# Thermonuclear Operation Space Lift

F. Winterberg

University of Nevada, Reno

**Abstract**

The "Project Orion" small fission bomb propulsion concept proposed the one-stage launching of large payloads into low earth orbit, but it was abandoned because of the radioactive fallout into the earth atmosphere. The idea is here revived by the replacement of the small fission bombs with pure deuterium-tritium fusion bombs, and the pusher plate of the Project Orion with a large magnetic mirror. The ignition of the thermonuclear fusion reaction is done by the transient formation of keV super-explosives under the high pressure of a convergent shock wave launched into liquid hydrogen propellant by a conventional high explosive.

## 1. Introduction

A principal obstacle standing in the way of a large scale access to space is the small energy per unit mass which is released in chemical reactions, requiring multistage rockets. An early study by von Braun estimated that in an "Operation Space Lift" a few hundred rocket launches would be needed to bring into low earth orbit the parts to assemble two Mars space ships in space [1]. Von Braun had assumed that the trip to Mars would be done by chemical rockets, but it would still require a very large number of launches into low earth orbit if the trip to Mars would be done by some nuclear electric propulsion system instead.

Because of the million times larger energy in nuclear reactions, this game changing potential was early on realized. But to fully utilize this potential requires going to much higher temperatures than the combustion temperatures of chemical reactions. It appeared that the only way to overcome this problem is a pulsed nuclear combustion, where the rocket motor is exposed only for a very short time, but where the waste-heat is released in the exhaust as in chemical rockets. This led directly to the idea to propel a spacecraft by a chain of small nuclear explosions. Since up until now no thermonuclear fusion explosion has been ignited without a fission bomb trigger, such a bomb propulsion concept must involve a fission reaction as for fusion boosted fission bombs. But as Dyson has pointed out, a fission reaction is subject to the tyranny of the critical mass, which means that small fission explosions with a small yield would be extravagant. For fusion explosions there is no tyranny of a critical mass, and in principle they could be made very small, but they are difficult to ignite. Attempts by Lawrence Livermore National Laboratory to ignite a small deuterium-tritium fusion explosion with a 2MJ laser have failed, but that does not mean that alternative non-fission ignition concepts would not work.

## 2. Ignition by a convergent shock wave

For rocket propulsion the ignition of a thermonuclear micro-explosion by a convergent shock wave would be of great interest if the ignition temperature can be reached in the center of this wave. There the medium through which the convergent shock wave is propagating would become a propellant heated up to high temperatures by the thermonuclear micro-explosion in its center. Therefore, let us analyze this proposal. According to Guderley [2] the temperature $T$ in a convergent shock wave propagating in hydrogen rises as

$$\frac{T}{T_0} = \left(\frac{R}{r}\right)^{0.9} \tag{1}$$

where $R$ is its initial radius. To reach the ignition temperature $T \sim 10^8$ K at a radius of $r \sim 1$ cm would, at an initial temperature of $T_0 \sim 10^4$ K, supplied by a chemical high explosive, require that $R \sim 10$ m, which is unrealistically large.

The idea to ignite a thermonuclear micro-explosions by a convergent shock wave driven with high explosives was proposed by the author in a fusion workshop at the Max Planck Institute for Physics in Goettingen, October 23-24, 1956, organized by the fusion pioneer C.F. von Weizsäcker [3].

While an imploding spherical shell is subject to the Rayleigh-Tayler instability, a spherical convergent shock wave is stable. This has been demonstrated in the 15 Megaton 1952 “Mike” test, where a sphere of liquid deuterium was ignited by a plutonium (or uranium) bomb, with the X-rays from the exploding fission bomb launching a Guderley convergent shock wave into the deuterium. Apart from this demonstrated stability of the Guderley convergent shock wave solution, its stability has also been confirmed in an extensive analytical study by Häfele [4].

Guderley’s convergent shock wave solution also predicts a rise in the pressure by

$$\frac{p}{p_0} = \left(\frac{R}{r}\right)^{0.9} \tag{2}$$

With high explosives producing pressures up to 1 Mb = $10^{12}$ dyn/cm$^2$ [5] and setting $R = 10^2$ cm, a pressure of 100 Mb = $10^{14}$ dyn/cm$^2$ would be reached at the radius $r \sim$ 1cm. Under these high pressures super-explosives can be formed on very short time scales, facilitating the ignition of a thermonuclear micro-explosion by a convergent shock wave [6, 7, 8].

## 3. Super-explosives

Under normal pressure the distance of separation between two atoms in condensed matter is typically of the order $10^{-8}$ cm, with the distance between molecules formed by the chemical binding of atoms of the same order of magnitude. As illustrated in a schematic way in Fig. 1, the electrons of the outer electron shells of two atoms undergoing a chemical binding form a “bridge” between the reacting atoms. The formation of the bridge is accompanied in a lowering of the electric potential well for the outer shell electrons of the two reacting atoms, with the electrons feeling the attractive force of both atomic nuclei. Because of the lowering of the potential well, the electrons undergo under the emission of eV photons a transition into lower energy molecular orbits.

Going still to higher pressures, a situation can arise as shown in Fig. 2, with the building of electron bridges between shells inside shells. There the explosive power would be even larger. Now consider the situation where the condensed state of many closely spaced atoms is put under high pressure, making the distance of separation between the atoms much smaller, whereby the electrons from the outer shells coalesce into one shell surrounding both nuclei, with electrons from inner shells forming a bridge. Because there the change in the potential energy is much larger, the change in the electron energy levels is also much larger, and can be of the order of keV. There then a very powerful explosive is formed, releasing its energy in a burst of keV X-rays. This powerful explosive is likely to be very unstable, but it can be produced by the sudden application of a high pressure in just the moment when it is needed. Because an intense burst of X-rays is needed for the ignition of a thermonuclear micro-explosion, the conjectured effect, if it exists, has the potential to reduce the cost of the ignition of thermonuclear micro-explosions by orders of magnitude.

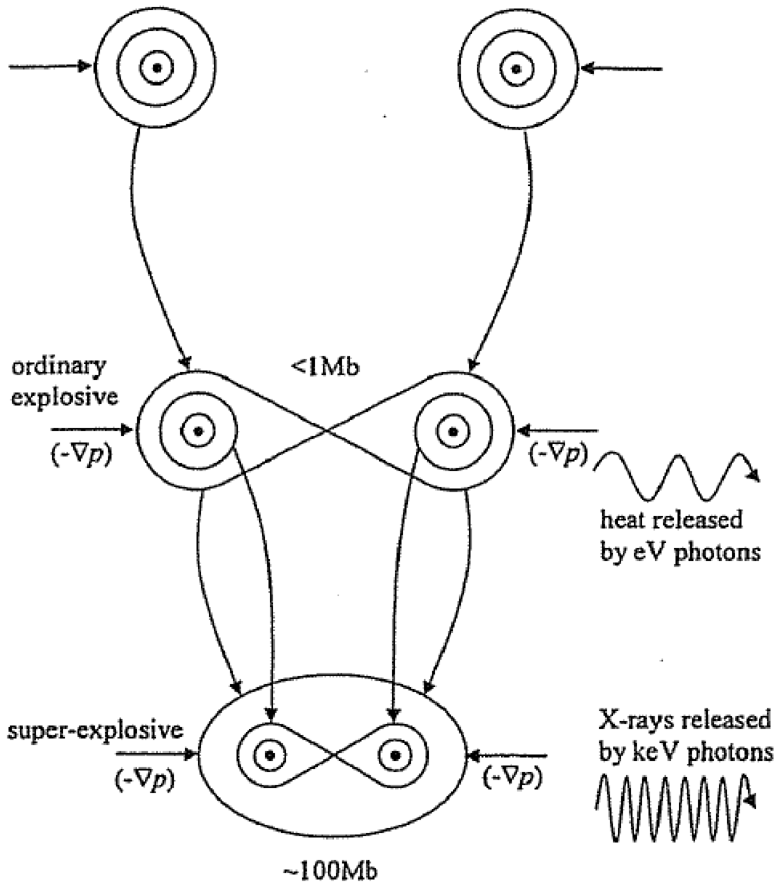
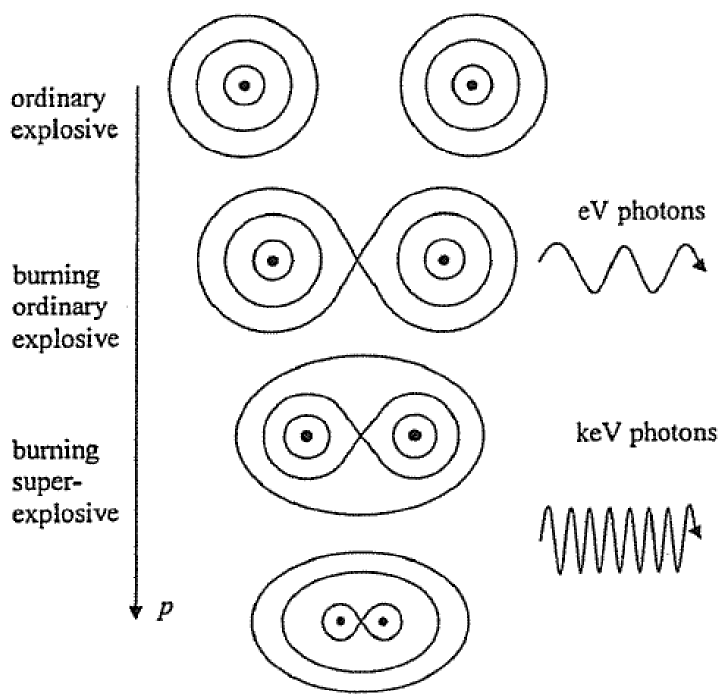



**Fig. 1**

*In an ordinary explosive the outer shell electrons of the reacting atoms form "eV" molecules accompanied by the release of heat through the eV photons. In a super-explosive the outer shell electrons "melt" into a common outer shell while inner electron shells form "keV" molecules accompanied by the release of X-ray keV photons.*

**Fig. 2**

*With increasing pressure electron-bridges are formed between shells melting into common shells.*



The energy of an electron in the groundstate of a nucleus with the charge *Z*e is

$$E_1 = -13.6Z^2\,(\mathrm{eV}) \qquad (3)$$

With the inclusion of all the *Z* electrons surrounding the nucleus of charge *Z*e, the energy is

$$E_1^* \approx -13.6Z^{2.42}\,(\mathrm{eV}) \qquad (4)$$

with the outer electrons less strongly bound to the nucleus.

Now, assume that two nuclei are so strongly pushed together that they act like one nucleus with the charge 2*Z*e, onto the 2*Z* electrons surrounding the 2*Z*e charge. In this case, the energy for the innermost electron is

$$E_2 = -13.6(2Z)^2\,(\mathrm{eV}) \qquad (5)$$

or if the outer electrons are taken into account,

$$E_2^* = -13.6(2Z)^{2.42}\,(\mathrm{eV}) \qquad (6)$$

For the difference one obtains

$$\delta E = E_1^* - E_2^* = -13.62Z^{2.42}\left(2^{2.42} - 1\right) \approx 58.5Z^{2.42}\,(\mathrm{eV}) \qquad (7)$$

Using the example *Z* = 10, which is a neon nucleus, one obtains $\delta E \approx 15$ keV. Of course, it would require a very high pressure to push two neon atoms that close to each other, but this example makes it plausible that smaller pressures exerted on heavier nuclei with many more electrons may result in a substantial lowering of the potential well for their electrons. For an equation of state of the form $p/p_0 = (n/n_0)^\gamma$, and a pressure of 100 Mb = $10^{14}$ dyn/cm$^2$, we may set γ = 3 and $p_0 = 10^{11}$ dyn/cm$^2$, where $p_0$ is the Fermi pressure of a solid at the atomic number density $n_0$, with *n* being the atomic number density at the elevated pressure $p > p_0$. With $d = n^{-1/3}$, where *d* is the lattice constant, one has

$$d/d_0 = \left(p_0/p\right)^{1/9} \qquad (8)$$

For $p = 10^{14}$ dyn/cm$^2$, $d/d_0 \sim 1/2$. Such a lowering of the inneratomic distance is sufficient for the formation of molecular states.

Calculations done by Muller, Rafelski and Greiner [9] show that for molecular states $_{35}$Br- $_{35}$Br, $_{53}$I- $_{79}$Au, and $_{92}$U- $_{92}$U, a twofold lowering fo the distance of separation leads to a lowering of the electron orbit energy eigenvalues by ~ 0.35, 1.4 keV, respectively. At a pressure of 100 Mb = $10^{14}$ dyn/cm$^2$ where $d/d_0 \cong 1/2$, the result of these calculations can be summarized by ($\delta E$ in keV)

$$\log \delta E \cong 1.3\times10^{-2} Z - 1.4 \tag{9}$$

replacing Eq. 7, where $Z$ is here the sum of the nuclear charge for both components of the molecule formed under the high pressure.

The effect the pressure has on the change in these quasi-molecular configurations is illustrated in Fig. 3, showing a $p - d$ (pressure-lattice distance) diagram. This diagram illustrates how the molecular state is reached during the compression along the adiabat $a$ at the distance $d = d_c$ where the pressure attains the critical value $p = p_c$. In passing over this pressure the electrons fall into the potential well of the two-center molecule, releasing their potential energy as a burst of X-rays. Following its decompression, the molecule disintegrates along the lower adiabat $b$.

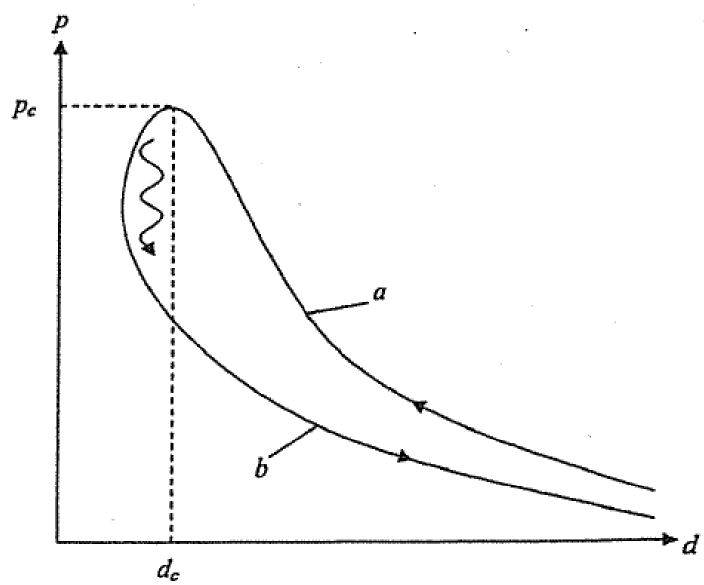



**Fig. 3**

*p – d, pressure-inneratomic distance diagram for the upper atomic and lower molecular adiabat.*

The natural life time of an excited atomic (or molecular) state, emitting radiation of the frequency $v$ is given by [10]

$$\tau_s \cong 3.95\times10^{22} / v^2 \text{ (sec)} \tag{10}$$

For keV photons one finds that $v \cong 2.4\times10^{17}$ s$^{-1}$, and thus $\tau_s \cong 6.8\times10^{-14}$ s.

By comparison, the shortest time for the high pressure rising at the front of a shock wave propagating with the velocity $v$ through a solid with the lattice constant $d$, is of the order

$$\tau_c \cong d / v \tag{11}$$

Assuming that $v \cong 10^6$ cm/s, a typical value for the shock velocity in condensed matter under high pressure, and that $d \cong 10^{-8}$ cm, one finds that $\tau_c \cong 10^{-14}$ s. In reality the life time for an excited state is much shorter than $\tau_s$, and of the order of the collision time, which here is the order of $\tau_c$.

The time for the electrons to form their excited state in the molecular shell is of the order $1/\omega_p \sim 10^{-16}$ s, where $\omega_p$ is the solid-state plasma frequency. The release of the X-rays in the shock front is likely to accelerate the shock velocity, exceeding the velocity profile of the Guderley solution for convergent shock waves.

A problem for the use of these contemplated super-explosives to ignite thermonuclear reactions is the absorption of the X-ray in dense matter. It is determined by the opacity [11]

$$\kappa = 7.23 \times 10^{24} \rho T^{-3.5} \sum_i \frac{w_i Z_i^2 g}{A_i t} \tag{12}$$

where $w_i$ are the relative fractions of the elements of charge $Z_i$ and atomic number $A_i$ in the radiating plasma, with $g$ the Gaunt and $t$ the guillotine factor.

The path length of the X-ray is then given by

$$\lambda = (\kappa\rho)^{-1} \tag{13}$$

This clearly means that in material with a large $Z$ value, the path length is much smaller than for hydrogen where $Z = 1$. This suggests placing the super-explosive in a matrix of particles, thin wires, or sheets embedded in solid hydrogen. If the thickness of the particles, thin wires, or sheets is smaller than the path length in it for the X-ray, the X-ray can heat up the hydrogen to high temperatures, if the thickness of the surrounding hydrogen is large enough for the X-ray to be absorbed in the hydrogen. The hydrogen is thereby transformed into a high temperature plasma, which can increase the strength of the shock wave generating the X-ray releasing pressure pulse.

If the change in pressure is large, whereby the pressure in the upper adiabat is large compared to the pressure in the lower adiabat, the X-ray energy flux is given by the photon diffusion equation

$$\phi = -\frac{\lambda c}{3} \nabla w \tag{14}$$

where $w$ is the work done per unit volume to compress the material, and $w = p/(\gamma - 1)$. For $\gamma = 3$, one has $w = p / 2$, whereby (14) becomes

$$\phi = -\frac{\lambda c}{6} \nabla p \tag{14a}$$

Assuming that the pressure e-folds over the same length as the photon mean free path, one has

$$\phi \sim (c/6)\, p \tag{15}$$

For the example $p$ = 100 Mb = $10^{14}$ dyn/cm$^2$ one finds that $\phi \sim 5\times10^{23}$ erg/cm$^2$s $= 5\times10^{16}$ W/cm$^2$, large enough to ignite a thermonuclear micro-explosion, and at a pressure of 100 Mb also large enough to satisfy for $r \leq 1$cm the $\rho r > 1$g/cm$^2$ condition for propagating burn.

If the conjectured super-explosive consists of just one element, as is the case for the $_{35}$Br-$_{35}$Br reaction, or the $_{92}$U- $_{92}$U reaction, no special preparation for the super-explosive is needed. But as the example of Al-FeO thermite reaction shows, reactions with different atoms can release a much larger amount of energy compared to other chemical reactions. For the super-explosives this means as stated above that they have to be prepared as homogeneous mixtures of nano-particle powders, bringing the reacting atoms as close together as possible.

## 4. The mini-fusion bomb configuration

As shown in Fig. 4, the deuterium-tritium (DT) fusion explosive positioned in the center is surrounded by a cm-size spherical shell made up of a super-explosive, surrounded by a meter-size sphere of liquid hydrogen. The surface of the hydrogen sphere is covered with many high explosive lenses, preferably of a high explosive made up of a boron compound, to increase the absorption of the neutrons making up 80% of the energy released in the DT fusion reaction. Each explosive has an igniter, and to produce a spherical convergent shock wave in the hydrogen the ignition must happen simultaneously, which can be done by just one laser beam, split up in as many beamlets as there are ignitors.

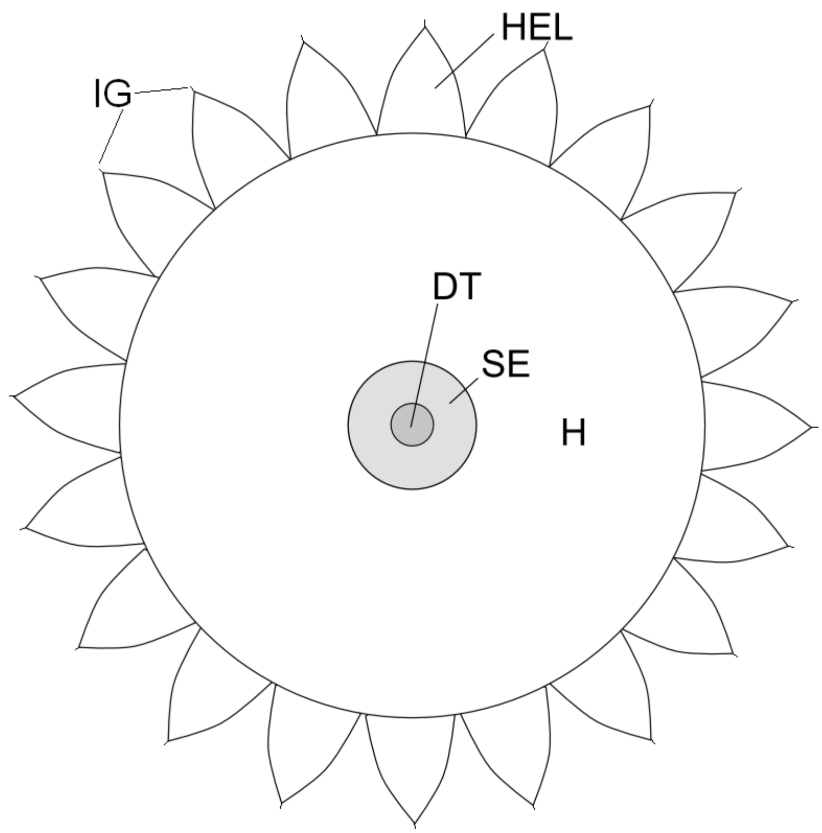



**Fig. 4**

*Pure fusion bomb assembly. HEL high explosive lens. IG ignitor. H liquid hydrogen. SE super-explosive. DT deuterium-tritium. (Not to scale)*

## 5. The propulsion unit

The propulsion unit is very similar to the one in a previous publication [10], where the fusion bomb assembly is placed in the focus of a 10 meter-size large metallic reflector, positioned around the focus of a magnetic mirror. The expanding fire ball compressing the magnetic field will there generate surface currents in the metallic reflector, making a magnetized plasma layer protecting the reflector from the hot plasma. The meter-size hydrogen sphere of the mini-fusion bomb is transformed into a fireball with a temperature of ~ $10^5$ K, or somewhat higher, with an exhaust velocity of ~ 30 km/s (Fig. 5). Cooling the metallic reflector can be done with liquid hydrogen becoming part of the exhaust, as in chemical liquid fuel rocket technology. This is unlikely to amount to more than 10% of the liquid hydrogen heated by the neutrons of the fusion explosion.

A meter-size ball of liquid hydrogen heated to $10^5$ K, has a thermal energy of $10^{18}$ erg, equivalent to 25 tons of TNT. At this temperature the pressure is ~$10^{11}$ dyn/cm$^2$. If the fireball expands from an initial radius of $R_o$ ~1 m to $R_1$ ~10 m, the pressure goes down to $10^9$ dyn/cm$^2$ ~$10^3$ atm, which is about 2 orders of magnitude smaller, and less than the tensile strength of steel.

At this pressure, the magnetic field strength at the surface of the steel will be of the order $10^5$ Gauss. The energy released by the eddy currents in the reflector can hardly be more than 10% of the energy released in the fusion explosion. The mass of a meter-size ball of liquid hydrogen is of the order 0.1 tons, such that 0.01 tons of liquid hydrogen would be available for the cooling of the reflector.

The pressure of $\sim 10^9$ dyn/cm$^2$ acting on the metallic mirror is transmitted to the space-lift to produce thrust. Because the thickness of the parabolic mirror is small in comparison to its radius, this would lead to a large circumferential hoop stress on the mirror, larger by a factor equal to the ratio of radius of the mirror to its thickness. This requires that the mirror be supported by external forces. These forces could be realized making the mirror's thickness comparable to its radius, which for a mirror made from steel would make it very heavy.

Adopting an idea by P. Schmidt and B. Pfau [13], who had shown that the wall thickness of cylindrical and spherical pressure vessels can be greatly reduced by surrounding them with a thick compact layer of a disperse medium composed of high tensile strength micro-particles. As shown in Fig. 5, to utilize this effect, the metallic mirror is placed inside a box filled with a compactified disperse medium, such as SiC (carborundum) or $AlO_3$.

If the disperse medium consists of mono-crystal particles ("whiskers"), it has a compressive strength of the order $\sim 10^{11}$ dyn/cm$^2$. Because of the friction between the particles of the disperse medium, a shear stress is set up in the medium which makes possible the radial reduction of the stress in a spherical configuration.

Setting $\rho$ as the friction angle between the particles of the disperse medium, one has for the maximum shear stress

$$\tau < \sigma_n \tan \rho \tag{16}$$

Where $\sigma_n$ is the normal component of the stress tensor. If plotted in a Mohr stress diagram as shown in Fig. 6, the maximum possible shear stress cannot exceed the line $\tau < \sigma_n \tan \rho$.

The maximum shear stress

$$\tau_{\max} = \frac{\sigma_{\max} - \sigma_{\min}}{2} \tag{17}$$

which in the Mohr stress diagram is given by

$$\sin \rho = \frac{\sigma_{\max} - \sigma_{\min}}{\sigma_{\max} + \sigma_{\min}} \tag{18}$$

and hence

$$\frac{\sigma_{\min}}{\sigma_{\max}} = \tan^2(45° - \frac{\rho}{2}) \tag{19}$$

The friction angle $\rho$ can be visualized by the slope of an imaginary "sandhill" made from particles of the disperse medium. For a "real" sandhill seen in nature, we estimate that $\rho = 45°$. Inserting this value into (19) one finds that $\sigma_{\min} / \sigma_{\max} \approx 0.1$.

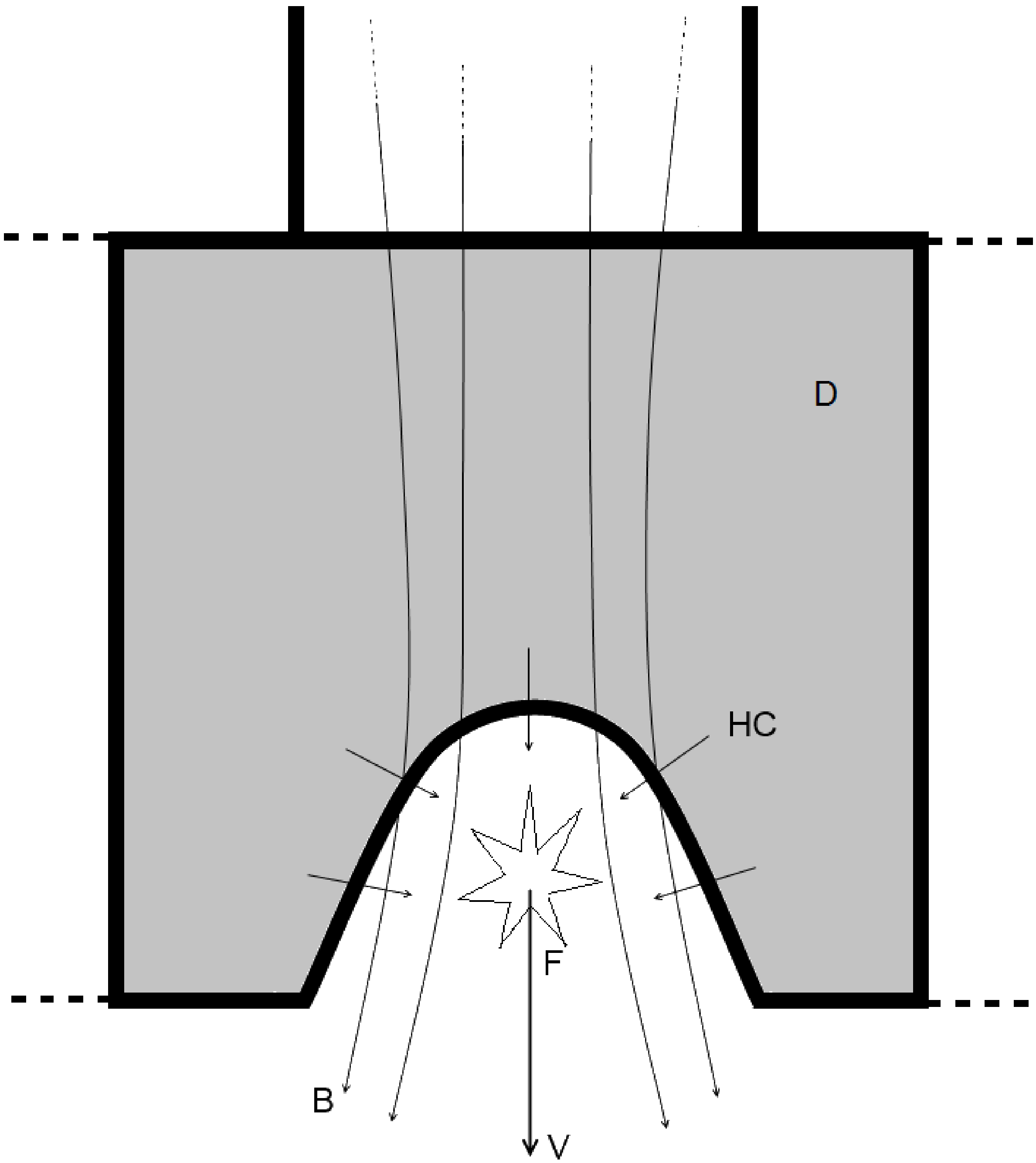



**Fig. 5**

*Propulsion unit: B magnetic field. F fireball. V exhaust jet, HC hydrogen coolant, D disperse medium*

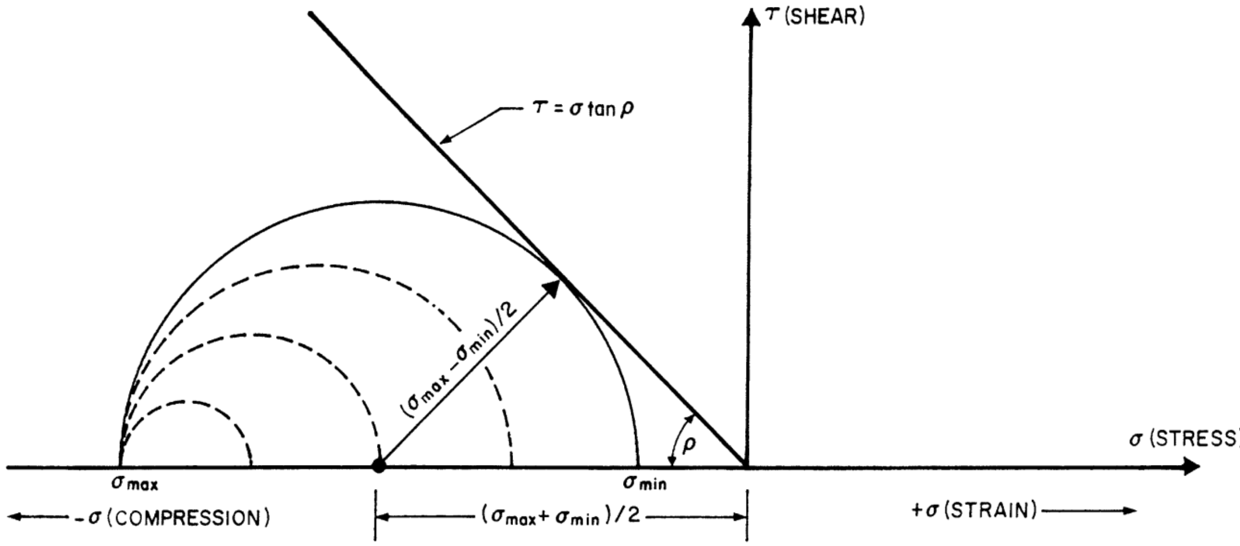



**Fig. 6**

*Mohr stress diagram for a disperse medium subject to frictional forces*

The pressure distribution in the disperse medium surrounding the metallic reflector is determined by the static equilibrium equation, which in Cartesian coordinates is given by

$$\frac{\partial \sigma_{ik}}{\partial x_k} = 0 \tag{20}$$

and in curvilinear coordinates by

$$\sigma^k_{i;k} = 0 \tag{21}$$

where the colon stands for the covariant derivative. For (21) one can also write

$$\frac{1}{\sqrt{g}} \frac{\partial}{\partial x^k} (\sqrt{g}\sigma^k_i) - \Gamma^l_{ik}\sigma^k_l = 0 \tag{22}$$

with the line element squared ( $ds^2 = g_{ik} dx^i dx^k$ ) defining the metric tensor and $g = \det g_{ik}$ . The $\Gamma^l_{ik}$ are the Christoffel symbols of the 2nd kind. For simplicity we may approximate the metallic reflector by a spherical shell. Then, introducing in the dispersive medium spherical coordinates $r, \theta, \phi$ , where the metric tensor is determined by the line element

$$ds^2 = dr^2 + r^2 (d\theta + \sin^2 \theta \times d\phi^2) \tag{23}$$

one has $\Gamma^1_{11} = 0$ , $\Gamma^2_{12} = \Gamma^3_{13} = 1/r$ and $\sqrt{g} = r^2 \sin\theta$ , and therefore from (22)

$$r \frac{d\sigma_r}{dr} + 2(\sigma_r - \sigma_\theta) = 0 \tag{24}$$

where $\sigma_r$ and $\sigma_\theta$ are the components of the stress tensor in the radial and transverse direction.

Because $\sigma_r = \sigma_{\max}$ and $\sigma_{\min} \approx 0.1\sigma_r$ one has

$$r \frac{d\sigma_r}{dr} = -1.8\sigma_r \tag{25}$$

hence

$$\sigma_r = \sigma_r^{(0)} \left( \frac{r_0}{r_1} \right)^{1.8} \tag{26}$$

where $r_0$ is the radius of the reflector with $r_1 > r_0$ . Assuming, for example, that $r_1 \approx 3r_0$ , approximately shown in Fig. 5, one finds that $\sigma_r^{(1)} = 0.14\sigma_r^{(0)}$ . For $\sigma_r^{(0)} = p_0 = 10^9\, dyn/cm^2$ , one has $\sigma_r^{(1)} = p_1 = 1.4\times10^8 dyn/cm^2 = 140atm$ . As in the Orion concept, this pressure is transmitted through shock absorbers to the spacecraft.

Because more than one propulsion unit is needed, a cluster of propulsion units are put together forming a disk as shown in Fig. 7. There, the pressure in the radial horizontal direction is computed in cylindrical coordinates $r,\phi$ . With $ds^2 = dr^2 + r^2 d\phi^2$ , and $\partial/\partial\phi = 0$ , one finds that $\Gamma^1_{11} = 0$ , $\Gamma^2_{21} = 1/r$ , and $\sqrt{g} = r$ . From (22) one finds that here

$$r\frac{d\sigma_r}{dr} + \sigma_r - \sigma_\phi = 0 \tag{27}$$

or with $\sigma_\phi \approx 0.1\sigma_r$ that

$$r\frac{d\sigma_r}{dr} = -0.9\sigma_r \tag{28}$$

and hence

$$\sigma_r^{(2)} = \sigma_r^{(1)}\left(\frac{r_1}{r_2}\right)^{0.9} \tag{29}$$

where $r_2 > r_1$ is the radius of the disc.

For $r_2 \approx 3r_1$, as shown in Fig. 7, one has $\sigma_r^{(2)} \approx 0.37\sigma_r^{(1)}$ . For $\sigma_r^{(1)} \approx 1.4\times10^8 dyn/cm^2$ , one has $\sigma_r^{(2)} \approx 5.2\times10^7 dyn/cm^2 = p_2$ .

Under these conditions the static equilibrium condition for a disc of radius $r_2$ and thickness $t$ is given by

$$2\times\pi r_2^{\,2} p_2 = 2\pi r_2 t\sigma_{\|} \tag{30}$$

where $t$ is the thickness of the hoop put around the disc at its radius $r_2$ , and $\sigma_{\|}$ the hoop stress. From (30) one obtains for the hoop stress

$$\sigma_{\|} = \frac{r_2 p_2}{t} \tag{31}$$

or

$$t = \frac{r_2 p_2}{\sigma_{\|}} \tag{32}$$

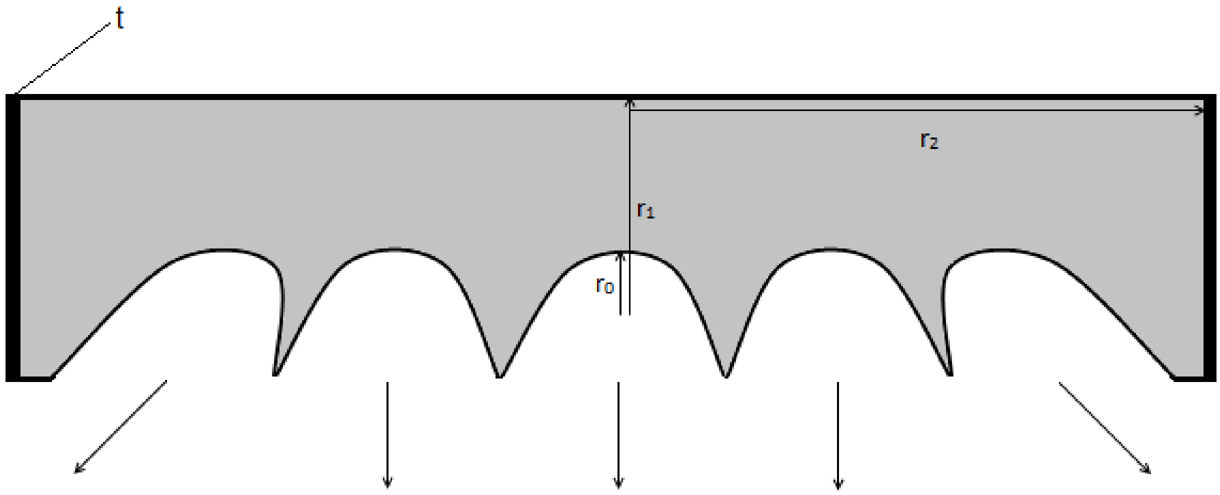



**Fig. 7**

*Radial cross section through assembly of propulsion units*

Assuming that the material of the hoop has a tensile strength of about $\sigma_{\|} = 10^{10}\, dyn/cm^2$, then with a disc radius $r_2 \approx 10m = 10^4\, cm$, and for $p_2 = 5 \times 10^7\, dyn/cm^2$, one obtains $t \approx 50cm$. Therefore, a hoop with such a thickness would hold the disc together.

## 6. Thermonuclear "Operation Space Lift"

A thermonuclear space lift can follow the same line as it was suggested for Orion-type operation space lift, but without the radioactive fallout in the earth atmosphere. With a hydrogen plasma jet velocity of 30 km/s, it is possible to reach the orbital speed of 8 km/s in just one fusion rocket stage, instead of several hundred multi-stage chemical rockets, to assemble in space one Mars rocket, for example. At an exhaust velocity of 30 km/s $= 3 \times 10^6$ cm, and the explosion of 1 ton hydrogen per second, the thrust would be $T = Vdm/dt = 3 \times 10^6$ cm/s $\times 10^6$ g/s $= 3 \times 10^{12}$ dyn = 3000 tons.

To stabilize the spacecraft against tilting, at least 3 propulsion units would be needed. With one propulsion unit expelling 0.1 tons of hydrogen at 30 km/s, this would require a cluster made up of 10 units, sufficiently large to stabilize the craft.

The launching of very large payloads in one piece into a low earth orbit has the distinct advantage that a large part of the work can be done on the earth, rather than in space. The proposed thermonuclear space lift would for this reason permit to launch the bulk of a large spacecraft directly into orbit.

## Conclusion

The feasibility of the proposed concept would be of great significance for the future of space flight. It does not require a large number of chemical rockets to bring the parts of a Mars craft, for example, into low-earth orbit. And it would not require the Mars craft to be assembled there, which would need to be done by a large number of people in the weightless vacuum of space.

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