Nuclear powered and reactionless rockets

Warren D. Smith*
wds@research.NJ.NEC.COM

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Abstract — **We consider using emissions from radioactive atoms as the "exhaust" of a "rocket" for space propulsion. The "alpha rocket" consists of a thin film of alpha emitting atoms on an inert backing film of thickness ≈ 40 microns. It achieves specific impulse values in the range $5 \times [10^2, 10^3]$ km/second. It seems likely to be practical. By using ^{254}Cf and ^{250}Cm, which instead decay by spontaneous fission, $4\times$ greater speeds become possible, but the engineering problems are much more difficult, perhaps insoluble.**

In contrast, the "beta rocket" is almost certainly not practical (although it *is* buildable) and is instead intended to make the point that an effectively *reactionless* drive is possible. This is because the beta rocket's exhaust is neutrinos. The neutrino emission is made anisotropic using parity non-conservation in weak interactions. This requires temperatures in the milliKelvin range. Specific impulses of 1 km/second are typical, although values up to 300 km/second are thinkable.

Because only low thrusts are feasible, these kinds of rocket could be useful only in deep space. In comparison, a chemical rocket employing HF combustion achieves specific impulse values of ≈ 4 km/second. The fastest manmade macroscopic object is Voyager 1 (17km/sec); Pioneer 11 temporarily reached 48km/sec during its Jupiter swingby.

Keywords — Space propulsion, reactionless drive, radioactivity, spontaneous fission, alpha decay, beta decay, parity nonconservation, lightsails, sputtering, radiation damage, interstellar travel.

In this report I'll propose two kinds of "nuclear powered rockets." The "alpha rocket" is of practical interest today, but the "beta rocket" is not.

The beta rocket is a very enjoyable conception despite its impracticality. To see why, ask yourself: What would the properties of the best possible rocket be?

1. Can achieve any desired acceleration up to, say, 10 "gee."
2. High "specific impulse" (ratio of impulse [momentum increment] delivered to mass of fully fueled rocket).
3. Produces zero exhaust hence is "pollution free." Note: this "reactionless" property at first seems to be impossible considering Newton's law of "equal and opposite reaction."

The beta rocket in fact can achieve all three of these properties in principle, and the latter two properties seem achievable in practice.

Unfortunately, I have reservations about the safety of both my ideas. They involve the use of radioactive isotopes. Any such use on a spacecraft (traveling at earth escape velocity 11.2 km/sec) involves kinetic energies large enough to cause complete vaporization of the entire craft and dissemination of the isotope, posing a health risk. However, such risks did not stop numerous previous space missions from proceeding, including a US Defense Dept. satellite which burned up on reentry in 1964, releasing somewhere around 50 lb of radioactive isotopes into the upper atmosphere and thus causing somewhere between 100 and 1000 cancer deaths. (A.Sakharov has called events such as these, and nuclear bomb tests, "perfect crimes.") This amount of isotope would actually be enough to give almost every human cancer, if it were somehow divided into equal doses to each.

Aside from that, our "alpha rocket" suggestion (§2), based on an alpha emitter on a thin inert backing film, seems both entirely feasible, and far superior in many ways to all competing proposals. Apparently the major limitations (which we analyse extensively) will be meteor grain impact damage (§4), and sputtering (§2.7). The α variant based on spontaneous fission would yield even better performance, but should suffer much more severely from safety, sputtering, and cost problems, which may be enough to prevent it from being feasible. Some simple experiments could address these issues.

1 Beta rocket

The idea is simple. Take a large ball of cobalt-60. Cool it to very low temperatures T and place it in a magnetic field B. (For the idea to work well, we require $2\mu B/(k_B T) \gg 1$ where μ is the magnetic moment of the nucleus. In the case of cobalt-60, $\mu = 5.685$ nuclear magnetons, and with $T = .001$ Kelvin and $B = 1$ Tesla we get $2\mu B/(k_B T) = 4.16$, which should suffice.) Cobalt-60 is radioactive with a halflife of 5.271 years. It decays by one beta (i.e. electron) emission and two subsequent gamma (i.e. photon) emissions. The energy of the emitted electron is 0.315 MeV. Now it was shown by Wu et al [25] that the

*NECI, 4 Independence Way, Princeton, NJ 08540. Patent applied for.

electron is emitted, under these conditions, *anisotropically*[1], preferentially in the direction opposite to the nuclear spin vector. The fraction emitted in this direction is at least 70%. However, since we are postulating a large ball, rather than a thin film[2], of ^{60}Co, and since beta rays are incapable of penetrating solid matter to depths of more than a few millimeters before getting absorbed, these electrons will not be emitted externally. However, the electron emission is known (because, e.g., of the need to conserve angular momentum) to be accompanied by a *neutrino* emission in the opposite direction, i.e. in the direction of the nuclear spin vector, and carrying roughly 60% of the total energy, i.e. 150% of the energy of the emitted electron, on average. This neutrino is not absorbed and constitutes our rocket's "exhaust."

Because neutrinos have such a tiny cross section for interaction with matter, the rocket is effectively reactionless. To an observer incapable of detecting neutrinos, this rocket would appear to be accelerating steadily while emitting nothing! Perhaps even more oddly, the rocket would also start spinning for no apparent reason (since the neutrinos all have the same helicity and hence each carry $\hbar/2$ angular momentum) although this effect would be very small (angular velocities well under 10^{-6} rotations per second would be expected, for reasonable linear sizes).

The momentum of a neutrino of energy E (assuming massless neutrinos) is E/c. Hence the specific impulse of this rocket, assuming the refrigerator and magnetic coils have much smaller mass than the fuel, would be

$$\frac{(.7-.3)\times 1.5\times .315\text{MeV}}{60\text{amu}\times c} = 1130\frac{\text{meter}}{\text{second}}. \qquad (1)$$

(If the anistropy is 100% instead of 70%, which was only a lower bound which we used in an effort to be conservative, then this would be 2.575 km/second.)

1.1 Comparison with conventional rockets

Let us compare this with the specific impulse of hydrogen-fluorine combustion, which is generally regarded as the maximum possible for a chemical-fuel rocket. (HF is highly toxic and corrosive.) The enthalpy of formation of HF is 273.3 kiloJoules/mole. Assume that 100% of this energy is converted to molecular translational motion in the x-direction. (This would in principle be possible with a perfect parabolic reflector and if the HF molecules never collided with each other.) The result is

$$\sqrt{2\times\frac{273.3\,\text{kiloJoule}}{20\,\text{gram}}} = 5228\frac{\text{meter}}{\text{second}}. \qquad (2)$$

These assumptions of maximal efficiency are somewhat biased in favor of HF, of course. A realistic engineering number is 4000, and 2900 for ℓO_2-kerosine.

[1] But the subsequent gamma emissions have a centrally symmetric angular distribution.

[2] It would seem technically infeasible to make a thin film of ^{60}Co over a very large flat surface area, while still having a Tesla of magnetic field everywhere.

According to press accounts, the Xe^{+1} ion engine on NASA's "Deep Space 1" probe (launched 24 October 1998, scheduled to fly by asteroid 1992 KD on 29 July 1999) achieves exhaust velocity 27 km/second. It produces .06 Newton of thrust (10 microgees of acceleration, since the craft masses about 600 kg) while consuming 2100 Watts of solar power. (Deduced energy efficiency: 38%.) This would use up its 82 kg of xenon in about 1.2 years.

1.2 Discussion

Obviously, our beta proposal could only be feasible in space where the fact that the rocket runs for time spans of order 5.3 years, is acceptable[3]. Hence the acceleration will be of order 10^{-5}meter/second$^2 \approx 10^{-6}$gee. However, in *principle* 10gee accelerations are possible by using an isotope with a halflife 10^7 times shorter, i.e. $\approx$ 17seconds. Indeed, tremendous accelerations are possible in principle. For example ^{9}Li has a halflife of only 0.177 seconds, and it emits an electron of higher energy (13.61 MeV) than ^{60}Co while at the same time having 6.67 times smaller nuclear mass. This would lead to a specific impulse estimate corresponding to (EQ 1) of 2.9×10^5 meters/second, and an acceleration of 1.6×10^5gee. But I do not see how, in *practice*, to use isotopes with halflife shorter than $\approx$ 10hours. The useful range would seem to be 10 hours to 10^5 years (the latter assuming anybody ever wanted an interstellar spacecraft).

To "turn off" the rocket, we merely let it heat up to temperatures (3 Kelvin will suffice) at which the ^{60}Co nuclei are randomly oriented. Unfortunately, ^{60}Co also emits gamma rays. These for many purposes could be viewed as undesirable (they might cause damage to the rocket's payload). But there are alternative isotopes which do not emit gamma rays, and by fastening the rocket's payload to the rocket itself by means of a long tether, effects of gamma rays could be mitigated.

In table 1 below, specific impulses were computed using the formula

$$\frac{(.7-.3)\times 1.5\times E}{m_{\text{nuc}}c}. \qquad (3)$$

Larger nuclear magnetic moments (tabulated below in units of nuclear magnetons) are desirable since they make it easier to polarize the nuclei.

Isotope	Halflife	E(MeV)	nuc.mag.	Spec.Impulse km/s
6-He	.807 sec	3.510		113
9-Li	.177 sec	13.61	3.439	292
10-Be	1520000 yr	.5561		11
32-Si	160 yr	.227	.488	1.4
33-P	25.3 day	.249		1.5
35-S	87.2 day	.167	1.00	.9
39-Ar	268 yr	.565	-1.3	1.8

[3] The milliKelvin cooling requirement also might be hoped to be much easier in deep space than it is on Earth. Although arguably cooling to Kelvin temperatures would be easy in deep space, I claim that milliKelvin cooling will be too onerous to be practical. The usual laboratory methods of cooling to these temperatures are either to use a ^{3}He isotopic refrigerator or nuclear demagnetization cooling.

44-Ar*	11.87 min	.354		1.6
45-Ca	162.7 day	.257	-1.327	1.1
59-Fe*	44.51 day	1.565	.29	5.1
60-Co*	5.271 yr	.315	3.799	1.1
90-Sr	29.1 yr	.546		1.2
90-Y	2.67 day	2.282	-1.630	4.9
99-Tc	213000 yr	.293	5.685	.57
106-Ru	1.02 yr	.039		.071
232-Pa*	1.31 day	1.34		1.1
234-Pa*	6.69 hr	2.19		1.8
249-Cm*	64.15 min	.902		.70

Table 1. Some beta- (electron) emitters. (*: also a gamma emitter. Too many digits of precision have been given in the last column.)

1.3 Conclusion

Although gram quantities of matter are routinely cooled to milliKelvin temperatures in many labs, I think the difficulties in trying to do this with large quantities (kg or more) of matter, especially radioactive matter, will be so severe as to render the entire beta plan unattractive. Alternatively one could cool to .1 Kelvin and use a 100 Tesla field, but this is also very difficult. This, combined with the fact that the specific impulse numbers are only comparable with conventional chemical rockets, also makes the beta rocket unnattractive. My main rationale for mentioning the beta rocket idea was *not* its usefulness, but rather purely for the amusement and conceptual value of the "reactionless drive" concept – an amazing "magic trick" which, I claim, ought to be at least demonstrable as an effect, despite its lack of practicality as a space drive. The alpha rocket, on the other hand, actually *does* look practical.

2 Alpha rocket

It is also possible to power a rocket using considerably more boring – but probably more effective – radiation physics. Consider a film of alpha-emitter below a backing film made of nonradioactive matter. (Each film thickness is ≈ 40 microns.) Alpha particles (i.e. ^{4}He nuclei) emitted "upward" would be absorbed whereas those emitted "downward" would fly off into space and provide thrust. To "turn off" the rocket we simply "fold up" the film, to turn it on we unfurl the film.

2.1 Stopping power

The backing film should be made of a material with high stopping power per unit mass. "Stopping power" is decrease in energy of alpha particles per unit length of material traversed. Most materials have comparable stopping powers per unit mass, but materials with few neutrons (they are "deadweight") tend to be better. This is because at high energies stopping power is proportional to

$$Z_t Z_p^2 / M_t \tag{4}$$

Z is charge, M is mass, and the subscripts p and t are for the projectile being stopped and the target atoms stopping it, respectively [26]. High density polyethylene $H(CH_2)_nH$ (preferably made with light isotopes ^{12}C and ^{1}H) is probably a good absorber; but it probably will be susceptible to radiation damage[4]. Such damage could be avoided by using elements rather than compounds, and preferably ones featuring "healing" of chemical bonds (metals should work).

According to tables of implantation ranges [26], the two best elements, per unit mass, for stopping alpha particles are Lithium and Carbon. More precisely, the "best" elements are the ones which maximize the quotient of alpha range divided by density. 6Mev alpha particles have a range of 25μm in C and 102μm in Li, with respective standard deviations of .65 and 2.8μm. These are both about 1.4 times better per unit mass than Aluminum foil (range $29 \pm .7\mu$m, and density 2.699grams/cm^3, versus C's 2.267 and Li's .5298).

2.2 Other properties

This alpha rocket would become charged to high voltages in normal operation (due to the fact that the ejected α particles each carry +2 charge), and it would not have the elegant "reactionless" property, but these two disadvantages may not be very severe in most applications. For example, compensatory discharging would be possible with a heated filament or sharp point to emit electrons, which would keep the voltages down to some reasonable level (which doubtless could be adjusted by moving the sharp point). Indeed this charging effect, if controlled, will be beneficial, see footnote 9 and §2.10. Also, the use of an exhaust consisting of alpha particles leads to much greater specific impulse values than the use of neutrinos of the same energy (and larger energies usually happen, as well). Meanwhile, the need for milliKelvin cooling (or any cooling), a severe disadvantage in the beta proposal, is avoided.

2.3 Specific impulse numbers, suggested isotopes

Under the conservative[5] simplifying assumptions that the backing film is made of the same material (but not radioactive) as the emitter and has the same[6] thickness, and the total thickness of the two films combined is chosen to be 1 in units such that an alpha particle is absorbed after traversing length $L = .982$ inside the material, and finally assuming that the alpha particles lose energy at a constant rate per unit length of material traversed [26], we conclude that the

[4] Of course, with any sensible choice of the inert backing material, the alpha rays would not cause any appreciable fraction of it to become radioactive (cross sections for alpha-induced nuclear reactions being much smaller than for scattering, and many such reactions do not cause radiactivity anyway). But they might cause it to disintegrate.

[5] In view of §2.1, in reality we would be using a backing film made of much lighter atoms than the emitter, and having much less stopping power – although larger stopping power *per unit mass*. So the backing film would be much thicker than the fuel film although it would mass somewhat less than it.

[6] Numerical work suggests that our choice of 50:50 thickness ratio is optimal under this assumption.

specific impulse is

$$.2704\frac{\sqrt{m_\alpha E}}{m_{\mathrm{nuc}}}. \tag{5}$$

Isotope	Halflife	E(MeV)	Spec.Impulse km/s
148-Gd	75 yr	3.1828	64
154-Dy	3 Myr	2.87	58
223-Ra*	11.435 day	5.979	58
225-Ac*	10.0 day	5.935	58
226-Ra	1599 yr	4.870	52
227-Th*	18.72 day	6.146	58
228-Th*	1.913 yr	5.520	55
230-U*	20.8 day	5.992	57
236-Pu*	2.87 yr	5.867	54
238-Pu*	87.74 yr	5.593	53
240-Cm	27 day	6.397	56
241-Am*	432.2 yr	5.637	52
242-Cm*	162.8 day	6.216	55
244-Cm*	18.11 yr	5.902	53
248-Cf x	334 day	6.369	54
250-Cf x	13.1 yr	6.129	53

Table 2. Some alpha emitters.
(*: also emits gammas, x: xrays. Too many digits of precision have been given in the last column.)

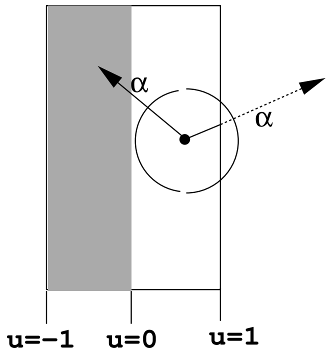

Figure 1: Derivation of specific impulse formula

More precisely, the magic number $.2704 = .3513 - .0809$ in (EQ 5) is

$$\frac{\sqrt{2}}{2}\int_0^1\int_0^1\left(\sqrt{(2L-\frac{1-u}{x})_+}-\sqrt{(2L-\frac{1+u}{x})_+}\right)x\,\mathrm{d}x\mathrm{d}u, \tag{6}$$

with $L = .982$ gotten by maximizing this. (Notes re EQ 6: u is the x-coordinate of emission in a film rescaled to be the u-interval $[-1, 1]$, and $x \in [0, 1]$ is the x-coordinate of a random point on a unit hemisphere of emission directions. We use Archimedes's observation[7] that such an x is uniform in $[0, 1]$. By w_+ we mean w if $w > 0$, otherwise 0; the square roots arise because velocity is proportional to square root of energy; and energy loss is proportional to distance traveled inside the film. One square root is for α particles ultimately emitted forwards, the other backwards; each has its own hemisphere of emission directions. The u-integral is from 0 to 1, not -1 to 1, because only the right half of the film contains α-emitter.)

[7]Archimedes used this in $\approx$ 300BC to demonstrate that the surface area of a sphere is the same as that of the curved surface of a cylinder of the same radius and height.

2.4 Multiple decays

The specific impulse figures for single isotopes in table 2 greatly *underestimate* the true specific impulse in some cases, because we have ignored the fact that many isotopes decay to *another* radioactive isotope and so on for quite a while. Here are some examples.

$$\begin{aligned}
&{}^{249}\mathrm{Cf}\xrightarrow[\substack{\alpha\,6.295\\351\,\mathrm{yr}}]{}{}^{245}\mathrm{Cm}\xrightarrow[\substack{\alpha\,5.623\\8500\,\mathrm{yr}}]{}{}^{241}\mathrm{Pu}\xrightarrow[\substack{\beta\\14.4\,\mathrm{yr}}]{}{}^{241}\mathrm{Am}\xrightarrow[\substack{\alpha\,5.637\\432.2\,\mathrm{yr}}]{}\\
&{}^{237}\mathrm{Np}\xrightarrow[\substack{\alpha\,4.957\\2.14\,\mathrm{Myr}}]{}{}^{233}\mathrm{Pa}\xrightarrow[\substack{\beta\\27\,\mathrm{day}}]{}{}^{233}\mathrm{U}\xrightarrow[\substack{\alpha\,4.909\\.159\,\mathrm{Myr}}]{}{}^{229}\mathrm{Th}\xrightarrow[\substack{\alpha\,5.168\\7900\,\mathrm{yr}}]{}\\
&{}^{225}\mathrm{Ra}\xrightarrow[\substack{\beta\\15\,\mathrm{day}}]{}{}^{225}\mathrm{Ac}\xrightarrow[\substack{\alpha\,5.935\\10\,\mathrm{day}}]{}{}^{221}\mathrm{Fr}\xrightarrow[\substack{\alpha\,6.457\\5\,\mathrm{min}}]{}{}^{217}\mathrm{At}\xrightarrow[\substack{\alpha\,7.202\\32\,\mathrm{ms}}]{}\\
&{}^{213}\mathrm{Bi}\xrightarrow[\substack{\beta\\46\,\mathrm{min}}]{}{}^{213}\mathrm{Po}\xrightarrow[\substack{\alpha\,8.537\\4\,\mu\mathrm{s}}]{}{}^{209}\mathrm{Pb}\xrightarrow[\substack{\beta\\3.3\,\mathrm{hr}}]{}{}^{209}\mathrm{Bi},
\end{aligned}\tag{7}$$

$$\begin{aligned}
&{}^{240}\mathrm{Cm}\xrightarrow[\substack{\alpha\,6.397\\27\,\mathrm{day}}]{}{}^{236}\mathrm{Pu}\xrightarrow[\substack{\alpha\,5.867\\2.87\,\mathrm{yr}}]{}{}^{232}\mathrm{U}\xrightarrow[\substack{\alpha\,5.414\\68.9\,\mathrm{yr}}]{}{}^{228}\mathrm{Th}\xrightarrow[\substack{\alpha\,5.520\\1.91\,\mathrm{yr}}]{}\\
&{}^{224}\mathrm{Ra}\xrightarrow[\substack{\alpha\,5.789\\3.7\,\mathrm{day}}]{}{}^{220}\mathrm{Rn}\xrightarrow[\substack{\alpha\,6.404\\56\,\mathrm{sec}}]{}{}^{216}\mathrm{Po}\xrightarrow[\substack{\alpha\,6.906\\.14\,\mathrm{sec}}]{}{}^{212}\mathrm{Pb}\xrightarrow[\substack{\beta\\11\,\mathrm{hr}}]{}\\
&{}^{212}\mathrm{Bi}\xrightarrow[\substack{\beta\\\mathrm{fast}}]{}\xrightarrow[\substack{\alpha\\\mathrm{fast}}]{}\xrightarrow[\substack{\beta\\\mathrm{fast}}]{}{}^{208}\mathrm{Pb},
\end{aligned}\tag{8}$$

$$\begin{aligned}
&{}^{242}\mathrm{Cm}\xrightarrow[\substack{\alpha\,6.216\\163\,\mathrm{day}}]{}{}^{238}\mathrm{Pu}\xrightarrow[\substack{\alpha\,5.593\\88\,\mathrm{yr}}]{}{}^{234}\mathrm{U}\xrightarrow[\substack{\alpha\,4.856\\.245\,\mathrm{Myr}}]{}{}^{230}\mathrm{Th}\xrightarrow[\substack{\alpha\,4.771\\75400\,\mathrm{yr}}]{}\\
&{}^{226}\mathrm{Ra}\xrightarrow[\substack{\alpha\,4.870\\1599\,\mathrm{yr}}]{}{}^{222}\mathrm{Rn}\xrightarrow[\substack{\alpha\,5.590\\4\,\mathrm{day}}]{}{}^{218}\mathrm{Po}\xrightarrow[\substack{\alpha\,6.114\\3\,\mathrm{min}}]{}{}^{214}\mathrm{Pb}\xrightarrow[\substack{\beta\\27\,\mathrm{min}}]{}\\
&{}^{214}\mathrm{Bi}\xrightarrow[\substack{\beta\\19\,\mathrm{min}}]{}{}^{214}\mathrm{Po}\xrightarrow[\substack{\alpha\,7.833\\.16\,\mathrm{ms}}]{}{}^{210}\mathrm{Pb}\xrightarrow[\substack{\beta\\22\,\mathrm{yr}}]{}\\
&{}^{210}\mathrm{Bi}\xrightarrow[\substack{\beta\\5\,\mathrm{day}}]{}{}^{210}\mathrm{Po}\xrightarrow[\substack{\alpha\,5.407\\138\,\mathrm{day}}]{}{}^{206}\mathrm{Pb},
\end{aligned}\tag{9}$$

$$\begin{aligned}
&{}^{235}\mathrm{U}\xrightarrow[\substack{\alpha\,4.38\\700\,\mathrm{Myr}}]{}{}^{231}\mathrm{Th}\xrightarrow[\substack{\beta\\25.5\,\mathrm{hr}}]{}{}^{231}\mathrm{Pa}\xrightarrow[\substack{\alpha\,5.06\\32500\,\mathrm{yr}}]{}{}^{227}\mathrm{Ac}\xrightarrow[\substack{\beta\\21.8\,\mathrm{yr}}]{}\\
&{}^{227}\mathrm{Th}\xrightarrow[\substack{\alpha\,6.04\\18.7\,\mathrm{day}}]{}{}^{223}\mathrm{Ra}\xrightarrow[\substack{\alpha\,5.86\\11.4\,\mathrm{day}}]{}{}^{219}\mathrm{Rn}\xrightarrow[\substack{\alpha\,6.82\\4\,\mathrm{sec}}]{}{}^{215}\mathrm{Po}\xrightarrow[\substack{\alpha\,7.38\\1.78\,\mathrm{ms}}]{}\\
&{}^{211}\mathrm{Pb}\xrightarrow[\substack{\beta\\36\,\mathrm{min}}]{}{}^{211}\mathrm{Bi}\xrightarrow[\substack{\alpha\,6.62\\2.15\,\mathrm{min}}]{}{}^{207}\mathrm{Tl}\xrightarrow[\substack{\beta\\4.8\,\mathrm{min}}]{}{}^{207}\mathrm{Pb}.
\end{aligned}\tag{10}$$

2.5 Spacecraft options

"Multistage" alpha rockets are possible by making a large-mass alpha rocket based on a short-lived isotope as the first stage, and a smaller-mass rocket based on a longer-lived isotope as the second stage. The first stage is discarded once the acceleration with it becomes less than the acceleration of the second stage alone[8].

[8]The backing portion of the first stage's film that is pancaked on top of the second stage's film, could be much thinner since the second stage film will serve as its absorber. This trick would save mass, which in many cases would more than compensate for the lost thrust from the second stage.

Consider a 3-stage alpha rocket of this type massing $\approx$ 100 Kg and consisting of $\approx 10^3$ square meters of film[9]. Let the three stages, with masses, say, 100, 25, and 5 kg respectively, be the following portions of the three decay chains above[10]

1. ^{225}Ac (10 day halflife). This is the tail of the ^{249}Cf decay chain.

2. ^{240}Cm (27 day halflife for start up, 74 year halflife total). Alternatively one could just start from ^{228}Th (in the tail of this decay chain) for only a 2 year halflife (for those unwilling to wait 74 years for the second stage to get going) although less energy yield.

3. ^{226}Ra (1621 years). This is the tail of the ^{242}Cm decay chain[11].

Thus after a mere 5000 years, the 1kg payload would acquire a velocity of 850 km/second, i.e. $.0028c$, figuring (conservatively from table 2) 50000 meters/second per alpha decay. (The beta decays provide comparatively negligible thrust.) By comparison, galactic escape velocity is about $.001c$. Even higher speeds ($.0036c$) would be reached by those willing to subscribe to the multimillion year plan in footnote 11. I am not recommending these timescales, of course; indeed in §4 we'll see that thrusting for travel lengths of > 10 lightyears (as would be needed for the 5000 year plan) would be subject to severe dust impact problems. But only a few hundred years thrusting would be needed with the "impatient people's plan" (same footnote) to reach $.0025c$; this plan would enable reaching the Alpha Centauri triple star system (4.3 light years away) in about 1800 years. There are also various other ways to mix and match subchains of these decay chains. Another possibly useful[12] one is ^{230}U, which decays with an initial halflife of 21 days (the succeeding decays are much faster) through 5 alpha and some beta decays to reach ^{206}Pb.

[9] It should be possible to omit entirely any structural elements intended to prevent the film from crumpling, because the self-charging effect we mentioned before will force the film to stay flat, due to intercharge repulsion. An alternative: by spinning the film centrifugal force would also make it stay flat; very light tensile elements such as kevlar line would suffice to prevent film rupture. The point is that microgee acceleration forces causing crumpling or folding are easy to counteract.

[10] The fact that Rn is a gas at room temperature should not be a problem because significant quantities won't be created until 10 years after launch, by which time the craft would be so far from the sun that it would be cold enough for Rn to solidify. Also Rn will never be more than a tiny atomic fraction of the isotope present at any time.

[11] One could also start this chain earlier at ^{234}U if one were willing to wait much longer to reach the (greater) final speed. Of course if you are willing to wait millions of years to reach full speed, then you might as well replace this stage with the entire decay chain of ^{249}Cf (start up time: 351 years). Impatient people could instead choose the 2-year alternative second stage and then use as the third stage, the original 74-year second stage plan.

[12] Or possibly not. After 3 alpha decays ^{230}U becomes ^{218}Rn, which is a gas with halflife 35ms. At temperature 300 kelvin and assuming thermal velocities of the Rn atoms, the Rn atoms would go 6 meters before decaying. The atoms would leave the film and most would probably be lost. However, if diffusion times out of the film were a lot longer than 35ms, then this would be OK.

In a 1kg payload could be, e.g., CD-ROMs containing the entire human genome, a small library, frozen plant seeds or other cells (considering some lifeforms can live for > 1800 years, they might last this long; see also [24][18]), and instructions... The fact that such things are possible with today's technology forces us to concede the *possibility* that life on Earth was started by some similar shipment from extraterrestials.

2.6 Comparison with conventional chemical fuel rockets

These velocities greatly exceed those achievable by any other propulsion method which seems feasible at this time, with the possible exception of lightsails.

A dramatic illustration of α's superiority may be provided thanks to the exponential nature of the "rocket equation" satisfied by chemical fuel rockets – reaching a final velocity V using exhaust velocity v requires a fuel/payload mass ratio of $e^{V/v} - 1$. Assume (maximally optimistically to make our point) the container holding the fuel, and the rocket engine, weigh nothing. (Hence "staging" is pointless.) Then accelerating even a *nano*gram payload to $.0028c$ using a 100% efficient HF rocket ($v = 5.228$ km/second) would require a total fuel mass of 4×10^{58} kg, which greatly exceeds the mass of the universe.

2.7 Sputtering

A possible crushing objection to the alpha rocket is the prospect that the alpha particles would *eject* atoms from the film. If these were fuel atoms, that would be wasted fuel. If they were backing film atoms, that would destroy the backing film, essential for operation. Either way, your trip is over.

Since typically order 10ev of energy is deposited per atom in the path of a rampaging alpha particle, which is easily enough energy to eject all of them, this initially appears to be a very serious problem. Furthermore, "sputtering," intentional ejection of atoms from surfaces using energetic ions in a DC or RF gas discharge to cause the ejection, is a well known phenomenon.

However, in reality most hit atoms immediately hit the next atom, slowing down, and also most of the energy is used to ionize electrons rather than move atoms, so the atoms all cool off rapidly and can't be ejected. Still, it seems possible for an alpha to eject a blob of up to 100 atoms near its point of emergence from the surface. That level of damage, if typical, would destroy the whole plan.

Consulting [3][5][22][23], we find out that sputtering rates tend to increase under conditions of larger stopping power per candidate ejected atom (i.e.: more particle mass and charge, more charge on the candidate ejected atoms) and if the atoms are bound less strongly together. Furthermore, sputtering yield (mean number of ejected atoms per incident particle) peaks when the incident particles have energies of 200-2000 ev per nucleon. Larger or smaller particle energies cause less sputtering – in the former (naively surprising) case because the energy transfer is predominantly to electrons, not atoms. Remember, each atom in the path of the particle receives a roughly *constant* amount of energy, *independent* of the particle energy – and if a larger fraction of that energy is in the form of ionization rather than atomic motion, we get less sputtering. Indeed, above about 1Mev, alpha particles lose $< 1\%$ of their energy to nuclear motion.

Now fortunately, alpha particles, with mass 4 and charge 2, are much less massive than the ions usually employed for sputtering (^{40}Ar, $^{\approx 84}$Kr, and $^{\approx 131}$Xe). The energies per nucleon we are considering (6 Mev per 4 nucleons, for a 6 MeV alpha particle) are far outside the peak sputtering range (which is about 2 kev for α particles).

For example, consider [3] sputtering of Ti by $^4He^+$ projectiles at normal incidence. The experimentally observed sputtering yield is 0.01 for 100ev projectiles, rising to a peak of about 0.08 for 2kev projectiles. At 20kev, the sputtering yield is back down to 0.011.

This data suggests that sputtering is not going to be a problem for us – we expect well below .01 atoms ejected per alpha particle.

However, there is one factor we have not yet considered: in these sputtering experiments, the projectiles always came from *outside* the target. In our case, they are emerging from *inside* the target. Might this cause a considerable difference in sputtering yield? Experimentally, sputtering yield does depend on the angle of the incident beam and is maximized at angles ranging from 55° to 88° away from normal incidence, with the larger angles (more nearly parallel to the surface) being preferred at very high projectile energies. This makes theoretical sense also – more of the projectile energy is deposited close to the surface at glancing incidence. In sputtering, 80-90% of the atoms ejected are on the topmost atomic layer and almost all ejectees are from the top 4 atomic layers. Using the maximum-yield angle tends to give yields 3-5 times higher than normal incidence. Sputtering caused by emergent projectiles *has* been studied (although considerably less than conventional sputtering) under the name of "transmission sputtering" [3] [20] [11]. Here are a few data points: For 200kev Argon ions impacting Gold, the maximum transmission sputtering yield (achieved at Au foil thickness of 50nm) is about 25, versus about 10 for conventional sputtering. For 50kev Helium ions impacting Au, the maximum transmission sputtering yield (achieved at Au foil thickness of 110nm) is about .05, versus .01 for conventional sputtering. For 250kev Argon ions impacting Copper, transmission sputtering yield is about 11.5, versus 4 for conventional sputtering. That suggests that emergent sputtering is going to increase ejection yields versus conventional sputtering by a factor of 2.5-5.

For some reason, the experimentalists have apparently never tried just putting a chunk of alpha emitter in a vacuum chamber and seeing how many radioactive atoms manage to sputter off the emitter to reach a collector someplace else in the vacuum vessel. This would be a much simpler experiment that the ones they actually tried (using ion beams and thin foil targets). What happens after various surface treatments (and how much do they affect the energies of the outcoming alphas)? There is good reason to believe that deposited surface films could reduce sputtering yields.

Summary: our sputtering yields almost certainly will be below 0.05 ejected atoms per emitted alpha, and perhaps much lower. Appropriate deposited surface films, very light in comparison with the heavy emitting nuclides (and hence having little effect on performance), might be useful to reduce sputtering further.

2.8 Other forms of radiation damage

In addition to sputtering (ejection of atoms) radiation also alters the state of non-ejected matter. Would such "radiation damage" be severe enough to injure our rocket?

Such questions are best answered by experiment, but I believe that, *with the right film material,* radiation damage will be a non-issue because even a "maximally damaged" film will still be strong enough. Remember, our film is subjected to very low stresses and hence can be very weak.

The main forms of damage will be: Alpha rays hitting film atoms will displace them, creating interstitials and vacancies. Stopped alpha rays will be helium atoms trapped inside the film. These defects will then "heal" due to diffusion, and the heliums will diffuse out of the film. The diffusion rates depend upon the temperature and the material. In the worst case, these rates are almost zero – and due to the well known Arrhenius dependence $D = D_0 e^{-E_a/k_B T}$ of diffusion constants D in solids on temperature T, in the cold of deep space this worst case will probably be realized. In that case healing will proceed until the atoms arrange themselves into a "local minimum" of potential energy with "walls" substantially higher than $k_B T$, and then no further healing will occur. Call this "minimal healing."

What I mean by "maximal damage" is: imagine these forms of radiation damage proceeding forever with only minimal healing. The resulting state of matter will be called "maximally damaged." (Maximally damaged metal might seem more amorphous than crystalline, for example.) I suspect that even maximally damaged films will be strong enough for our purposes, in many cases[13]; c.f. §2.8.2.

2.8.1 The right film materials

I recommend elements, or metal alloys, as film materials, not compounds such as plastics or oxides. This is because radiation damage could break chemical bonds in compounds.

2.8.2 Effects of radiation damage

In most metals, radiation actually *increases* tensile strength – but brittleness increases, and ductility and "impact strength" decrease. Trapped helium atoms can tend to congregate near grain boundaries, causing "helium embrittlement." (I would expect considerable brittleness anyway at the low temperatures in space, but would not expect that to matter, except possibly when furling up the film. It

[13] An additional imponderable: It may be that diffusion rates in radiation damaged material differ substantially from undamaged material.

might be necessary to pre-heat the film, e.g. by resistance heating, at that point. Heating could also be used to cause healing/annealing effects and exponentially increased diffusion, which might be desirable; vibration, which might also be induced electromagnetically or acoustically, might also increase diffusion.)

One way to reduce the helium problem (if it is one) would be to try to manufacture the films intentionally porous at micron or smaller length scales to speed up diffusion of helium atoms out into space. Porous films would of course have the same stopping power characteristics and hence the same performance for rocketry purposes, as monolithic films.

2.8.3 Swelling and curling

Metals exposed to high radiation fluxes at temperatures of about .3-.5 times their melting point can swell by up to 15% in volume. This is due to vacancy formation and subsequent agglomeration of the vacancies into "voids" (diameter 50-500nm) via diffusion. Helium may play a role in the stabilization and nucleation of such voids. Since Lithium melts at 454Kelvin, operation at some forseen temperatures might cause this effect in Li film, although at the low temperatures in most space, such voids should not form.

Suppose that such swelling does occur, and more in one side of the film than the other. The result would be curling of the film. Curling might also be expected just from temperature changes (the film is just a large bimetallic strip thermometer). To prevent this curling from having a disastrous effect, I recommend constructing the film as small-area segments linked by flexible wires as in figure 2.

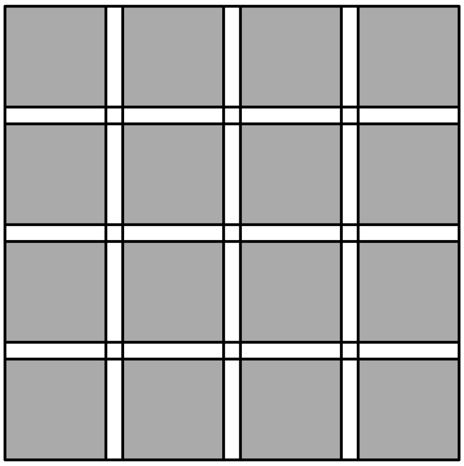

Figure 2: Segmented film

This should cause everything to be pretty immune to all kinds of distortions and volume changes.

2.9 Same idea, but now spontaneous fission, not alpha decays?

The main (99.7%) decay modes of ^{254}Cf (halflife 60.5 day) and ^{250}Cm (80%, halflife 9700 yr) are spontaneous fission. This rare decay mode (these two are the only known isotopes with this as their main mode and life longer than 1 hour) seems *much* better than α decay for rocketry purposes since the fission fragments are so heavy (a 139-115 mass split is typical) and since more energy also is available (typically 160-190 Mev per fragment).

So, why can't we use the same plan as for the alpha rocket (inert film backing with radioisotope film on top) only now with spontaneous fission?

We can, but there are serious additional engineering, cost, and safety problems.

1. The films need to be much thinner, and hence less robust, than for alphas, since large-Z ions are much more easily stopped. Typical stopping lengths are now only 5 microns.

2. Also, innocent bystander atoms seem much more likely to be wastefully ejected by fragments flying by – the sputtering ability of the high-Z, high mass fission fragments is perhaps 100-1000 times larger than that of alpha particles. We are still well above the maximum sputtering energy range (i.e. 30-300 kev, i.e. 500-5000 times smaller) so there is still hope that sputtering damage can be kept low enough.

3. Also, the ejected fragments will themselves often be radioactive, causing "pollution." Alpha particles, in contrast, are harmless.

4. Although some alpha emitters are fairly cheap (^{238}Pu costs \$850/gram in 1999), ^{254}Cf and ^{250}Cm are not on the market, nor are they likely ever to be cheap. (The best way of producing ^{254}Cf seems to be with the aid of very high neutron fluxes from thermonuclear explosions; the neutron fluxes in fission reactors are not large enough to produce macroscopic amounts.)

But if these problems are evadable and/or don't matter, the specific impulse values one can reach will be tremendous.

For the purposes of making an estimate, assume fission into two equal fragments moving in opposite directions with $E = 170$Mev per fragment. The plan is for one fragment to be absorbed and the other ejected. Directions are random on the unit sphere. Assume the mass of the backing film is the same as the mass of the fuel film.

In that case (using the same absorption model as before) the specific impulse is roughly

$$.5408y\sqrt{E/m_{\text{nuc}}} \tag{11}$$

where y is the yield fraction (of decays which are spontaneous fissions) and m_{nuc} is the mass of the decomposing nucleus. We thus estimate a specific impulse value of 4340 km/second for ^{254}Cf, and 80% of this for ^{250}Cm. This[14] is $.0145c$ and $.0116c$. Because now 25% of the total rocket

[14] This exceeds the specific impulse values that could be derived from hypothetical future D-T or D-D fusion powered rockets (assuming 100% fusion yields with the neutrons produced radiated in random directions, but the remaining fusion products nozzled in one direction).

mass is ejected (as opposed to the alpha particle case where only a small percentage, which we ignored, was) we get a 12.5% bonus: the ultimate velocity is 1.125 times this.

Again multistaging is possible; by making a 2-stage spontaneous fission rocket, the first stage powered by ^{254}Cf, the second by ^{250}Cm, one could accelerate a 1kg payload using about 36kg of film (half of the film mass being inert, and the stage 2 film massing, say, 6 kg, and the stage 1 film 30 kg) in 30000 years to speed $0.022c$. The first $0.012c$ would be achieved in only 6 months. With a 1-stage ^{254}Cf rocket one could reach $.013c$ in 6 months, allowing reaching Alpha Centauri in only 330 years.

2.10 A few additional details

Of course, even with the very small thrusts proposed here, by thrusting "sideways" rather than directly upward we can climb by increasing spirals out of any gravity well whose escape velocity is less than the ultimate velocity of our rocket. (E.g., the sun's.) No energy is wasted, if we are in vacuum. In such scenarios, the only number that matters much is specific impulse, hence my concentration on it. Of course all this *won't* work if we are in an atmosphere, since energy conservation then won't hold. Launching from Earth will always require high thrust systems.

I won't discuss the problems of steering the rocket and building a navigation system capable of keeping it on course for thousands of years in the presence of considerable radiation. But I think this is not much of an obstacle. E.g. many present day spacecraft work fine despite carrying amounts of radioisotopes similar to those in our proposal. Electron discharging via sharp points could be parasited as a source of small amounts of power, and manipulation of such points would be one possible way to deform the film (another would be pulling on strings) to effect steering.

3 Comparison with Lightsails

Lightsails [13][14] may not be feasible and are certainly much less feasible at present than our alpha scheme. This is because they depend on very large expanses of very *thin* reflective film. Methods are not presently available for handling such films. In contrast the films required for alpha rockets are $\approx 10^3$ times thicker and have correspondingly smaller area, so seem fully within the boundaries of current technology.

The formula for ultimate velocity of a lightsail orthogonally oriented to the sun's rays is

$$\left(\frac{2RP_{\text{sun}}}{m_{\text{sun}}cGD} - 1\right) v_{\text{esc sun}} \tag{12}$$

This suggests that it is impossible to do much better with any feasible nuclear reaction.

Incidentally, science fiction literature often contains mentions of a hypothetical "Bussard ramjet" which would garner hydrogen from interstellar space somehow, fuse it, and send the high speed fusion products out the back to get thrust, accelerating at $\approx$ 1gee, or in some versions at increasing rates, forever [21] and approaching lightspeed. This idea is ridiculous for many reasons. One is that any such "jet" is incapable of ever exceeding its exhaust velocity (acceleration would then cease), which is $\ll c$. Meanwhile rockets are capable.

where $P_{\text{sun}} = 3.9 \times 10^{26}$ Watts is the total luminosity of the sun, G is Newton's gravitational constant, c is the speed of light, the mass of the sun is $m_{\text{sun}} = 1.99 \times 10^{30}$ kg, R is the reflectivity of the film, and D is the film's areal density, i.e. the film thickness times its volume density.

So if we assume (maximally optimistically) that an Al film 100nm thick can be made (gold leaf 70nm thick can be made, but gold is the most malleable metal, and aluminum is in second place) and it magically remains stretched out and normally oriented to the sun's rays always while requiring zero extra structural mass, and it has 90% reflectivity [6], then it will ultimately reach 64.3 times the sun's escape velocity. The sun's escape velocity is $v_{\text{esc sun}} = \sqrt{2Gm_{\text{sun}}/(1\text{A.U.})} = 42.133$ km/second starting from 1A.U.$= 1.50 \times 10^{11}$ meter away from the sun[15]. In other words, such a lightsail could, under our maximally optimistic assumptions, reach an ultimate velocity of $.009c \approx 3000$ km/second, i.e. 3 times faster than our 3-stage alpha-rocket, but slower than its spontaneous fission variant.

4 Drag and damage from interstellar matter

The density of all matter in the subset of our galaxy constituting the solar "neighborhood" is reckoned to be 88×10^{-22} kg/meter^3. Of this 88: 30 is stars, 14 is white dwarfs, 6 is gas (this density is equivalent to about 5 hydrogen atoms per cm^3), .9 is dust grains, and 32.1 (the rest) is unknown. Some regions of interstellar space near the galactic plane have gas densities as large as 10^2 atoms per cm^3 (cold clouds); others as small as .1 atoms per cm^3 (between clouds) [1]. There seems to be disagreement among various authors about the mass density of the grains, and about their size distribution. For example Draine & Lee [8] would replace the above ".9" by .02. Most grains have radii $r = .005$-$.25$ microns, according to [8] (in interstellar space) but most grains have $r = 91$-424 microns according to [16] (in the solar system). On the other hand, in low Earth orbit, experiments with sensors on early satellites showed [19] that the number N of particles of mass$> m$ grams hitting each square meter per second, for m in the important range $10^{-11} < m < 10^{-6}$ (radii 1-50 microns), obeyed

$$N \approx 10^{-17} m^{-1.7}. \tag{13}$$

Grain mass densities near Earth are 1000 times larger than in interstellar space [16] but this should not matter very much since our craft will only spend a small fraction of its life in grain-rich areas.

The amount of hydrogen and dust grain mass hitting per meter^2 of film area per lightyear of travel, is, assuming the 5 atom/cm^3 matter density, .08 grams. Meanwhile the mass of a film per square meter is 5 grams per micron of film thickness (assuming 5 grams/cm^3 density of film material). This amount of mass density in space is going to have a negligible drag effect on 100-micron thick films such as in the alpha rocket. However, for the very thin films (100nm)

[15] Higher velocities are possible if the sail is "unfurled" closer to the sun; the escape velocity from the sun's surface is $.002c$.

envisioned for lightsails, especially in regions with comparatively high gas densities, the drag effect could be very serious.

We can estimate damage due to dust grain impacts by crudely assuming all the grains have equal radii r microns and density 2.26 grams/cm^3 (graphite). (Some grains are silicate with density 3.3grams/cm^3.)

The grain mass hitting per meter^2 (conservatively assuming a grain density of 10^{-21}kg/meter^3 of space, which is 11 or 500 times larger than the interstellar average) per lightyear of travel is .009 grams, i.e. $10^8 r^{-3}$ grain impacts.

Assuming these excavate impact craters of diameter 9 times the grain diameter (which might seem to be very conservative, at least based on known experiments [16]), we get a fractional area of film destroyed of $3 \times 10^{-3} r^{-1}$, per lightyear of travel, where remember, r is in microns. This damage bound is highly sensitive to the controversial "typical grain radius" value, but should be acceptably small for short journeys ($\leq$ 10 lightyears) if $r \geq .25$. For long journeys and if grains are small, common, and/or highly effective at excavating craters, this could be devastating. But the situation is likely to be even worse than this.

Studies with millimeter particles launched from 2-stage light gas guns and charged micron particles launched from 3MV van de Graaff generators (the latter occasionally can produce particle speeds exceeding 100 km/second for particles massing $\lesssim 10^{-19}$Kg) [2][4][12][15] show the following "empirical laws of particle impact." Once the projectile greatly exceeds the speed of sound in the target and projectile materials ("hypervelocity"), the impact is always explosive and always (if the target is an infinite halfspace and the impact is perpendicular) creates a roughly hemispherical crater. If the projectile and target materials are fixed then the volume of the crater is proportional to the kinetic energy of the projectile and is maximized at perpendicular incidence. For iron dust particles impacting water ice, the mass of the excavated material is about 1.2×10^{-4}Kg/joule, which is about 400 times larger than the mass that could be vaporized by that energy, but only about 76 times larger than the mass that could be melted by that energy. For 1mm-diam steel spheres impacting aluminum, the excavated mass is about 1.9×10^{-5}Kg/joule, i.e. about 25 times the mass that could be vaporized by that energy, but only about 2.2 times the mass that could be melted by that energy.

If the target is a film rather than a halfspace, $> 75\%$ all the projectile's kinetic energy is known to be extracted if the film is thicker than about twice the projectile's diameter (for Fe particles impacting aluminum foil) [15].

Anyway, for graphite spheres impacting aluminum, the model above suggests that for perpendicular impacts at 750km/second (.0025c), the crater radius should be about 210 times (not 9 times!) the projectile radius. (We now assume crater radii are the same in films as they are in bulk targets.) This amplifies our earlier area-damage estimate by a factor of 540; the entire film would be destroyed after only about r lightyears of travel at .0025c, where r is the typical grain radius in microns.

This is not quite as devastating as it may sound, because, e.g., with our 3-stage scheme to reach .0025c in a few hundred years (end of footnote 11), the final speed is essentially attained in the first .25 light years. After that point, film destruction is irrelevant. Also, during most of this period of acceleration, the speed is well below .0025c, so each grain causes much less damage. We **conclude** that meteor damage (at least for this particular plan) should be acceptable[16].

5 Some comparatively crazy ideas

NASA's NERVA nuclear-fission powered hydrogen rocket was abandoned in the 1960s. It was ridiculously unsafe and inherently incapable of exceeding thermal exhaust velocities at temperatures at which solids exist, hence a priori pointless versus chemical rockets[17].

General Atomic's "Orion" project (T.Taylor and F.Dyson) proposed an enormous craft (20 kilometers diameter) powered by 30 million tons of hydrogen bombs, traveling at .003c. (A "less conservative" design weighed only half a million tons and only a few km in diameter. All designs had big shock absorbers.) F.Dyson's unclassified analysis [9] of this plan seems wrong in several ways:

1. Dyson assumed 1 megaton hydrogen bombs existed with mass 1000 kg. However, the $\approx$ 20 kiloton fission bombs that leveled Hiroshima and Nagasaki are known to have weighed 3200 and 4500 kg respectively. Also, the "Mark 6" 30 kiloton fission bomb that was accidentally dropped during a US Air Force exercise on Mars Bluff, South Carolina, on 11 March 1958 (the resulting non-nuclear explosion destroyed a house and injured several people) weighed 3450 Kg and was 3.25 meter long and 1.55 meter in diameter.

2. The cost of fuel was estimated purely as cost of deuterium, ignoring labor costs and plutonium cost to build the bombs. I suspect that would have multiplied their cost estimate (which was 1 USA GNP) by at least 10. (In 1999 dollars, Deuterium costs about 1200\$/kg, and purified ^{239}Pu about 4.8×10^6\$/Kg. Assuming each bomb has 10kg of ^{239}Pu, that is 48 million dollars already, which exceeds the cost of a ton of deuterium by a factor of 4.)

3. The energy estimates ignored the fact that a large fraction of the energy of an H-bomb exploding in vacuum would have been carried off by fast neutrons. (In a reaction in which a He nucleus and a neutron are emitted, conservation of momentum implies the neutron

[16] Also, it is possible that grain impact damage could be reduced by a factor of 10 by using multilayer films separated by layers of vacuum. (Much of the excavated crater material might then be able to reattach itself and would not be lost.)

[17] Actually, there is *some* point to them. Although nuclear reactor temperatures necessarily are at most about half those in an oxyhydrogen flame, one can use an H_2 exhaust rather than H_2O, i.e. 9 times lighter molecules. The result could be $\sqrt{9/2} \approx 2.1$ times faster exhaust speeds.

will have about 4 times the energy of the He nucleus.) I don't think these neutrons could have been usefully employed to get thrust because they would not have been reflected or absorbed by the thin copper sheeting Dyson had in mind. My guess: this would have decreased Orion's specific impulse by a factor of 5.

Clearly it will not be possible to launch this gigantic craft any time soon due to its cost and size. On a *cost per unit mass* basis alone, though, the Orion plan is an extremely good one.

R.Forward [13] proposed laser pushed lightsails, including a 1000km diameter fresnel lensed laser consuming more power than the entire human race, huge expanses of far thinner freestanding films than have ever been made, etc.

6 Some maybe not so crazy ideas

R.Zubrin [27] had an interesting idea of using a current (50kAmpere) in a superconducting loop (63km diameter; wire diameter 2.5mm; tensile strength 1600Newton; total mass 5500kg) whose axis was perpendicular to the sun's rays, to generate a magnetic field ($\approx 10^{-6}$Tesla; total field energy 8×10^7Joules); this field would deflect protons in the "solar wind," and hence the loop would be accelerated, either outward from the sun, or conceivably even "sideways." This idea could only work within a specific range of distances from the sun, perhaps 2-20 A.U., and requires for its operation high-T_c superconductive wire of fairly high tensile strength ($\geq 8 \times 10^7$Pascal) and high critical current density ($\geq$ 800kAmp/cm^2). Such wires are not presently available, but plausibly might be developed in the next 20 years. It seems possible to achieve speeds of perhaps .001c, almost as fast as the speed ($\approx$ 400km/second=.0013c) of the solar wind itself. Zubrin also pointed out that the best application of this "magsail" might be for *deacceleration* at one's destination.

Freeman Dyson [private communication, 1999] suggested (and numerous others have suggested) using a small nuclear reactor to generate electricity which in turn would power an ion gun. This would have the vast advantage, versus the alpha rocket, that it could be turned on and off without loss. This idea perhaps could also yield performance (i.e. final speed) superior to the alpha rocket. But this would only be possible with MeV ion accelerators of lower mass, higher efficiency, higher beam currents, and higher reliability than those currently available; also the device for converting nuclear heat to electrical energy, and the radiator for getting rid of waste heat, would both have to have a better combination of reliability and power/mass ratio than the devices currently available. One or both of us may analyse this idea in more detail in a later publication.

7 Acknowledgement

Freeman J. Dyson encouraged me to write §2.8.

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