultimate power source which drives the interstellar probe is located near the laser 'photon launcher' in the solar system. This has the tremendous advantage that the 'off-board' power source does not have to be accelerated with the probe. Therefore, although the power source required may be large, it can have reasonable specific power (power per unit mass). We can therefore be confident that such a power source can be designed without impossibly exotic technologies. However, among other problems, the inherent dispersion of a laser beam limits the acceleration of the interstellar probe to a region very close to the source (_e.g._ to $10^{-5} D^2$ light-year even for a gamma-ray laser, where D is the dimension of the optical surfaces in meters . The probe must therefore be accelerated very rapidly. The resulting high optical quality and the power and efficiencies required in the laser, combined with the limitations imposed by the probe's waste heat rejection system, again present technological problems with no forseeable solution.

1.3 Pellet-stream Propuslsion

The fundamental physical limitation presented by the optical dispersion of a laser source can be overcome by using a pellet stream rather that a photon stream for the momentum transfer. In the microscopic limit, this solution would involve launching the probe itself, e.g. from a linear mass driver. However, the enormous specific energy of the probe ($4.5 \times 10^{16} v^2/c^2$ joule/kg for a probe with velocity relative to the velocity of light of v/c) would require breaking it down into a large number of subassemblies, each of which would have to be capable of withstanding the 10^3-10^7 gravities acceleration used during launch, and would then rendevous for automatic reassembly. This may prove impractical.

The optimum solution appears to be to launch a stream of small mass pellets which are intercepted by the probe and transfer momentum to it. The pellets would be launched, for example by a very long linear electromagnetic mass driver, which would be located in the solar system and supplied with nuclear or solar power. The pellet stream would be very carefully aimed (collimated) immediately after launch and perhaps recollimated occasionally during flight. The pellets would be intercepted by an interstellar probe, for example by converting them to plasma and reflecting the plasma by letting it rebound off of the the field of magnets carried on the probe (i.e. in a manner somewhat analogous to the expulsion of plasma from a magnetically insulated reaction chamber in a pulsed fusion propulsion system). The central concept which makes this apparently outrageous idea seem quite feasible is the following.

> The absolute pointing accuracy of the mass launcher is not a serious limitation. The probe detects the incoming pellets and adjusts its position to stay in the stream; modest course corrections after the main acceleration phase then put the probe on target. Only the relative velocity dispersion between one pellet and the next makes a significant demand on the performance of the propulsion system. This relative velocity dispersion can be measured extremely accurately by letting the pellet stream drift over very long baselines, and can be corrected by imparting small momentum increments to the pellets.

In this paper an outline of the pellet-stream propulsion concept is presented including (i) probe kinematics (ii) mass driver requirements (iii) correction of initial velocity dispersion in the pellet stream (iv) interaction of the pellet stream with the interstellar medium (v) momentum transfer and specific power of the probe propulsion system. General formulas are derived, and a high performance, Daedalus-type mission [4] and a less technologically demanding, low performance mission are analyzed as illustrative examples. Finally, the impact of the pellet-stream propulsion concept on Interstellar Studies and the long range goals of the existing space program is assessed.

2. PROBE KINEMATICS*

In this Section we describe the mission profiles which can be achieved by pellet-stream propulsion. We use the momentum balance of the probe to determine the specific power arriving at the probe and also the power requirements for the pellet-stream launcher.

2.1 Conservation Equations

The momentum balance of the probe is

$$m_p dv_p/dt = 2\mu(\dot{m}_s v_r/v_s) v_r \quad , \qquad (1)$$

where m_p = total mass of probe, v_p = velocity of probe, v_s = velocity of pellets in stream, $\dot{m}_s v_r/v_s$ = (doppler shifted) rate of pellet mass arriving at the probe, μ is the momentum transfer efficiency ($\mu = 1$ for elastic rebound; $\mu = 1/2$ for 'stop and drop'), and

$$v_r = v_s - v_p \qquad (2)$$

is the relative velocity of the pellet stream with

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*The equations in Section 2 are in mks units. In other Sections the units are either mks or specified in the text. The units listed in Table 1 are chosen for convenience and do not indicate that the symbols listed have these units in the text.

respect to the probe. The (doppler shifted) power intercepted by the probe is

$$P_p = (1/2)(\dot{m}_s v_r/v_s)\ v_r^2 \quad , \tag{3}$$

and the power with which the intercepted stream particles were launched is

$$P_s = \dot{m}_s v_s^2/2 \quad . \tag{4}$$

An important parameter for any high power propulsion system is the specific power S_p processed by the propulsion unit on board the probe. In particular, the total mass m_p of the probe is the sum of the payload mass m_o and the mass P_p/S_p of the propulsion unit; in terms of S_p we have

$$m_p = m_o + P_p/S_p \quad . \tag{5}$$

Eqs.(1)-(5) determine the kinematics (position as a function of time) of the probe in terms of the relevant engineering-limited parameters which are S_p, the pellet-stream launch velocity v_s, and the launcher power P_s. The present calculation is nonrelativistic (i.e. assumes all velocities are small compared to the velocity of light), which is adequate for the missions of interest here.

2.2 Acceleration For Duration of Flight

As an example of the probe kinematics, we consider the case where the following three parameters are constant in time: P_p (power into propulsion unit), S_p (propulsion unit specific power), and v_s (pellet-stream velocity viewed from earth). We calculate the maximum pellet-stream launcher power P_s needed during the course of a given mission. Such mission profiles have the advantage that the probe and pellet-stream launcher are constant during the mission and therefore are the most conceptually (and perhaps also technically) straightforward. A disadvantage is that some of the capital investment involved in producing high launcher power P_s is not utilized for probe acceleration during the early part of the mission. (The extra power available, however, may be useful for other purposes such as launching pellet-stream collimators, c.f. Section 4.) In the present case, Eqs.(2) and (3) can easily be used to eliminate v_r and $\dot{m}_s$ from Eq.(1). Eq.(1) can then be integrated once to give

$$v_p = v_s\ (1 - (1-\nu t)^{1/2}) \tag{6}$$

where

$$\nu = (8\mu P_p)/(m_p v_s^2) \quad , \tag{7}$$

and integrated again to give the distance to the probe

$$l = v_s(t-[2(1-(1-\nu t)^{3/2}]/[3\nu]) \quad . \tag{8}$$

For given total mission time t_*, total distance $l_* = l(t_*)$ and specific power S_p, there is an optimum pellet launch velocity which minimizes the power $P_{peak} = P_s(t_*)$ which is required to launch the pellets which arrive at the probe at time t_*. This is illustrated in Fig. 1 for $\mu = 1$ (elastic rebound) and for various values of probe specific power S_p. The specific power is given in multiples of

$$S_* = l_*^2 t_*^{-3} \quad . \tag{9}$$

The power and velocity are given in the natural dimensionless units of $P_* = m_o S_*$ and $v_* = l_* t_*^{-1}$ on the left-hand and bottom scales of Fig. 1. The power and velocity are also shown on the inner right-hand and upper scales of Fig. 1 for a specific high performance mission with $l_* = 5.91$ ly, $t_* = 50$ yr, $m_o = 450$ tonne (and $S_* = 0.79$ MW/kg, $P_* = 0.36$ TW $= 0.36\times10^{12}$ W, $v_*/c = 0.12$), and on the outer scales for a low performance mission to Proxima Centauri with $l_* = 4.29$ ly, $t_* = 130$ yr, $m_o = 10$ tonne (and $S_* = .024$ MW/kg, $P_* = .24$ GW, $v_*/c = .034$). Fig. 1 shows that, if a high specific power can be processed by the probe, then the required launcher power is low; this is

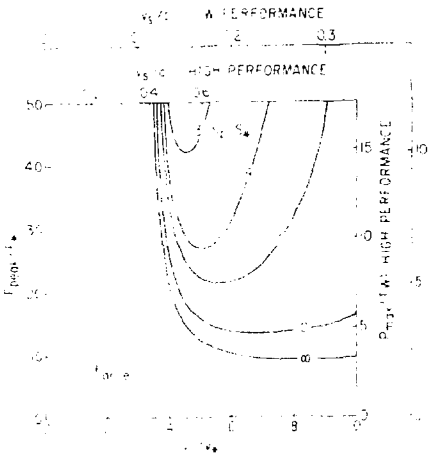

Fig. 1. [illegible] requirement vs. pellet-stream velocity v_s [illegible] acceleration over the whole mission (f_{accel} = 1). S_p = specific power at probe, S_* = [illegible], P_* = [illegible], $v_* = l_* t_*^{-1}$. For discussion of the upper and right-hand scales see [illegible].

because [illegible] stream pellets [illegible] large S_p but small P_*. [illegible] probe specific [illegible] below [illegible] it is impossible to [illegible] l_* in a time as short as t_* [illegible] of pellet velocity and power [illegible] the type analyzed here.

Fig. 1 also shows that there is an optimum pellet-stream velocity, which minimizes the power P_{peak} which is required for launching the last pellets which arrive at the probe. In the 'low performance' mission analyzed below we shall choose the pellet velocity $v_{s,opt}$ which minimizes P_{peak}. It may turn out, however, that it is more advantageous to choose a lower value of v_s (e.g. to reduce the length of the pellet launcher) at the cost of a higher P_{peak}; as an example, we do this is the 'high performance' mission analyzed below.

2.3 Including a Coast Phase

The above mission profile analysis assumed powered flight for the duration of the mission, in order to minimize specific power requirements. It may, however, be desirable to include a coast phase in the mission. At the cost of a slightly more massive propulsion system, this will free the mass launcher for other missions, reduce the distance over which the pellet stream must be collimated, and reduce the maximum required source power (which is used very inefficiently near the end of the missions analyzed above). It is a straightforward matter to generalize the above analysis to this case. We use Eq.(8) out to a distance $l_{accel}(t_{accel})$ and thereafter $l = l_{accel} + (t-t_{accel})v_{final}$, where $v_{final} = v_p(t_{accel})$ is given by Eq.(6). Fig. 2 shows results analogous to those of Fig. 1 for acceleration over half of

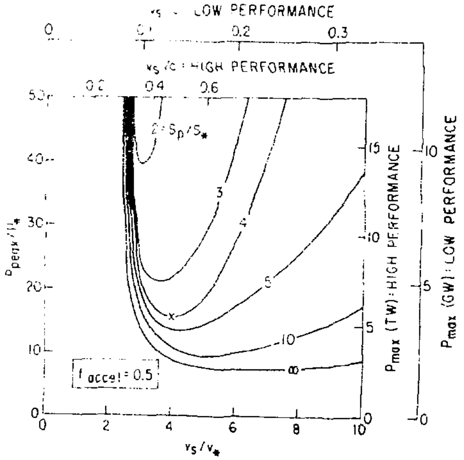

Fig. 2. Peak power vs. v_s as in Fig. 1 except acceleration occurs over half of mission distance (f_{accel} = 0.5). x indicates low performance mission detailed in Table 1.

the total distance travelled ($f_{accel} \equiv l_{accel}/l_* = 0.5$), and Fig. 3 shows results for $f_{accel} = (0.21$ ly / 5.91 ly$) = 0.036$, which is the 'acceleration fraction' used in the Daedalus mission [4].

2.4 Mission Requirements vs. f_{accel}

A comparison of Figs. 1 and 2 shows the advantage of accelerating over a moderate fraction of the mission (with P_p, S_p, and v_s constant). But Fig. 3 shows that acceleration over too small a fraction of the mission requires very high source power. In fact, an acceleration fraction $f_{accel} \sim 0.5$ is probably optimal for the type of missions analyzed here, as shown in Fig. 4. In Fig. 4 we vary f_{accel} and plot the optimal pellet velocity $v_{s,opt}$ and the associated minimal values $P_{peak}|_{v_{s,opt}}$ of P_{peak} (e.g. the minima of the curves in Figs. 1 to 3).

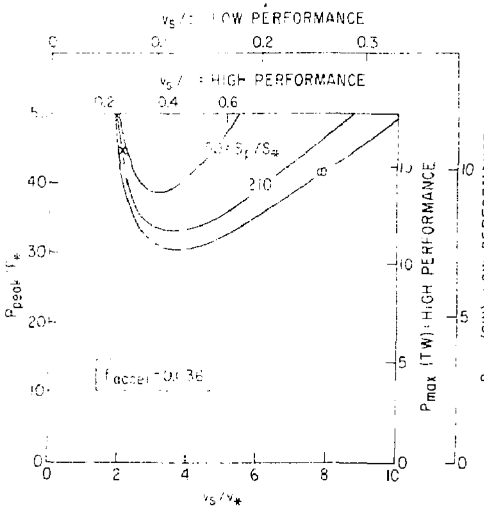

Fig. 3. Peak power vs. v_s for $f_{accel} = 0.036$. x indicates high performance mission detailed in Table 1.

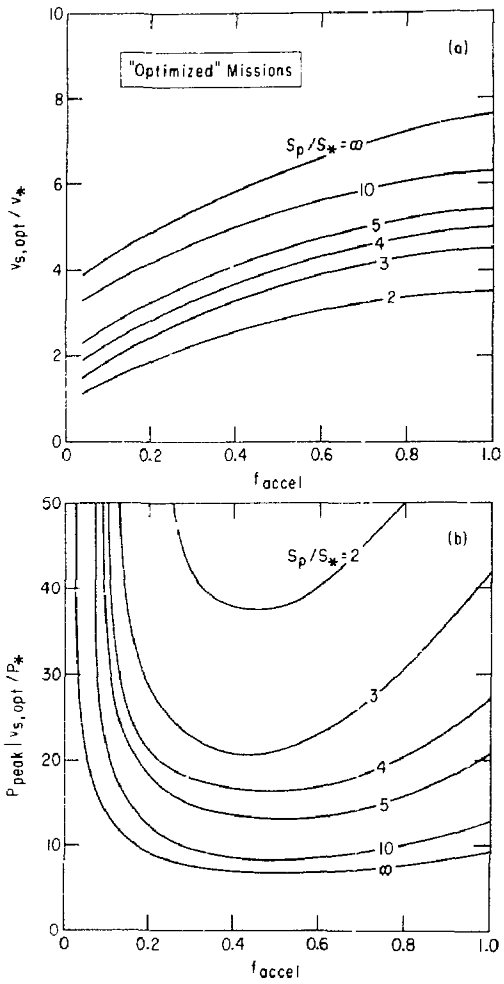

Fig. 4. (a) Values $v_{s,opt}$ of pellet stream velocity which give (b) lowest peak power requirement, plotted vs. f_{accel}.

2.5 Other Mission Profiles

It is straightforward to generalize the above analysis, for example to relax the requirement P_p = constant, so that the source power can be left on for the full mission and used more efficiently near the end of the mission. However, since a *shorter acceleration phase* makes it easier to collimate the particle stream, we will find it adequate to restrict ourselves to the analysis whose results are shown in Figs. 1 to 4.

2.6 Scaling

An important aspect of the above analysis is the strong dependence of the technological requirements on the parameters $l_\star$, $t_\star$, and m_o. In particular, the technological problems become much less severe for a moderate increase in the total mission time $t_\star$. For example, the specific power $S_p \propto l_\star^2 t_\star^{-3}$ and the source power $P_s \propto m_o l_\star^2 t_\star^{-3}$ scale as the inverse cube of $t_\star$. Also, the length of the pellet launcher scales as $l_\star^2 t_\star^{-2}$. Finally, the maximum average acceleration experienced by the probe is $a_{max} \propto l_\star t_\star^{-2}$. Since the mechanical stresses for which the probe must be designed may be proportional to a_{max}, the difficulty of achieving a given specific power S_p may scale as $a_{max} S_p \propto l_\star^3 t_\star^{-5}$, so that a modest increase in the mission time $t_\star$ will make the design of the propulsion unit much easier.

3. PELLET LAUNCHER REQUIREMENTS

The above kinematics define the typical values of v_s and P_s required of the mass launcher system.

3.1 Pellet Launcher

First consider v_s, which determines the product of the length L_s and acceleration a_s of the pellet-stream launcher

$$a_s L_s = 4600 \ (v_s/c)^2 \quad , \qquad (10)$$

where a_s is assumed constant and measured in megagravities (1 Mgrav = 9.8×10^6 m/s^2) and L_s is in megameters.

Among the many possible schemes for launching pellets, the most straightforward involve linear magnetic accelerators. If such an accelerator is stationed in space, it can be extended essentially without limit, as was apparently first noted in 1950 by Clarke [8], who also prophetically speculated that an electromagnetic launcher might conceivably be put to some unspecified use for interstellar flight. A 'conventional' magnetic accelerator uses copper driving coils to propel a superconducting pellet or bucket, and would be hard-pressed to achieve the submicrosecond switching times required here. Faster switching could be achieved by the 'superconducting quench gun' [9]. A suitable system can undoubtedly be designed by using sufficiently large coils and power supplies, but determing the size and cost will require a detailed engineering analysis. The present cost of an electromagnetic mass driver is on the order of one person-year per meter, but this cost could be larger for more sophisticated technologies or could be markedly reduced by mass production of the system components. With respect to the achievable pellet acceleration a_s, it should be noted that accelerations of 0.3 Mgrav with a ~1 g pellet over a 4 m path have been obtained with a 'rail-gun' electromagnetic accelerator [10]. Much higher accelerations of 4 to 8 Mgrav were postulated for the injector to launch fuel pellets into the Daedalus reaction chamber [11]. If extended for use as a pellet-stream launcher, an accelerator with a_s = 0.3 - 4 Mgrav would have a length $L_s \sim 10^5$ km (and a total mass of possibly several million tonnes).

The launcher would be built in a large number of subsections, between which the pellet velocities would be corrected by 'trim' coils. The station-keeping requirements required to correct accelerator misaligment due to gravitational perturbations within the solar system have been considered and found to require very modest propulsion systems on the mass driver segments.

3.2 Source Power

The power requirement for any near-term interstellar mission is rendered formidable by the high specific energy of the payload (e. g., 0.1 GW-century/tonne for v_{final}/c = 1/10). Three possible solutions for the power source include nuclear power, bioconversion of solar power, and physical conversion of solar power.

The nuclear power option would allow locating the mass launcher far from the sun, to minimize solar system perturbations of the pellet-stream trajectory. For example, a lower power version of the 10^5 GW Daedalus engine using magnetohydrodynamic conversion of the exhaust plasma energy at modest efficiency would be adequate for the initial missions.

The bioconversion option involves specially bred organisms converting sunlight to DC power, presumably in an asteroidal or lunar environment near 1 AU from the sun. The main expense beyond research and development of the biological system would be preparing the 10^2 km^2/GW of substrate needed (assuming 1% photoelectric conversion efficiency) for growth of the system. Although the biological engineering problems would be formidable, it is unsafe to assume that they will not be solved within the next 100-200 years.

A third solution would be physical conversion of solar power, possibly by photoelectric cells or a heat engine placed in near-solar orbit to reduce the required area of the collectors. Surprisingly, the use of rotational energy from solar sails mounted on 'windmills' near the sun might also be a possibility if sufficiently strong, lightweight, temperature resistant sail material and supports are developed.

4. PELLET STREAM VELOCITY DISPERSION

The problems involved in correcting the velocity dispersion of a pellet stream have been outlined by Chilton et al., [12]. The final velocity dispersion is determined by the accuracy with which position and time-of-flight measurements can be made. A series of course correction stations would be located downrange from the launcher along the pellet stream. Each station would be, for example, three times farther downrange and produce one-third as much velocity adjustment. The courser adjustments could be made electromagnetically or electrostatically, and the finest adjustments might be made remotely by light pressure from a high power laser or by interaction with a plasma gun or neutral atom stream. It suffices here to consider the limitations on the finest velocity adjustment.

The velocity dispersion of the pellet stream in the directions transverse to the stream flow can be measured to ~10^{-9} m/s using a flying-spot detector to measure the pellet position to 1 mm and using a drift baseline of 10^6 m. The longitudinal dispersion is measurable to ~10^{-7} m/s by calculating the time-of-flight along this baseline (>0.01 s) and the length of the baseline, using a laser transponder and atomic clocks. This information is then relayed further downrange to remote devices which, for example, apply light pressure producing 10^{-4} (± 10%) m/s^2 acceleration for 10^{-5} s in the transverse direction and for 10^{-3} s in the longitudinal direction. More accurate control of the velocity dispersion may be possible with a longer baseline, but this is unlikely to be useful. It may be desirable to repeat this collimation of the velocity dispersion of the pellet stream at intervals along the pellet-stream flight path, as discussed in more detail below.

5. INTERSTELLAR MEDIUM

The pellet stream will undergo dispersion in the interstellar medium due to encounters with interstellar grains and gas and due to fluctuations in the gravitational potential, radiation pressure, and magnetic fields. Interstellar grains appear to pose the worst problem and place a lower limit on the mass of the pellets in the stream. Variations in the interstellar gas drag and other small forces may introduce some long wavelength modulation on the flow of the pellet stream, but seem unlikely to vary significantly from one pellet to the next if the average pellet separation is sufficiently small (e.g. < 10^6 km).

The local interstellar grain density is probably within an order of magnitude of 10^{-25} kg/m^3, with a typical grain mass of perhaps m_g ~ 10^{-16} kg [13]. The dispersion due to grains bouncing elastically off the stream pellets is trivial. However, it seems likely that collisions with grains will cause some vaporization and erosion of the projectiles. With each encounter, escaping gas will impart a reactive velocity increment

$$\Delta v = (\eta\, m_g v_s^2)/(m_s (2H_s)^{1/2}) \quad , \qquad (11)$$

where H_s is the latent heat of sublimation (6×10^7 J/kg for a graphite surface) and η is the fraction of absorbed energy carried away by the gas escaping with specific energy H_s. Using Martin's application [13] of Powell's formula [14] gives $\eta \simeq 2 \times 10^{-3}$ and thus $\Delta v \simeq 10^{-6} (v_s/c)^2/m_s$ where m_s is the mass of a stream pellet in kg.

If the stream pellets have a density of about 3000 kg/m^3, then the displacement caused by the above velocity increments Δv can be shown by a dimensionless analysis of the relevant diffusion equation to be

$$\Delta l \approx 20\, l_{ly}^{3/2} (v_s/c)/m_s^{2/3} \text{ km} \quad , \qquad (12)$$

where l_{ly} is the distance travelled by the pellet in light years and m_s is the mass of the stream pellets in kg, and we have assumed 10^{-9} grains/m^3. Evidently, for pellets travelling over fractions of a light-year, the dispersion is not unreasonable for gram to kilogram pellets but may be inconveniently large for pellets much lighter than a gram. It should be noted that this estimate of Δl may be an order of magnitude or more too low if the grains are more abundant or if they are significantly nonuniform in size. On the other hand, Δl may be an order of magnitude or more lower if we have overestimated the grain matter density or the erosion efficiency η.

It may be possible to reduce the dispersion Δl by creating a honeycomb surface on the stream pellets to retard gas escape and thereby decrease η. Alternatively, if η is unavoidably large not only for grains but also for interstellar gas atoms impinging on the probe, then the steady gas drag might be used to orient projectile-shaped pellets to minimize the area swept out by the projectiles. Both of these options may place limitations on the acceleration which can be tolerated at launch, however, because they require highly structured projectiles.

6. INTERCEPTING THE STREAM

Focusing the pellet stream onto the probe propulsion device is complicated by the large relative velocity of the stream and probe and by the apparent impossibility of trailing any device more than a few hundred kilometers behind the probe. Four possible solutions are suggested.

First, a series of 10^2 or more pellet collimators, which limit the dispersion of the pellet stream to a few meters, could be prelaunched or shed from the probe. These collimators would function in a manner similar to the initial velocity dispersion corrector, discussed above in Section 4. Second, the probe could detect the incoming pellets using its communications antenna as a radar, and accurately fire microprojectiles at the incoming stream pellets to deflect them onto the desired trajectories. Third, the relative velocity of the stream and probe could be reduced arbitrarily (at the expense of higher pellet-stream launcher power), so that the probe could either drag a course correction device or even move into the path of each stream pellet. Fourth, the acceleration phase of the mission could take place over a fraction of a light year (again at the expense of higher pellet-stream launcher power). This final option not only reduces the dispersion of the incoming stream but also frees the stream launcher for other missions.

7. PROBE PROPULSION UNIT

The purpose of the propulsion unit is to reflect incoming stream pellets while producing a minimum amount of energy dissipation. Two methods are considered. For both methods, the incoming pellets are assumed to be focused to arbitrary accuracy by the course correction systems discussed above.

One possible propulsion unit would rebound the stream pellets with a high efficiency electromagnetic mass driver. However, the energy storage required (4.5×10^{14} J/kg for $v_r/c = 0.1$) may be prohibitive unless the stream pellets are very small.

Alternatively, the [illegible] particles may be converted to plasma by impact with small particles or a gas stream. The incoming plasma could then be reflected magnetically. A fairly detailed example of a possible system for magnetic reflection of a plasma is given in the Daedalus design [4]. In this design, the plasma is reflected by compression of a preexisting magnetic field against a conducting shell. The inductive heating of such a shell was considered to be manageable in the Daedalus study, and would be relatively smaller in a pellet-stream plasma reflector since the mass used for fuel storage, delivery, and ignition could instead be used to increase the size of the shell. (The radiative heating would also be insignificant in the pellet-stream plasma reflector by using impactor particles or ionization of the pellet to create a plasma at some distance from the chamber. The plasma would then expand and arrive at the chamber at very low density and moderate temperature and hence without producing significant radiative heating.) The absorbed energy could be reradiated at a rate up to megawatts per kg of shell material [6] if the shell were [illegible] or well coupled to thin foil radiators. The size of the reflector would be at least the radius of curvature of an incoming [illegible] m for v_p/c = 0.1 and a 10 Tesla magnetic field. The actual lower limit to the propulsion system size and mass would be determined by the collective behavior of the reflecting plasma, the analysis of which is beyond the scope of this study.

For both of these propulsion methods, it would be desirable to find a way to disperse each incoming stream pellet into a number of subpellets to be processed by the propulsion unit (e.g. by magnetic dispersal, controlled fracture, or detonation of a chemical reaction or partial phase change in a structured subpellet assembly).

8. NOMINAL HIGH-PERFORMANCE MISSION

The above discussion has outlined the major requirements of the pellet-stream propulsion concept and a number of conceptual methods for meeting these requirements. Evidently there is ample room for the creation of more ingenious methods and the optimization of the mission profile, but this is beyond the scope of a preliminary proposal. Here we must be content to describe the parameters of suboptimal mission profiles. A nominal high-performance mission will be described and compared to comparable missions using on-board fusion propulsion and remote laser propulsion. A less ambitious mission will also be described in Section 9, below.

8.1 Nominal Missions

8.1.1 Pellet-stream

First consider a pellet-stream mission. The parameters chosen to define the high performance pellet-stream mission, shown in the second column of numbers in the top part of Table 1 (see next page), are taken from the Daedalus study [4]. The acceleration distance for the probe is taken to be the same as for the Daedalus mission, and the specific power processed by the propulsion system is taken equal to that of the Daedalus reaction chambers. These constraints and the pellet stream kinematics then limit the available missions to those shown by the curve labelled [illegible] = [illegible] in Fig. 3. We pick the point marked by a x in Fig. 3 as an illustration of a reasonable compromise between launcher power and pellet exit velocity. The characteristics of the pellet launcher itself are then defined by assuming the same pellet acceleration system used for pellet injection into the first stage of the Daedalus pulsed fusion engine [11]. A 2.8 gram pellet mass then requires 2 s of acceleration and a minimum pellet firing interval of about 0.5 s. The launcher must be 73000 km long and requires a maximum power of 15 TW (averaged over a firing interval). The overall requirements are summarized in the second column of Table 1. Collimation of the pellet stream could be accomplished by 39 collimators spaced at 340 AU intervals if each collimator can detect and correct the course of pellets laterally spread over about ±100 m.

TABLE 1. Interstellar Missions

Parameter	(units)	Symbol	Value: Pellet-stream, Performance: Low	Pellet-stream, Performance: High	Daedalus, Stage: 1st	Daedalus, Stage: 2nd	Daedalus, Both	Laser
Parameters defining missions								
Total distance	(ly)	l_*	4.3	[illegible]	–	–	5.9	5.9
Total time	(yr)	t_*	130	50.	–	–	50.	50.
Payload mass	(tonne)	m_L	[illegible]	[illegible]	–	–	450	[illegible]
Specific power	(MW/kg)	β_p	[illegible]	[illegible]	170	110	–	[illegible]
Acceleration distance	(ly)	l_{accel}	[illegible]	[illegible]	.05	.16	.21	.21
Derived kinematic parameters								
Probe final velocity	[illegible]	V_{final}	[illegible]	[illegible]	.05	.12	.12	.12
Probe acceleration time	(yr)	t_{accel}	[illegible]	3.8	2.1	1.5	3.4	3.4
Max. ave. acceleration	(milli-g)	a_{max}	.76	47.	130	47.	130	35.
Power production								
Max. ave. [illegible] power	(TW)	P_{max}	[illegible]	14.	37.	2.6	37.	[illegible]
Time power [illegible]	(yr)	–	[illegible]	3.8	2.1	1.5	3.5	[illegible]
On-board propulsion system mass	[illegible]	[illegible]	[illegible]	[illegible]	220	20.	240	[illegible]
Pellet launcher/collimator defining parameters								
Pellet launcher acceleration	[illegible]	[illegible]	[illegible]	[illegible]	3.9	8.4	–	–
Pellet mass	[illegible]	[illegible]	[illegible]	[illegible]	2.8	[illegible]	–	–
Collimator size	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	–	–
Pellet launcher, derived parameters								
Pellet-stream velocity	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]
Launcher dimension	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]
Time to accelerate pellet	[illegible]	–	[illegible]	[illegible]	[illegible]	[illegible]	–	–
Min. time between pellet launches		–	[illegible]	[illegible]	.004	[illegible]	–	–
(Rest) mass launched	[illegible]	–	.0047	.16	46.	[illegible]	[illegible]	.04
Collimators, derived parameters								
Longitudinal accuracy	(cm)	–	.0046	.15	500	[illegible]	–	–
" "	(microradian)	–	[illegible]	[illegible]	4x10	[illegible]	–	[illegible]
Collimator spacing	(AU)	–	560	[illegible]	–	–	–	–
" "	(ly)	–	[illegible]	[illegible]	–	–	–	–
Number of collimators		–	240	[illegible]	–	–	–	–

8.1.2 Laser Propulsion

The laser propulsion mission in Table 1 assumes acceleration of the payload by a 1000 Å laser over a distance of 0.21 ly, after which the laser is turned off. We take kinematic and power requirements as derived by [illegible] [6], using a combination of the most optimistic parameters given in his examples: a relatively cool [illegible] °K metal foil reflector with surface density 0.01 kg/m^2 and with (total emissivity)/(laser light absorptivity) = 1. These assumptions define the mirror diameter of 4.7 km and the mirror mass of 170 tonne. For a given mirror performance, the only parameter of those listed in Table 1 which depends on the laser wavelength λ is the diameter of the power source. The case chosen (λ = 1000 Å, source diameter = 100 km) illustrates the magnitude of the optical engineering problem. Significant improvements at shorter wavelengths are unlikely, due to decreases in the source efficiency η_{laser} (set equal to 1 in Table 1), difficulties with the source optics, and [illegible] the thickness required in the vehicle mirror at X-ray and γ-ray wavelengths.

There are laser propulsion methods which are more sophisticated (and technologically complicated) than the simple mirror system considered here [7]. However, the order-of-magnitude requirement on the laser optics (which is the main point of interest here) is not fundamentally different from those for simple reflection, so we have not complicated the present comparison by considering other laser propulsion methods.

8.1.3 Fusion Rocket

The Daedalus mission parameters are reproduced in Table 1 for comparison with the pellet-stream and laser missions. The mass and specific power of the [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] launcher [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] evident from the bottom portion of Table I.

8.2 Comparison [illegible]

8.2.1 [illegible]

The [illegible] [illegible] fraction of the pellet-stream [illegible] magnitude [illegible] in the [illegible] [illegible] and [illegible] significant impact [illegible] By contrast, [illegible] rapidly [illegible] performance [illegible] slightly [illegible]. A further advantage of pellet-stream [illegible] laser propulsion [illegible] any [illegible] for collimating or collecting the stream over interstellar distances. In [illegible] power required for pellet-stream [illegible], using essentially the same launcher, [illegible] inverse cube of the fraction [illegible] of the distance over which the probe is accelerated, for small values of [illegible]. [illegible] for a fixed laser power [illegible], since the divergence of the laser beam is [illegible], and acceleration must take place over a given fraction of the mission.

Comparing pellet-stream to fusion rocket propulsion, we note that the Daedalus engines rapidly become unmanageably large if their specific power is significantly increased. In particular, it should be noted that the Daedalus reaction chamber would be essentially equivalent to the pellet-stream interception chamber except that the reactions in the Daedalus pellets produce neutrons which are assumed to be reabsorbed in the pellet with a leakage of one part in 10^{14} [11] (!). Any degradation in the pellet performance would be disastrous for the fusion propulsion scheme, but not necessarily of major importance for pellet-stream propulsion.

8.2.2 [illegible] Power, and Mass [illegible]

The fusion rocket engines require larger power for the same payload than a pellet-stream probe, since the fusion fuel must be accelerated by the rocket. The lower power required for pellet-stream acceleration means that, if the Daedalus engines could be built, they could be used to power several reusable pellet-stream launchers even at modest power conversion efficiency.

Also note that the Daedalus fuel contains the rare isotope He^3. By contrast, the smaller reaction mass required in the pellet stream could in principle be made of almost any material. (In practice, careful pellet design and choice of materials may be necessary if high-acceleration launching and high-specific-power catching are used.)

8.2.3 Launcher Dimension

The linear dimension of the pellet stream launcher is very large, especially if low acceleration (10^{-3} to 10^{-1} Mgrav) is used. However, the pellet-stream launcher can be constructed modularly of relatively simple components, unlike a fusion engine. And it does not require the extreme tolerances (better than one part in 10^{14}) of the laser optics. A more careful comparison of the effort required to contruct a practicable version of each propulsion engine would nevertheless be desirable.

8.3 Summary

To summarize the comparison of propulsion systems for rapid interstellar travel, pellet-stream propulsion offers one to two orders of magnitude improvement over a fusion rocket in terms of propulsion system mass, reaction mass requirements, and power consumption. Further advantages are reusability of the primary power system and probably less exotic engineering requirements. With respect to laser propulsion, the pellet-stream approach probably requires much less exacting engineering in the local power source. If the pellet stream can be accurately collimated or [illegible] [illegible] the [illegible], it may also allow momentum transfer over longer distances, with a consequent reduction in the power source requirement.

9. LOW PERFORMANCE MISSION

The leftmost column of numbers in Table 1 lists a self-consistent set of low performance parameters for a 130 yr mission to Proxima Centauri. The kinematic parameters are given by the point marked with a x on Fig. 1. Since the mass of the probe is no longer determined by the minimum size of an ignited fusion engine, it has been assumed that a smaller probe mass of 10 tonne is allowed by probe miniaturization and the use of very large data reception antennas in the solar system. It is also assumed that the particle-stream pellets are dispersed into subpellets shortly before encountering the probe (in order to obtain a smooth power load on the propulsion unit), and that interstellar dispersion of the pellets is given by Eq.(11). (If these conditions do not hold, then more pellet-stream collimators may be required.) The more modest acceleration of 0.3 Mgrav assumed for the pellet launcher forces a very long launcher system (200,000 km), but the overall cost of the system will not be unreasonable for a moderately developed space manufacturing industry if the costs for mass production and assembly of the launcher components are not greatly in excess of 1 person-year per km.

The other technological requirements for the low performance mission are considerably less demanding than for the high performance missions in Table 1. It appears that all of the technological demands may be reasonable. For example, the 3.8 GW of power required for the pellet launcher could be provided by a single solar power satellite station, and a 10% absorption of the 100 kW/kg incident on the probe could be reradiated at 400 ^{o}K by a 0.015 mm thick foil containing 10% of the propulsion system mass. The maximum acceleration experienced by the probe *(averaged over the time needed to intercept a small number of pellets)* is less than one milligravity.

10. OPTIMIZATION

No attempt has been made here to optimize the pellet-stream mission kinematics. Such optimization should allow relaxation of the mission requirements by a small factor. For example, if the pellet velocity is allowed to var. over the mission, then the maximum required pow for a given mission will be smaller.

It is even conceivable that fully optimized pellet-stream system could also incorporate laser propulsion or on-board fusion. Reaction mass could be transferred through the pellet stream to a laser-driven system, or fuel and/or reaction mass could be transferred to a fusion rocket. This latter concept would obviate the need for acceleration of massive on-board stores of rocket fuel. It would also allow collection of the pellet stream at low relative velocity, representing an improvement over the recent proposals of spreading fusion fue pellets in the path of a laser propelled [7] fusion rocket [15] as an 'acceleration runway'.

11. MANNED TRAVEL

Both laser and pure rocket propulsion may be limited to flyby missions if the interstellar flight time is to be ~50 yr. If it is instead desired to arrive at destination with negligible velocity, laser propulsion would require on-board reaction mass and a large improvement in range over that discussed above. Nuclear rocket propulsion would require vast fuel supplies (e.g. ~10^4 tonne/payload-tonne for Daedalus). If one further realizes that the only solution to manned interstellar travel within reach of our (admittedly rudimentary) biological technology is the massive interstellar ark [16], then the requirements for rapid manned interstellar travel become truly astronomical.

With pellet-stream technology, a number of possible solutions are available which could require much more modest improvements on flyby technology. In order of increasing 'purity' of the pellet-stream approach, these are (i) remote fueling of a nuclear rocket prior to its deceleration (ii) remote fueling during deceleration (iii) partial deceleration with a slow, prelaunched, pellet stream, followed by remote fueling of a deceleration rocket (iv) collisional deceleration using a low velocity pellet stream launched from the destination by a small advance crew or automaton and (v) deceleration on a pellet stream rebounded from a lead ship. In each case, the acceleration phase would occur by the pellet-stream methods discussed above.

Considering the deceleration methods mentioned above, fueling prior to deceleration could occur with low relative velocity between the fuel stream and the rocket. This is the most conceptually straightforward proposal and would itself represent an enormous improvement over pure rocket technology. On the other hand, the rebound concept would avoid nuclear rockets altogether but demand an expendable, high-power-density device to accurately reflect a pellet stream back toward the manned vessel. Of course, once the 'interstellar highway' has been traversed, then a pellet-stream launcher can be constructed at the other end for relatively easy two-way travel if there is any motivation to do so.

12. IMPLICATIONS FOR INTERSTELLAR STUDIES

The pellet-stream propulsion concept has considerable import for three main concerns of an area of research which has been called Interstellar Studies [4], namely (i) interstellar exploration (ii) interstellar settlement and (iii) the search for extraterrestrial intelligence. We consider these in turn.

12.1 Interstellar Exploration

The main thrust of this paper has been to demonstrate that pellet-stream propulsion offers order of magnitude improvements relative to fusion rocket propulsion. While fusion rocket propulsion may be posible in several centuries in a solar-system-wide economy, pellet-stream propulsion can probably be accomplished in the order of a century in a near-earth ('cis-lunar') economy. That such a possibility exists may bring studies of interstellar propulsion from the realm of an 'existence proof' into a realm where more detailed designs will suggest a useful direction for the development of advanced propulsion concepts for local use. It also suggests an additional rationale for a spaceborne manufacturing capability in earth orbit [17,18].

It should be noted that the high performance pellet-stream mission analyzed in Section 8 of this paper borrows extensively from Daedalus technology. Given that this assumed technology may be overly optimistic, particularly with respect to the power density in the on-board propulsion system, a more realistic low performance pellet-stream mission, such as that outlined in Section 9, might in fact take a century or more. This would extend the timescale for interstellar exploration, but the magnitude of the investment required should still be considerably less than the solar-system-wide effort required even for a more conservative Daedalus concept.

12.2 Interstellar Settlement

The ultimate motivation for interstellar exploration is undoubtedly the dream of interstellar settlement. It can be argued that interstellar settlement would be a tremendous boon for human cultural diversity and may even be essential for the survival of our progeny on historically -> paleoanthropologically significant timescales (10^4 -> 10^6 yr). Not only would a pellet-stream launcher provide a continuing facility for launching interstellar settlement, but the special advantages of pellet-streams for deceleration would enormously facilitate manned settlement. In addition, the prior launching of pellet-stream collimators for interstellar probes would provide a natural step-by-step path in establishing 'highways to the stars' and eliminating the technological and possibly the political, psychological, or sociological barriers in the way of manned interstellar exploration and/or settlement. Thus, the more clearly indentified path towards interstellar settlement offered by pellet-stream technology may help make a primary goal of Interstellar Studies a reality in the mind of contemporary man.

12.3 Extraterrestrial Intelligence

Finally, it should be noted that the relatively straightforward path to the stars offered by pellet-stream propulsion should also be available to any other culture in the galaxy which has experimented with physical technology. This lends credence to the suggestion there is unlikely to exist a large number of technological civilizations (e.g. $\geq 10^3$) which have arisen independently in the galaxy. This is because any one of these civilizations could at any point over millions of years have initiated interstellar settlement and spread throughout the galaxy at a rate which is physically limited to no less than about 1/10 of the speed of light.

Note in particular that pellet-stream propulsion works best with interstellar stream collimators and with a station at destination to launch reaction mass for deceleration. Pellet-stream technology is therefore particularly suited to short trips and permanent settlement of nearby stellar systems, i.e. to a wave of interstellar settlement which by a process analogous to natural selection could eventually reach every niche in the galaxy, including our own solar system. The existence of this possibility may be in contradiction to the absence of definitive evidence of extraterrestrials in the solar system. One possible conclusion is that technological civilizations are rare (and therefore distant) or are entirely absent from the galaxy. Of course, the possibility of pellet-stream propulsion does not directly impact a wide variety of other explanations (c. f. Hart [20]) for the absence of definitive evidence of extraterrestrials in the solar system, but it does render even more untenable the original explanation [21] that interstellar travel is either too difficult or impossible.

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POSTSCRIPT

An analysis of an advanced propulsion concept and its consequences is being circulated in the form of the main text of this report in the expectation that it may provide interesting reading for a number of members of the scientific community in general and for fusion researchers who may be particularly interested in the uses of high technology in the long term. Although the analysis presented therein adds only a little to what has already been published about propulsion using fusion as an energy source, some of the issues which are discussed do have relevance to the long term uses of controlled fusion. Since this series of reports generally deals with topics related to controlled fusion, the following comments have been added as a postscript to this report in order elaborate on the issues which may be relevant to the eventual fate of fusion research.

LONG TERM USES OF CONTROLLED FUSION

Any discussion of the practical uses of controlled fusion must consider long time scales. For example, present U.S. Department of Energy Policy assumes that controlled fusion will not contribute the major fraction of electrical generation capacity in the U.S. until the mid-21st century [p1]. A brief retrospection on the state of industrial technology at the beginning of the 20th century suggests that major changes in other fields may occur on such a time scale. It therefore behooves us to take a wide perspective when considering questions relevant to trends in the development of fusion research. The accompanying text touches on two topics relevant to the eventual fate of fusion technology.

The first topic of interest is alternative sources of energy for the long term. With respect to electricity generation, the main competitors of controlled fusion are thought to be solar power options such as land based steam generators or photovoltaics. Given that these systems are typically an order of magnitude more expensive than nuclear power options, proponents of controlled fusion have often implicitly assumed that reasonable success in the controlled fusion effort would make it the primary source of electrical power in the long term [p2]. Such a conclusion may be naive, in that it neglects technological developments which have not yet had any practical realization and gained wide public notice, but which may be expected to be important on a long time scale. Such developments are briefly discussed in Section 3.2 of the accompanying text.

One such development is the construction of a large scale manufacturing capacity in space. This would allow the construction of solar power stations in an environment with very low mechanical stresses and a continuous source of high intensity radiative energy flux, which could result in an order of magnitude improvement in efficiency of electricity production [p3]. From the perspective of 1979, the large capital investment required to construct a space manufacturing capability makes this option look very unattractive as a near term energy source [p4]. However, looking backward from a century from now, one might find that a space manufacturing capability had existed for some time, perhaps for reasons unrelated to electricity generation [p4]. One could easily imagine in such a circumstance that solar power satellite stations would be competitive with nuclear fusion in the long term.

A second consideration is the development of biological technology, which may now be at a stage comparable to that of physical technology a century ago when, for example, the fundamental equations of electromagnetics had only recently been formulated. As noted in Section 3.2, it is quite possible that biological technology will lead to the development of an inexpensive, possibly self-replicating, system capable of photoelectric conversion at a modest but acceptable efficiency. It would certainly be foolhardy to claim that such a development could not occur within a century, and it could come much sooner. (It should be noted that the existence of the required technological base may be accompanied by formidable hazards.) Such a development would provide a very strong competitor for controlled fusion, and related technology might also significantly transform the patterns of energy use.

A second topic which may be relevant to the long term uses of controlled fusion is rocket propulsion. There is an extensive, if scattered, literature on fusion rockets [p5]. It has been assumed that fusion would ultimately be used in the most advanced propulsion systems, because it liberates the highest energy density of any fuel for which any remotely feasible propulsion system has been proposed. Thus, even if controlled fusion were not to become the eventual choice for an inexhaustible source of energy for electricity generation, interest in controlled fusion for advanced propulsion systems might continue. The main thrust of the accompanying text is to show that this is not the case. Instead, it appears that the enormous problems associated with creating a usefully high power density in a controlled fusion rocket can be avoided by the simple expedient of locating the power source near the earth or sun, and transferring momentum to the propulsion unit through a stream of high velocity pellets.

The upshot of all of of this is a new perspective on the long term uses of controlled fusion. On the one hand it seems possible (probable, in the author's opinion) that technologies which have not yet been deployed will become competitive with controlled fusion on the time scale of a century, perhaps less. On the other hand, it appears that other applications besides electricity generation do not provide a longer term future for controlled fusion. This is not to imply that there are not likely to be future applications of fusion research. On the contrary, if present expectations of the direct (cost) and indirect (environmental) economic consequences of extracting increasingly intractable fossil or fissile fuel reserves are correct, then controlled fusion may play a crucial role in the energy economy of the 21st century. But this will require development which proceeds in a timely fashion and addresses problems on the relevant timescale. The fusion community can not afford to be starry eyed about a milleniai energy economy which will never exist, or to ignore technological developments in seemingly unrelated fields in the complacent surity that fusion is the long term solution to the energy problem. If such a narrow perspective is taken, then mistakes may be made; a wider perpective may help fusion to find a suitable role amongst future energy sources.

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