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THE HELIOS PULSED NUCLEAR PROPULSION CONCEPT

(Title: Official Use Only)

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June 2, 1965

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THE HELIOS PULSED NUCLEAR PROPULSION CONCEPT

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and L. A. Simons†.

Lawrence Radiation Laboratory, University of California
Livermore, California

June 2, 1965

I. SUMMARY AND CONCLUSIONS

During the past year or so, a scheme for pulsed propulsion by means of contained explosions has been re-examined with some care.^{1,2,3} The occasion of first suggestion of the Helios concept is not known to us, but it has been a recognized possibility for many years⁴ and was briefly discussed in reports published at LRL in 1957 by Robert Fox.⁵ This paper will summarize characteristic features of the concept, especially with reference to system optimization studies and analysis of heat transfer to the engine structure.

The goal of the present study has been to gain an understanding in principle of the contained nuclear pulse engine — to identify the major problems, to define optimum systems, and to make an overall appraisal of its value.

A Helios-propelled vehicle would make use of a containment vessel — perhaps 30 feet in diameter — in which small nuclear explosive charges would be placed, together with a few hundred pounds of hydrogen. Firing of a charge would result in bringing the mixture of charge residue and hydrogen to a high temperature — say 5000 or 6000°K — and subsequent release through a nozzle would provide propulsive thrust. This process would be repeated several thousand times, at intervals likely to be 10 seconds or longer. High impulsive acceleration loads would be moderated by a system of shock absorbers between the engine and vehicle.

Considerable effort has been put into system studies seeking, for stated missions, the engine configuration and operating parameters which give minimum initial weight and number of pulses. Analytical studies of detailed

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-2-

technical problems which seem most fundamental to the Helios scheme have also been pursued, with main areas of investigation being in explosion hydrodynamics, heat transfer to the vessel walls, pulsed propellant discharge behavior, nozzle design, and in engine-vehicle coupling problems. An experimental study of layered structural materials with possible suitability for the pressure vessel walls is in progress.

Conclusions drawn from the studies to date may be summarized as follows: No fundamental fault in the concept has been found. Many processes involved are not well understood, and in fact could not be without application of extensive and painstaking theoretical and experimental efforts, but there is no reason to doubt that such efforts would result in a working engine.

The practicality of this propulsion concept would depend critically on the availability of a suitable nuclear charge, especially with respect to reliability, since an accidental excess yield or fragmented explosion could destroy the pressure vessel. Achievement of low charge mass is also of great importance.

Engineering problems in reaching a workable detailed design would be as severe as in most of the currently discussed advanced propulsion schemes.

Most of the detailed technical study has been based on materials and engineering design believed attainable within a decade or so. Under this restraint, performance advantages over other propulsion schemes do not appear to be great for the range of missions currently in the planning and proposal stages. For the manned Mars landing mission, for example, it is not thought likely that a reduction in total system mass by as much as a factor of two below that of a solid-core nuclear rocket system could be achieved. Even this great an improvement would require remarkable achievements in design, especially in suppression of heat deposition in the containment vessel, as will be apparent from the paper of E. Platt at this conference.⁶

Unpredictable advancements in a number of areas could change this conclusion, especially for very large payloads and mission ideal velocities, which stand most in need of high-specific-impulse systems. Achievement of a very high strength-to-weight ratio containment vessel, of very lightweight nuclear charges, or of striking advances in surface heat protection could bring a sharp rise in the competitive position of the Helios engine.

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-3-

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In view of these findings, it appears that development of Helios with a view even toward detailed design studies would be inappropriate at this time. The concept, however, is one of possible importance in the future, and should be clearly understood in principle.

II. SYSTEM PERFORMANCE

A. General Ground Rules

Basic to any discussion of vehicle performance is a knowledge of the specific impulse the engine can be expected to deliver and a description of the mission which the vehicle must accomplish. The many sources of degradation of the specific impulse are covered by Platt⁶; in the following discussion we consider only the effects of pulsing and of a finite nozzle. The missions flown are determined solely by a total ideal velocity increment, ΔV , through which the vehicle is to be accelerated. This ignores the interplay between the planetary gravitational fields and the rate at which the engine is pulsed, as discussed by Platt. We further ignore the gains to be realized from staging and report results for a single-stage vehicle.

The study presented below is based on technology believed available to a development program starting within the next decade.

B. Gas Properties

For computational purposes the gas composition is fixed as follows: Primarily, the propellant is considered to be hydrogen; however, a certain amount of charge residue will be present in addition. For want of a better approximation, we have assumed throughout our calculations that the energy release is independent of the mass of the charge, which we have set at 70 lb (this is thought to include expendable positioning gear left in the chamber). The composition is now determined by χ , the mass ratio of hydrogen to all of the material in the chamber. In order to arrive at reasonable gas thermodynamic properties we have further assumed that the charge debris, largely high explosive residue, acts like carbon both from a chemical and molecular weight standpoint. Tables⁷ of thermodynamic functions of reacting mixtures of hydrogen and carbon over a wide range of temperature, pressure, and χ are used to determine the change in enthalpy for an isentropic expansion through a finite nozzle.

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-4-

These tables indicate that so long as there is dissociated hydrogen in the gas (between 5 and 95%), the mixture behaves like a perfect γ -law gas with a $\gamma \simeq 1.20$. This holds throughout most of the temperature and pressure range of interest.

C. Masses Explicitly Calculated

1. Nozzle

The mass of the expansion nozzle is based on the assumption that all of the thrust is taken at the throat of a conical nozzle of 20° half-angle. An empirical formula which fits a more exact estimate of the mass is used:

$$M_N \approx k (\epsilon)^{1/2} p_0 r_t^3 \left(\frac{\rho}{\sigma}\right)_N. \quad (1)$$

Here k is a constant, ϵ the area expansion ratio of the nozzle, p_0 the initial pressure within the chamber, r_t the radius of the nozzle throat, and $(\rho/\sigma)_N$ the weight/strength ratio for the nozzle material.

2. Pressure Vessel

The minimum mass of a spherical pressure vessel that can withstand a steady internal pressure p without yielding is given by

$$M_s = \frac{(3/2)p V \frac{\rho}{\sigma_s}}{1 - (3/2) \frac{\rho}{\sigma_s}}. \quad (2)$$

Here V is the cavity volume in the shell, ρ is the density of the shell material and σ_s is its yield stress. As noted in Sec. III. B. 6, we include a factor of 4 in p to allow for the rapid step to "steady-state" pressure and the momentum transfer of the pulse, plus a safety factor of a little less than 2. We thus have

$$M_s = \frac{6 p_0 V \frac{\rho}{\sigma_s}}{1 - 6 \frac{p_0}{\sigma_s}}. \quad (3)$$

The variable term in the denominator is a thick-shell correction (where the shell becomes a measurable fraction of the radius).

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-5-

3. Fixed Mass of Payload M_F

This is an input number hiding a multitude of sins. Included in this mass are such things as the nozzle throat valve, shock absorbers and shadow shields. Calculations indicate that the total mass of these three is probably less than 10 tons. Also assumed to be included as payload are life support and observational equipment, target planet excursion modules, and Earth atmospheric re-entry vehicle.

4. Further Mass Allowances

The propellant (hydrogen) will have to be stored as a liquid. This will require not only tank mass but also a certain amount of insulation to prevent loss by evaporation during the long coasting periods of the orbit. Preliminary calculations have indicated that a mass of about 8% of the useful propellant will have to be carried along. This includes, in addition to the tanks and insulation, the amount of hydrogen used to keep the tanks pressurized and the amount that evaporates during flight.

Associated with each nuclear charge will be a mass for storage and handling. We estimate this to be about 5 lb per charge. As stated earlier, we have assumed that each charge will weigh around 70 lb.

5. Total Mass of Vehicle, Hydrogen, and Charges

Each pulse will exhaust a mass of gas composed of the charge debris δM_C and the propellant δM_H . These masses are related through the variable " χ " as indicated earlier:

$$\delta M_H = \frac{\chi}{1 - \chi} \delta M_C. \quad (4)$$

Let us say that it takes N pulses to accelerate the vehicle through the mission velocity increment ΔV . Then the total amount of effluent required is

$$N(\delta M_H + \delta M_C) = \frac{N \delta M_C}{1 - \chi}.$$

Described in Sec. 4 above are the tankage allowances for both the charges and the hydrogen. We define α as the ratio of the hydrogen tankage mass to the useful hydrogen mass and β is the ratio of the charge storage and handling mass to the total mass of the charges.

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-6-

The total initial vehicle mass is then given by

$$\begin{aligned} M_0 &= M_N + M_S + M_F + (1 + \alpha) N \delta M_H + (1 + \beta) N \delta M_C \\ &= M_N + M_S + M_F + \frac{N \delta M_C}{1 - \chi} + \left[\frac{\beta + \chi(\alpha - \beta)}{1 - \chi} \right] N \delta M_C. \end{aligned} \quad (5)$$

The rocket equation now gives us another equation in terms of these variables, the mission ideal velocity ΔV , and the specific impulse I_{sp} :

$$\frac{M_0}{N \delta M_C} = \mu = e^{\Delta V / g I_{sp}}. \quad (6)$$

From Eqs. (4) and (5) we obtain

$$\left. \begin{aligned} M_0 &= \frac{\mu (M_N + M_S + M_F)}{1 - (\mu - 1) [\beta + \chi (\alpha - \beta)]}, \\ N \delta M_C &= (1 - \chi) \left(\frac{\mu - 1}{\mu} \right) M_0, \\ \text{and} \\ N \delta M_H &= \chi \left(\frac{\mu - 1}{\mu} \right) M_0. \end{aligned} \right\} \quad (7)$$

6. Quantities Derived from Thermodynamic Input

Immediately obtainable from the input values of temperature T_0 , pressure p_0 , and composition χ are such properties as gas density, specific energy, specific enthalpy, and specific entropy. When coupled with the total mass of gas in the cavity (indirectly obtained from χ and δM_C) the density yields the total volume in the cavity and thus the mass of the pressure vessel from Eq. (2); and the specific energy gives the total nuclear yield required to produce these conditions. The expansion ratio, ϵ , when used in conjunction with the initial enthalpy, produces the specific impulse for a finite nozzle; and a time constant for exhaust, τ (see Sec. III.B.3), fixes the nozzle throat area and thus the nozzle mass.

UNCLASSIFIED

-7-

D. Results

As a convenient figure of merit we have devised a cost parameter (\$) which depends upon the total vehicle mass and the number of pulses. It has been estimated that in the future, the freight charge for putting material into a low earth orbit will be around \$200 per pound. We further estimate that nuclear material will be relatively plentiful and the cost of the nuclear devices could be around $\$5 \times 10^4$ per charge. Such a cost analysis obviously neglects development charges. The cost parameter thus defined is artificial, but does yield useful information.

Results computed on the basis outlined above are shown in Fig. 1, where we plot curves of constant cost on the N vs r plane, r being vessel radius. Superimposed upon this is a grid of p_0 vs χ . To produce these curves we have fixed the temperature at 6000°K, the expansion ratio at 200, ΔV at 60,000 ft/sec, and the fixed mass at 100 tons. The curves close on the left because the mass of the pressure vessel increases rapidly with pressure — primarily due to the thick-shell correction to Eq. (2) — and on the right because the available enthalpy, and thus the specific impulse, decreases with decreasing pressure for fixed expansion ratio and initial temperature.

Figure 2 shows in a different way the effects of the gas composition χ and the expansion ratio ϵ . That there should be a (weak) minimum with respect to ϵ is easily seen. As the expansion ratio increases we transform more and more of the stagnation enthalpy into specific impulse, thus decreasing the total mass via Eq. (6). However, the nozzle mass is increasing with ϵ according to Eq. (1) and soon the mass increase from this source overshadows the decrease from the improvement in I_{sp} . This is a small effect since the nozzle mass is, in any account, a small fraction of the engine mass (less than 20%).

The simple model we have employed for these data is inadequate to show the existence of minima in \$ with respect to initial temperature, discharge time constant τ , and pulse rate. These come about as the result of considering the effect of temperature on the strength of the metals of the pressure vessel and nozzle and the effect of the pulse rate on the effective ΔV due to the influence of the gravitational field. Platt has shown⁶ that there is a practical upper limit to the specific impulse that the engine may deliver, based upon the temperature that the material of the pressure vessel reaches.

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-8-

This leads to the existence of a minimum in $\dot{Q}$ with respect to initial gas temperature. The heat load in the vessel walls is a function of τ , as will be shown in Sec. III.

Figure 3 shows the effect of varying the mission ΔV and payload on the total initial system mass.

III. HEAT TRANSFER

A crucial element in determining the feasibility of the Helios concept (and that of many other advanced propulsion schemes) is the heat load that the material of the engine must withstand. Toward this end, it is necessary to understand the various processes which take place within the engine during and following the release of nuclear energy.

A. Description of Firing Cycle

Chronologically, the events taking place prior to the nuclear detonation are as follows: A charge is positioned within the vessel and the nozzle throat is sealed. Next, the cavity is filled with propellant (hydrogen) which has removed from the vessel walls the energy deposited there by the previous charge. The high explosive (H.E.) which triggers the nuclear device is set off and the debris of the chemical reaction expands radially into the hydrogen toward the vessel wall. The chemical explosion is followed very shortly by the nuclear explosion.

In order more precisely to explain the events which now occur, we refer to a particular numerical example computed via a one-dimensional hydrodynamics and radiation-diffusion code. The postulated conditions are as follows:

Pressure vessel radius	15 ft
Charge mass (H.E. and nuclear)	50 lb
Mass of hydrogen	150 lb
Nuclear energy release (yield)	5×10^9 cal

The post-nuclear events are listed below:

- 1) The central charge mass rapidly expands into the surrounding H.E. By the time the expanding masses reach a radius of 150 cm, approximately 90% of the yield has been converted into kinetic energy in H.E.
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-9-

2) As the charge masses expand farther, the mass of hydrogen affected by the progressing disturbance begins to become significant. The kinetic energy begins to reappear as internal energy in the hydrogen as it is compressed and heated. The shock front, initially at a pressure of roughly 3 kbars, gradually drops to about 0.5 kbar as it approaches the wall. As the shock wave contacts the wall, 0.15 msec after "detonation," the yield energy Y is divided as follows:

Total kinetic energy	0.33 Y
Internal energy, H.E.	0.10 Y
Internal energy, hydrogen	0.57 Y

3) At the initial instant of reflection, the vessel wall is subjected to a peak pressure of 5 kbars, and a temperature in the adjacent hydrogen of 14,000°K. These values subsequently decay by a factor of 2 in times on the order of 10 μ sec and 20 μ sec, respectively.

4) Also at this time, nearly all of the mass contained within the vessel is compacted against the wall in a shell less than 75 cm thick. The returning shock wave rapidly traverses this region and disappears into the center, leaving the gases essentially at rest. The energy at this point is then divided as:

Total kinetic energy	5%
Internal energy, H.E.	18%
Internal energy, hydrogen	77%

5) The gases then implode toward the center of the vessel, reaching a maximum kinetic energy of 0.19 Y.

A subsequent shock wave, much smaller than the first, is formed at a radius of about 200 cm as the masses concentrate in the center of the vessel. This produces a second series of events similar in nature to the first, but reduced by nearly an order of magnitude as measured by the system kinetic energy. The second shock front arrives at 0.67 msec and has a pressure on the order of 0.15 kbar, producing a pressure peak at the wall of 0.6 kbar. After the second pulse at the wall, the kinetic energy oscillations in the vessel decay rapidly from a maximum of about 0.05 Y. The energy is finally divided as:

Internal energy, hydrogen	0.72 Y
Internal energy, H.E.	0.28 Y

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-10-

The opening of the throat valve is triggered by the arrival of the first shock wave and proceeds slowly in comparison to the events following the detonation. Indeed, we expect that the kinetic energy induced by the detonation within the gas will have all but disappeared by the time any appreciable fraction of the gas has been released. The hot gases now exhaust through the nozzle, completing a full firing cycle of the Helios engine.

B. Sources of Energy

1. Prompt Nuclear and Atomic

The nuclear reaction itself will irradiate the walls of the vessel with neutrons and γ rays. The energy associated with these represents about 6% of the total energy released. A portion of this radiation will be contained within the gases, and some will pass through the vessel walls and escape into space. Although no quantitative calculation can be made without an actual design, we believe that the total amount of energy of this form trapped within the material of the vessel walls can be held to less than 1% of the total nuclear yield. This energy will be fairly uniformly deposited throughout the material of the pressure vessel.

A first guess at the total energy associated with early x radiation from the nuclear charge is around 1/2% of the total yield. Proper design of the nuclear device can probably trap most of the energy within the confines of the fireball.

2. Early Thermal Radiation

As stated earlier, the numerical techniques by which we arrive at the dispersal of energy (excluding the above two forms) include only hydrodynamics and radiation diffusion. It may be inferred from the discussion of Sec. III. A that at least until the initial shock wave has reached the vessel wall, the gas will contain regions wherein there exist large thermal gradients and relatively cold hydrogen which is optically transparent. The diffusion approximation to the radiation transport equation is evidently invalid over certain regions of the gas at early times in the cycle. However, the temperatures are low enough that essentially all energy transport is through the hydrodynamic work done on and by the fluid. The energy radiated in the hot gas is so small that its neglect does not alter the hydrodynamic behavior of the gas. Formal computer results agree well with rough calculations in terms of the general behavior described below.

UNCLASSIFIED

-11-

Until the hydrogen near its interface with the charge residue (H.E.) is heated, the extremely hot fireball will radiate toward the cavity wall. Ionizing radiation — including the x rays mentioned above — emanating from this fireball will be strongly attenuated in the H.E. residue. Once the hydrogen near the H.E. begins to heat, its opacity increases, allowing it to absorb radiation and heat still more rapidly. Quite soon the opacity of the hydrogen has risen to a point where it completely blocks further radiation from the central regions. The time scale for this is negligibly short when measured in terms of the total radiant energy reaching the cavity wall. The hydrogen temperature near the H.E. interface is now between 1 and 3 eV and has a large negative gradient with radius. Since the opacity of hydrogen is an extremely strong function of temperature, it drops precipitously with increasing radius, creating what appears to the cavity wall to be a well defined surface in the hydrogen radiating toward the wall at a temperature of about 1 eV. This surface persists and is moved about by the passage of the shock wave for about the time it takes the shock to travel three cavity diameters. At this time the total energy released has been distributed throughout the cavity and although the central gases are still quite hot, they are highly expanded and contain only a small fraction of the total energy. Also by this time the gas will begin to feel the effects of the opening throat valve and will start falling in temperature due to isentropic expansion. It is also expected that a certain amount of mixing will have taken place, tending to make the gases in the cavity isothermal at a temperature of about 6000°K.

To find an upper limit to the energy incident on the vessel wall from this source, we assume that the radiation is blackbody at 10,000°K. Thus

$$\sigma T^4 = 1.4 \times 10^4 \text{ cal} \cdot \text{cm}^{-2} \cdot \text{sec}^{-1}. \quad (8)$$

The radiating surface will persist for probably no longer than 1.5 msec and will be moved about by the shock wave so that its average area is about one-half that of the vessel wall. Thus, about $10 \text{ cal} \cdot \text{cm}^{-2}$ in radiant energy from the fireball impinges upon the cavity wall. For the example discussed in Sec. A, this is about 0.53% of the total energy released.

3. Late Thermal Radiation

As indicated above, the gas should be roughly isothermal within a millisecond or so and will have begun to exhaust through the nozzle. As gas

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leaves the chamber, that which remains expands isentropically, dropping in temperature. R. Fox⁵ has shown that the time variation of the temperature of the gas in the chamber (assumed isothermal across the chamber) is

$$T(t) = T(0) \left[1 + \frac{t}{\tau} \right]^{-2} \quad (9)$$

where $T(0)$ is the gas temperature within the cavity after it comes to an isothermal state and prior to any appreciable amount being expelled. For a perfect γ -law gas, τ is directly proportional to the cavity volume and inversely proportional to the product of the effective throat area and the speed of sound in the gas at time $t = 0$.

If the gas within the cavity radiates like a blackbody, the total radiant energy striking the wall is the time integral of the instantaneous flux, i.e.,

$$\begin{aligned} \int_0^{\infty} \sigma T^4 dt &= \sigma T(0)^4 \int_0^{\infty} (1 + t/\tau)^{-8} dt \\ &= \sigma T(0)^4 (\tau/7). \end{aligned} \quad (10)$$

For the reasonable values of $T(0) = 6000^\circ\text{K}$, and $\tau = 0.2$ sec we have

$$\int_0^{\infty} \sigma T^4 dt = 50.1 \text{ cal} \cdot \text{cm}^{-2}. \quad (11)$$

In terms of the example of Sec. III. A the fraction of the energy incident on the wall is 2.65% of the total energy released.

4. Conduction

Since the gas is in intimate contact with the cavity wall, both conductive and convective heat transfer may take place. The former is but a lowest-magnitude special case of the latter wherein the only gas motion allowed is a radial expansion or contraction. An upper bound to the total conductive heat transfer can be obtained by postulating that the temperature of the wall be kept at zero.

UNCLASSIFIED

-13-

Carrying out a calculation which takes into account the time-varying temperature and density of the gas (see Ref. 3), we find that the heat conducted to the wall is given by

$$Q_1 = \int_0^\infty k \frac{\partial T}{\partial r} dt = k_0 T(0) [p(0) \tau]^{1/2}, \quad (12)$$

where the constant k_0 is a function of the gas properties and $T(0)$, $p(0)$ are the gas temperature and pressure at the beginning of the expansion.

For the case quoted in the section above ($\tau = 0.2$ and $T(0) = 6000^\circ \text{K}$) we have, for a pressure of 100 atm, $Q_1 = 2.8 \text{ cal} \cdot \text{cm}^{-2}$. The fraction of energy transferred to the wall by pure conduction is thus 0.15% of the total energy released.

5. Convection

Pure conductive heat transfer presupposes a stable thermal gradient in the gas which tends to protect the wall from the hot material within the cavity. Turbulent motion will, however, destroy this cold layer and continuously supply the wall with hot gases from the interior. The heat flux, abetted by convection, is expected to be considerably larger than that due to conduction along. Near the nozzle, the flow of gas leaving the chamber will provide strong convective motion at the wall, and it is in this region that the greatest amount of convective heat transfer is expected.

In the absence of detailed knowledge of the three-dimensional hydrodynamic behavior of the gas we have made an estimate of this mode of energy transfer by assuming that the cavity wall behaves like a cylindrical duct carrying gas at the same mass flow rate and temperature as the gas actually leaving the vessel. We have shown³ the heat transferred per unit area in this duct to be

$$Q_2 = 140 \left(\frac{\tau}{0.2} \right)^{0.2} \left(\frac{T(0)}{6000} \right)^{1.2} \left(\frac{D}{10} \right)^{-1.8} \text{ cal} \cdot \text{cm}^{-2}, \quad (13)$$

where D (in feet) is the postulated duct diameter. The heat transfer rate starts quite high and falls off very rapidly [it goes as $(1 + t/\tau)^{-1.1}$ for a γ -law gas with $\gamma = 1.2$] and thus most of the heat transfer is over within about 0.02 sec. Considering conduction within the material of the vessel

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-14-

wall, the temperature of the surface will roughly be given by

$$T_s \approx Q(k \rho C_p t)^{-1/2}. \quad (14)$$

With

$$\begin{aligned} Q &= 140 \text{ cal} \cdot \text{cm}^{-2}, \\ C_p &= 0.1 \text{ cal} \cdot \text{g}^{-1} \cdot ^\circ\text{K}^{-1}, \\ k &= 0.1 \text{ cal} \cdot \text{cm}^{-1} \cdot \text{sec}^{-1} \cdot ^\circ\text{K}^{-1}, \\ \rho &= 7.8 \text{ g} \cdot \text{cm}^{-3}, \end{aligned}$$

and

$$t = 0.02 \text{ sec},$$

we have

$$T_s \approx 4000^\circ\text{K}$$

which is high enough to vaporize iron. It thus appears that a protective coating must be provided within the chamber in the region of the nozzle exit.

6. Energy of Vibration

The sudden rise in internal pressure accompanied by the initial shock wave will set the pressure vessel into vibration. This vibration will damp out, and the associated energy will mainly be transferred into heat deposited throughout the material of the vessel. An estimate of the energy involved can be obtained by assuming that only the fundamental mode of oscillation is excited. If the gas pressure were to increase in a single step to its final value, the maximum stress in the vessel would be just twice that which would remain after all oscillations had died out. The first shock wave and each reflection adds a small momentum impulse and so adds to the maximum stress. We have estimated that for the example of Sec. A the increase in stress due to the shock waves is about 15% of maximum stress in the absence of shocks. Thus the vessel must be designed for a pressure 2.3 times the steady value. This allows no safety factor, and so we have used an overall factor of 4 in determining the required vessel wall thickness δ :

$$\delta = 4 \frac{p_0 r}{2\sigma_s}. \quad (15)$$

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-15-

Here p_0 is the final pressure at time $t = 0$, r is the radius of the cavity, σ_s is the yield stress, and δ is the thickness of the shell. The energy of stress per unit mass is given by

$$\epsilon = \frac{\sigma_s^2}{\rho} \left(\frac{1-\nu}{E_s} \right) \quad (16)$$

where ρ is the shell density, ν is Poisson's ratio, and E_s is Young's modulus for the shell material. Thus the maximum total energy of stress to be dissipated in the vessel wall is given by

$$\begin{aligned} Q_s &= \left[\frac{\sigma_s^2}{\rho} \left(\frac{1-\nu}{E_s} \right) \right] \left[4\pi r^2 \left(4 \frac{p_0 r}{2\sigma_s} \right) \rho \right] \\ &= 8\pi r^3 p_0 \sigma_s \left(\frac{1-\nu}{E_s} \right) . \end{aligned} \quad (17)$$

Assuming

$$\begin{aligned} p_0 &= 1.01 \times 10^8 \text{ dynes}\cdot\text{cm}^{-2} \\ \sigma &= 2.13 \times 10^{10} \text{ dynes}\cdot\text{cm}^{-2} \\ \nu &= 0.3 \\ E_s &= 2.08 \times 10^{12} \text{ dynes}\cdot\text{cm}^{-2} \\ r &= 15 \text{ ft} = 457.2 \text{ cm}, \end{aligned}$$

we obtain

$$Q_s = 1.78 \times 10^7 \text{ cal.}$$

This is 0.36% of the total energy released.

A shock wave passing through the vessel wall leaves energy in its wake. We may make an upper estimate by referring to Eq. (16): The maximum intensity of the shock wave of Sec. A is around 5 kbars. Using the physical properties quoted above we see that the shock wave can leave only about 4.7×10^5 cal in the pressure vessel. This almost a factor of 50 below the energy of gross vibration and is thus negligible.

7. Summary

Nuclear radiation and vibration will deposit heat uniformly throughout the material of the pressure vessel, while the other sources carry energy to the inner surface of the vessel only. Convective transfer, especially near

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-16-

the nozzle entrance, would result in such a large deposition of heat that it seems clear some protection against it must be provided. This protection would also, of course, reduce the other modes of surface heat deposition. The estimates made here must thus be interpreted as only a general indication of heat transfer amplitudes.

Table 1 summarizes the results in this spirit, with the convective contribution in parentheses since it must be presumed absent or reduced in a workable engine.

No functional dependence is given for the deposition of nuclear radiation; it depends upon the charge design and vessel geometry in a complicated manner and the 1% value of charge yield fraction given is meant only as a rough upper limit.

The rise of temperature of the vessel as the result of a single pulse is of interest. Generally we find that the ratio of vessel mass to nuclear yield is about 20 tons per ton of H.E. equivalent energy, or about 0.02 gram per calorie. A heat capacity of $0.1 \text{ cal} \cdot \text{g}^{-1} \cdot ^\circ\text{K}^{-1}$ would result in a 500°K rise in temperature if the whole yield were deposited and thus a 5°K rise for each unit percent of the yield deposited in the shell.

UNCLASSIFIED

-17-

Table 1. Energy Delivered to Pressure Vessel

Source	Charge yield fraction	Surface heat (cal·cm ⁻²)	Energy deposition functional dependence
Prompt nuclear radiation	0.0100	--	--
Early thermal	0.0053	10	Constant
Late thermal	0.0267	50	$r^2 \tau T_0^4$
Conduction	0.0015	3	$r^2 T_0 (p_0 \tau)^{1/2}$
Convection	--	(140)	$r^2 \frac{T_0}{D^2} (\tau T_0 D)^{0.2}$
Vibration and shock	0.0037	--	$r^3 p_0$
TOTAL	0.047	63 (~ 200)	

Notation: τ = discharge time constant
 r = pressure vessel radius
 T_0 = initial chamber temperature
 p_0 = initial chamber pressure
 D = equivalent diameter of vessel considered as
cylindrical duct.

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-18-

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Fig. 1. Curves of fixed mission cost, showing functional relationship among chamber radius R , number of pulses N , chamber pressure p , and propellant hydrogen fraction χ .

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Fig. 2. Mission cost vs chamber pressure for fixed values of nozzle expansion ratio ϵ and hydrogen fraction χ , and for continuously optimized values of ϵ and χ .

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Fig. 3. Relationship of payload mass to total initial mass for various mission ideal velocities.

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