Silver Spring, Maryland

APL/JHU TG-20
January 14, 1947

NUCLEAR-POWERED FLIGHT

By

An Informal Committee

of

THE APPLIED PHYSICS LABORATORY

of

THE JOHNS HOPKINS UNIVERSITY

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FIRST PROGRESS REPORT

2015 1

14 January 1947

TO: L. R. Hafstad

FROM: A. E. Ruark

SUBJECT: Transmittal of Progress Report entitled "Nuclear-Powered Flight", by an Informal Committee of the Applied Physics Laboratory of the Johns Hopkins University.

In accordance with your verbal instructions of about 9 June 1946, the Committee has considered the general problem of air vehicles driven by nuclear power. Three copies of the subject report are respectfully submitted herewith. A first draft was submitted October 25, 1946. Since that time many errors have been corrected and much new material has been added. The initial distribution is indicated in the report.

Your comments and those of other interested persons will be appreciated by the Committee. Review by suitable members of APL is hereby requested.

It is believed that any further work on this subject at APL should be carried on by a small staff with fresh instructions, and that the existing large committee should be discharged in the near future.

FOR THE COMMITTEE

Arthur E. Ruark, Chairman;
Technical Supervisor
for Research Laboratory.

AER:rh

Encl. 3 -- Copies 1, 2, and 3 of subject report.

[redacted]

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CHAPTER VI. HIGH TEMPERATURE MATERIALS

By Arthur E. Ruark

1. Introduction

In earlier chapters, pile surface temperatures ranging from about 2000°K (1725°C) to 3000°K (2725°C) have been considered for various vehicles. Since there must be a temperature drop in the pile to bring the energy to the gas-solid interface, it is clear that we are considering a range in which customary ceramics have little strength. In the absence of softening and spalling data for very pure graphite and beryllia we cannot specify the temperatures which must be chosen for nuclear-powered rockets, ram-jets and turbojets. Therefore results for a range of temperatures have been given, wherever it seemed useful. However, a few data can be presented to indicate possibilities and to guide structural studies. We consider in succession the following topics: high-melting elements and compounds, piles, control rods, and protection of an atomic warhead against neutrons.

2. High Temperature Materials

Table 1 presents the melting points of a number of solids which may be useful for high temperature structures. The list also contains fissionable materials and a few boron and beryllium compounds which interest us because of their neutronic characteristics.

The sources used in compiling this table are "The Handbook of Physics and Chemistry," "The Chemical Engineer's Handbook," and a recent report of Kachik, Hummel, and Henry which gives a very complete survey of borides, carbides, and nitrides; this is reproduced in Appendix 3. As stated in their report, it is striking that practically all of the borides, carbides, and nitrides studied resist decomposition at high temperatures. The report

Table 1. Melting Points of Solids for High Temperature Use

Degrees Centigrade

Elements		Oxides, Silicates		Borides		Carbides		Nitrides	
C	>3500			CrB(3)	4000(?)	0.8TaC,0.2HfC	3940	TaN	3090-2800
W	3370			HfB	3060	0.8TaC,0.2ZrC	3930	BN	3000(4)
Re	3000					HfC	3880		
						TaC	3870		
						ZrC	3530		
						CbC	3500		
						TiC	3140		
Ta	2850	ThO_2	>2800	ZrB	2990	WC	2870	ZrN	2980-2930
Os	2700	MgO	2800	WB	2925	W_2C	2860		
Mo	2620	ZrO_2	2700			VC	2830	TiN	2930
Ru	2450	BeO	2570			MoC	2690	ScN	2650
Ir	2350	$CuZrO_3$	2550			Mo_2C	2685		
B(1)	2300	$ZrSiO_4$	2550			B_4C	2500-2350		
		UO_2(2)	2176						
		Al_2O_3	2050						
Rh	1985								
Cb	1950								
Zr	1900								
U	<1850								
Th	1845								
Ti	1800								
Yb	1800								
Be	1350								

Notes: (1) Boron boils at 2550°C.
(2) U_3O_8 decomposes before melting.
(3) See Text.
(4) BN sublimes below M.P. The M.P. given was obtained under pressure.

The table of elements includes all which melt above 1800°C.

gives some data on resistance to corrosion by gases, which varies according to the position of the metal-component in the periodic table. The authors remark that the carbides of group IV and group V elements combine the best resistance to oxygen, hydrogen, nitrogen, and water vapor at high temperatures.

Through the kindness of Mr. I. R. Kramer of ONR our attention has been directed to the high melting compound, chromium boride. At present this material is used, in combination with large percentages of nickel, as a spray coating on metals.

Mr. A. R. Parilla has called our attention to the work of Ryschkewitsch on pure alumina, beryllia, zirconia, and magnesia. It appears that this investigator has developed a technique for manufacturing these pure oxides without binding material. It is stated that pure alumina has the following physical properties:

Compressive Strength,	greater than	500,000 psi
Tensile Strength,	approximately	40,000 psi
Modulus of Elasticity,	approximately	60,000,000 psi
Microhardness,		3000 kg/mm^2

It is also stated that these values are substantially maintained at temperatures up to about 1000°C. We mention this material not because of its melting point (2050°C) but because these physical properties are exceptional and because the method of manufacture may open new fields in missile technology.

The striking points in Table 1 are these:

(a) Only three elements, carbon, tungsten, and rhenium, melt above 3000°C.

(b) All oxides listed melt below 3000°C.

(c) It has been reported to us that chromium boride has a melting point of the order of 4000°C. This requires a check, in view of the fact that only three other borides have

melting points close to 3000°C.

(d) Attention is called to the existence of several carbides and mixtures or alloys of carbides, melting above 3500°C. These are the highest-melting compounds known.

3. Pile Materials and Structure

For the 5000 mile rocket, summarized on Page 4.17, the burning time will be about 220 seconds, in which time 50 tons of hydrogen must pass through the tubes. After that the reactor must be shut off. Structural integrity will depend on the short-time flow-properties of the hot pile material, and if the pile be made of carbonaceous material, its reaction with hot hydrogen must be considered. Conditions are quite different in the ram-jet. If the vehicle flies at a height where the air density is 1/10 of the value at the earth's surface, each square foot of intake area will require about forty pounds of air per mile of flight, or 100 tons for a 5,000-mile flight lasting several hours. The lower gas density (as compared with the rocket case) will favor less rapid corrosion, and creep during the time of flight will presumably be more important.

It is suggested that carbon (density about 138 lb./cu. ft.) is a favorable moderator for a pile in a liquid-hydrogen rocket. Carbides of fourth and fifth group metals are not competitors because of neutron absorption, but could be used in minor quantities as structural elements.

The ram-jet pile is more difficult. Oxides and silicates are logical materials for use in an oxidizing stream, but Table 1 shows that for the best of these materials the margin between melting point and proposed operating temperature is narrow. It appears necessary to use BeO, or to employ carbon as a skeleton for the pile structure, with a BeO coating to provide surface protection. At points in the interior of the pile, presumably the

BeO would be molten. So far as we can find, no attempt has been made to develop such structures. Thoria is doubly attractive for such a purpose because it is very refractory (M.P., 2800°C), and because it undergoes fission by fast neutrons. Also, some fissionable U 233 may be produced. (We do not have the equilibrium times for production of this substance from Th232 by the neutron, beta, beta process.)

The reinforced-concrete principle can be used to give greater structural integrity to the whole mass. Although tungsten, for example, would be highly oxidizable in the hot air stream, it could be used for a skeleton of reinforcing rods covered with the moderator material.

4. Control Rods

The cross-sections of several elements useful for absorbing slow neutrons are as follows:

B^{10}	3,000 barns
Cd	2,600
Cd isotope responsible for absorption (113)	80,000
Gd	30,000

From this it is clear that the favored position of cadmium in nuclear research is due to the convenient properties of cadmium metal and not to any exceptional properties of the natural cadmium mixture of isotopes; also, that separated cadmium 113 might be remarkably interesting. Any rare earth mixture rich in gadolinium should be a very valuable neutron absorber.

In the absence of data on cadmium carbide, we note that boron carbide melts at 2,350 to 2,500°C. This is not sufficiently high, for the conditions assumed in this report, so the use of rare earth compounds is in order. We suggest that investigation of the following control devices (or variations of them) may be fruitful:

(a) CrB or CdC in carbon tubes, or in the pores or cavities of a suitable carbon body.

(b) Alloys or mixtures of TaC, and HfC, with reasonably small percentages of gadolinium compounds.

(c) Alloys or mixtures containing separated cadmium isotopes.

5. Protection of the Warhead against Neutrons

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DOE 6.2 (a)

The question now arises whether neutrons from the pile can transmute so much of the uranium in the warhead that it becomes poisoned, to an extent which will prevent its explosion at the target. Here we have to deal with the effect of poisoning on a fast neutron reaction. We have only

limited information on the fast-neutron cross-sections of the fission products and their progeny, as a function of the neutron energy; 4 barns is a fair estimate and no exceptional cases are anticipated. However, to take care of any unfortunate combination of unknown circumstances, let us see what shielding will be required to reduce the neutron flux to utterly negligible values.

(We wish to avoid discussion of the limited chains initiated by slow or fast neutrons which fall on the warhead uranium, because the average length of such chains will be sensitive to the cross-sections employed, and will depend on the unknown geometry of the bomb.)

Suppose then, that in the nuclear energy rocket of Page 4.17, the center-to-center distance of the warhead and the pile is about 500 cm., to make room for a liquid hydrogen tank. This is surely an underestimate. When the tank is full, the number of neutrons which can reach the warhead directly is negligible, but when the tank is partly empty, we fall back on the absorption in the TNT, or in additional absorbers.

We list the following approximate data:

Number of fissions per gr of fuel	$1.5\ 10^{15}$
Grams of fuel	$4.6\ 10^{7}$
Total fissions during the powered flight	$6.7\ 10^{22}$
Approximate number of neutrons escaping	$7.4\ 10^{22}$
No. of neutrons striking 1 sq. cm. of the bomb material	$2.4\ 10^{16}$

Consider them to be a parallel stream. Three feet of TNT is satisfactory as a neutron slower. If then a small amount of gadolinia can be incorporated in the inner portions of the TNT to absorb the slow neutrons, the bomb will require no other shielding because of the following data:

Absorption coefficient of gadolinia for thermal neutrons: 750 per cm.

Fraction of the neutrons passing a 1 mm. gadolinia layer: 10^{-32}

If, on the other hand, this change is not possible, it may be necessary to reduce the neutron flux by outside shielding, probably 20-30 cm. of highly hydrogenous material and 1 mm. of gadolinia. This shielding would have to be applied all around, because more fast neutrons will get at the warhead by passing out from the missile and being reflected back to it than the number which pass directly to it. This makes it clear that a very moderate weight of absorber will reduce the effects in the warhead to negligible values. The situation will be similar in regard to the shielding of electrical controls, etc., as far as neutrons are concerned, but the gamma ray problem has no such attractive solution.

The fuel in a nuclear hydrogen rocket may also need protection against loss by boiling due to absorption of energy from nuclear radiation, as pointed out by Alvarez (Ref. 2). McClure and Kershner suggest that this might be accomplished by having an outside fuel compartment, serving as a neutron slower and to some extent as a preheater, and separated from the main tank by gadolinia. The additional weight may necessitate a much larger rocket for the same payload.

Reference: Norton, F. M., Refractories, McGraw-Hill, 1942.

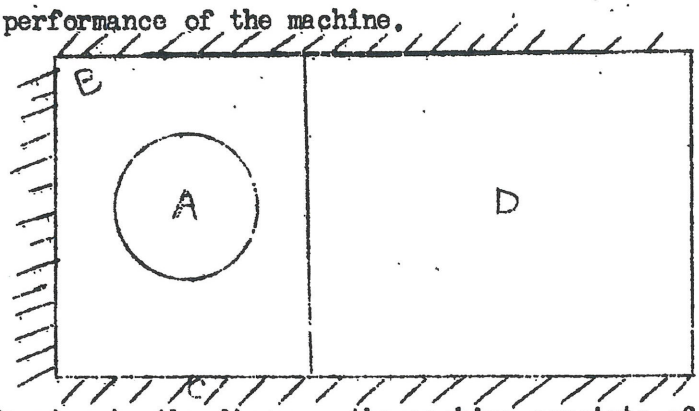
Alvarez, L., talk on nuclear-powered planes and rockets, before the Aero Club, Washington, D. C., Dec. 1946.

APPENDIX 1. THEORETICAL DISCUSSION OF A SMALL HOMOGENEOUS ENRICHED REACTOR

Reproduction of a talk before the American Physical Society, Chicago meeting, June 1946.

By R. F. Christy,
Institute for Nuclear Studies, University of Chicago

I will first describe the "water boiler" physically in order to provide a picture of what we will be talking about. Then I will go into a little detail of the neutron design of the machine. Then I will sketch the performance of the machine.



Referring to the diagram, the machine consists of the reactor proper A surrounded by a neutron reflector B which is surrounded by a shield C except where it communicates with the graphite "thermal column" D. The reactor A consists of a non-corrosive (stainless steel) shell about a foot in diameter containing the uranium enriched in 235 (or plutonium) as a water solution of a suitable salt such as $UO_2\ SO_4$ or $UO_2(NO_3)_2$. The amount of uranium 235 is of order of 1 kilo. The neutron reflector (or tamper) B consists principally of beryllium oxide (BeO) in the form of bricks made by compressing the powder to as high a density as possible. The reflector occupies a cube of about four feet on an edge. The shielding C is several feet of concrete with possibly some lead on the inside. The thermal column D is a pile of graphite bricks perhaps 5 feet square and 8 feet long and serves the purpose of providing a high flux of essentially pure

The design problems in such a machine can be summarized as follows:

neutron design
cooling design
chemical (corrosion) design
structural design
control design
shielding design

There is an interplay between these problems but it is almost negligible compared to their interdependence in a graphite uranium machine where the whole design is very critical.

I want to discuss here principally the neutron design. The questions that should be answered for this purpose are:

1. How much U^{235} will be required?
2. In what concentration or how big a sphere is required?
3. What materials should be used in the sphere and as neutron reflector?
4. How big a reflector do we need?
5. Roughly what power can we extract -- how intense is our source?
6. How many neutrons of various kinds will we get for experimental work and how much shield do we need?

The amounts of material will be determined by more or less complicated diffusion calculations which can be carried out as follows. Our fundamental neutron equation reads:

creation/sec - absorption/sec - divergence (current) = $\frac{dn}{dt}$

now current = $-D \operatorname{grad} n$ $\quad D = \frac{\lambda v}{3}$ $\quad \frac{1}{\lambda} = N\sigma_s$

absorption/sec = $\frac{n}{\tau}$; $\quad \frac{1}{\tau} = N\sigma_a$ $\quad v = \frac{v}{\lambda}$

creation/sec = q

so $\frac{\lambda v}{3} \Delta n - \frac{n}{\tau} + q = \frac{dn}{dt}$

or for a steady state $\frac{dn}{dt} = 0$

$$\Delta n - \frac{n}{L^2} + \frac{3q}{\lambda v} = 0 \qquad L^2 = \frac{\lambda \Lambda}{3}$$

L is the diffusion length and $L^2 = \frac{\overline{r^2}}{6}$

In a multiplying medium we can write

creation = K absorption K is reproduction factor

$$\Delta n + \frac{K-1}{L^2} n = 0$$

According to the derivation, L was the diffusion length and was determined by the scattering absorption of the neutrons. However, if we are considering a slow neutron chain reaction, the fission neutrons which are made with an energy of order of 1 Mev must first be slowed down before they are absorbable. The problem cannot actually be treated as a one-velocity problem. The above equation can, however, be used as a fair approximation if by L^2 we understand $L^2 = \frac{\overline{r^2}}{6}$ where r^2 is the mean square diffusion distance between where the neutrons are created and where they are absorbed. Thus $L^2 = L^2_{sl} + L^2_{th}$ where L^2_{sl} is 1/6 the mean square slowing length. For the water boiler $L^2_{sl} >> L^2_{th}$ and we can practically neglect any variation of L^2 with concentration of U^{235}. For fission neutrons in water, L^2 is the same as for 1 or 2 Mev neutrons or about 25 cm^2.

For a spherically symmetric system the solution of the diffusion equation is

$$n = \frac{1}{r} \sin\left(\sqrt{\frac{K-1}{L}}\, r\right)$$

If we now impose the boundary condition at r R_c that n 0 corresponding to no neutron reflector we get

$$\frac{\sqrt{K-1}}{L} R_c = \pi \qquad \text{OR} \qquad R_c = \frac{\pi L}{\sqrt{K-1}}$$

R_c is called the critical radius and the condition in general is referred to as the critical condition. We see immediately that $K > 1$ for a self-sustaining chain reaction. Also, if K is considerably greater than 1, 1.5 or 2, then $R_c \simeq 4L$ so if $L \simeq 5$ cm

$$R_c \simeq 20 \text{ cm}$$

This is the radius of a water boiler without neutron reflector. The critical radius with a neutron reflector is somewhat smaller. Let us now find expressions for K and for the mass of U^{235}. By definition, K can be written

$$K = V_x \frac{\text{absorption in } U^{235}}{\text{absorption in inert material + abs. in } U^{235}}$$

where V is the number of neutrons per fission which we will take to be of order 2 or 3[1]. We can usually take the absorption in inert materials to be simply the absorption in hydrogen.

Let us measure the concentration C of U^{235} by the ratio

$$C = \frac{\text{abs. in } U^{235}}{\text{abs. in H}}$$

Then the density of U^{235} in grams/cc is simply

$$\rho_u = \frac{235 \times \sigma_H}{9 \times \sigma_u} C \simeq .01\, C$$

using $\sigma_H \simeq .3 \times 10^{-24}$ cm^2 and $\sigma_u \simeq 1000 \times 10^{-24}$ cm^2,[1]

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(1) Bohr and Wheeler, Phys. Rev., Sept. 1939

Now $K = \frac{VC}{1 + C}$

So, $R_c = \frac{\pi L}{\sqrt{\frac{VC}{1+C} - 1}}$

And the critical mass M_c is given by

$$M_c = \frac{4}{3}\pi R_c^3 \rho_u = .01 \times \frac{4}{3} \frac{\pi^4 L^3 C}{\left(\frac{VC}{1+C} - 1\right)^{3/2}}$$

From the above, we see that K has a maximum value of K = V for large concentrations of U^{235}. This implies a minimum critical radius given by $\frac{\pi L}{\sqrt{V - 1}} \approx 2.5L \approx 13$ cm. The critical mass becomes very large if we try to establish the chain reaction in too small a volume. Furthermore, there is a minimum concentration of U^{235} which can be used. This is determined by $K = 1$ or $C = \frac{1}{V-1} \approx .5$ or $\rho_u \approx .005$ gm/cc. The critical mass and radius becomes indefinitely large as the concentration is reduced toward this minimum.

From the expression for the critical mass M_c, it can be shown that M_c has a mimimum for a value of C which depends on V. For V 2 the optimum concentration

$$C \approx 3.3 \quad \text{or} \quad \rho_u \approx .033 \quad \text{and} \quad K \approx 1.5$$

Thus the minimum $M_c \approx 1.5$ Kg and for this concentration $R_c \approx 22$ cm.

One can proceed in an identical manner to calculate the critical mass for a reactor with heavy water replacing the water or even for a solid moderator such as graphite or BeO in which the U 235 is finely dispersed. These substances differ from the above in that they all have L much greater than for water but also the parasitic capture is much less so that the ~~characteristic~~ concentration measured in gm/cc is much less. The combination of

these two effects leads to results of the same order as that above for the critical mass although the reactor is then several times as large.

I would like to conclude with some comments on the output of the machine. The heat extraction is by means of a coiled tube carrying cold water through the inside of the reactor. The solution itself circulates simply by convection. A simple heat transfer calculation shows that a moderate sized coil of about 20 feet of 1 cm tubing suffices to remove about 10 kw. From this power one finds immediately that the flux (nv) of thermal neutrons in the reactor is about 10^{11}. In other words there are about 10^{14} fiss/sec in the reactor corresponding to about 3000 curies of fissions. Thus one could easily make 100 curies activity by irradiating a neutron absorber. In the "thermal column" where almost pure thermal neutrons are piped out one can obtain a flux of order 10^{7} n/cm^2 sec.

APPENDIX 2. ARE NUCLEAR-RECOIL ROCKET-MOTORS POSSIBLE?

(An idle play with numbers)

By G. Gamow

Since nuclear energy content per gram of material exceeds the chemical energy by a factor of many millions, it looks very pitiful that the best one can think at present is to increase the efficiency of chemical rockets by a mere factor of 2.5, using a slow nuclear reaction for heating hydrogen which is to serve as a working fluid. The difficulty in making a full use of nuclear energy in rocket propulsion lies, of course, in the fact that in order to turn an appreciable amount of the liberated latent energy into the mechanical energy of the mass-flow one must necessarily turn a comparable amount of energy into the heat, thus raising the temperature of the expelled masses. In the case of chemical energy this temperature increase amounts to several thousand degrees, and lies just near the limits permitted by the melting points of different materials which can be used for construction of the rocket-body. In the case of nuclear energy the temperatures obtained lie high above the evaporation point of any conceivable wall material, so that, pending the invention of a Maxwell's Demon who would prevent the liberated energy from going over into the thermal motion, or of a super-insulating layer which would transfer to the body of the rocket the pressure of super-hot gases without transferring any heat, a more reasonable utilization of nuclear energy for the purposes of rocket propulsion seems to be rather impossible. The situation being what it is, it is interesting to .

see what is the best performance of nuclear recoil motors making the direct use of the impulse of the reaction-particles. We will study here two such naive-models corresponding to a controlled and a spontaneous reaction.

A. Nuclear Recoil from a Fast Reactor.

Consider a cube of fissionable material of a critical size (about 10 x 10 x 10 cm) in which a fast neutron reaction is going on in a controlled way. (Fig. 1).

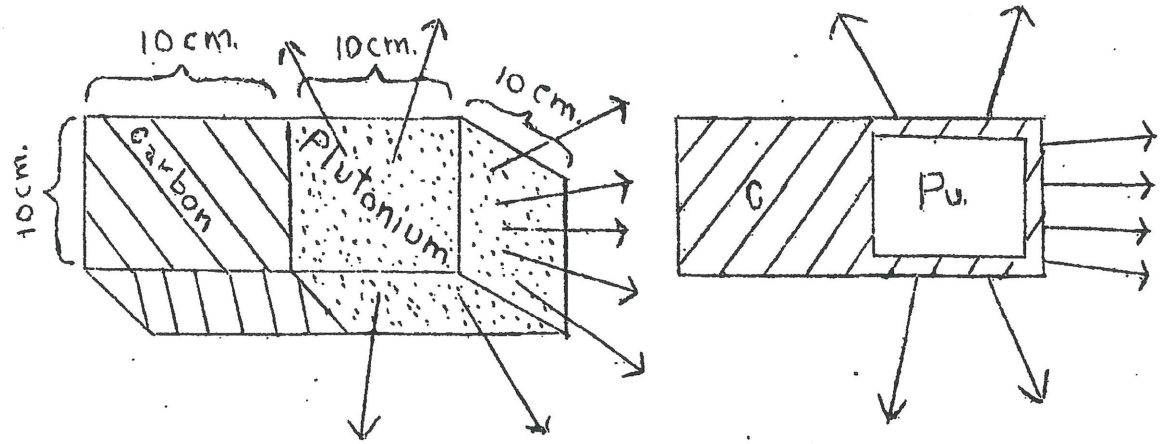

Figure 1.

This cube is surrounded by thin walls of carbon to prevent its breaking up when the temperature rises above the melting point of the metal. About one-half of the fast neutrons originating in fission escape through the outer surface of the fissionable material, and through the carbon walls into the surrounding space. If one of the carbon walls is made considerably thicker, say 10 cm, neutrons will communicate to our system a certain thrust in this direction. Since the walls should be kept at a temperature below the melting point of carbon, say at 3000°K, the cooling by radiation

will be:

$$10^3 \text{ cm}^3 \times 10^{-5} \times (3 \times 10^3)^4 \simeq 10^{12} \ \frac{\text{erg}}{\text{sec.}}$$

Since each fission process liberates about 3×10^{-4} erg (200 MEV) the reaction must be run at $\frac{10^{12}}{3 \cdot 10^{-4}} \simeq 3 \times 10^{15}$ fissions per second, and the total number of escaping neutrons directed toward the carbon block will be about $\frac{1}{6} \times \frac{1}{2} \times 3 \times 10^{15} = 2.5 \times 10^{14}$ per second. Since the velocity of fast fission neutrons (1 MEV) is about $10^9 \ \frac{\text{cm}}{\text{sec}}$, the total thrust will be:

$$1/2 \times 1.7 \times 10^{-24} \times 10^9 \times 2.5 \times 10^{14} = 2.1 \times 10^{-1},$$

where the factor 1/2 takes account of the angular distribution of the neutrons. On the other hand the mass of the reactor is:

$$20 \times 10^3 = 2 \times 10^4 \text{ gm.}$$

Thus the acceleration of the system due to neutron recoil is:

$$\frac{2.1 \times 10^{-1}}{2 \times 10^4} = 10^{-5} \ \frac{\text{cm}}{\text{sec}^2} .$$

This is 10^8 times smaller than the acceleration of gravity! Thus in order to be able to use such a motor for a rocket which would raise itself from the ground we must run the reaction 10^8 times faster which would raise the surface temperature of the reactor by a factor of 100. But there are no materials which would not melt at 300,000°K!

It may be noticed here, however, that if such a motor is shot out from the earth's gravity, it would start moving faster and faster covering the distance of $\frac{1}{2} \alpha t^2 = \frac{1}{2} \times 10^{-5} (3 \times 10^7)^2 = 4.5 \times 10^9$ cm = 45,000 km in the first year. But who cares!?

B. Radioactive Sail

Another possibility of building a rocket motor based on nuclear recoil consists in utilizing a thin layer of artificially produced, radioactive

material deposited on a thin metal sheet which can stop alpha-particles ejected in one direction (Figure 2). Since the range of ordinary alpha-particles in air is about 4 cm, their range in the radioactive material itself ($\rho \cong 20$) will be about $4 \text{ cm}/(10^3 \times 20) \cong 2.10^{-4}$ cm. If the temperature is to be held below 3000°K, the rate of energy production in the radioactive layer cannot be greater than

$$2 \times 10^{-5} \times (3000)^4 \cong 2.10^{11} \frac{\text{erg}}{\text{sec. cm}^2}$$

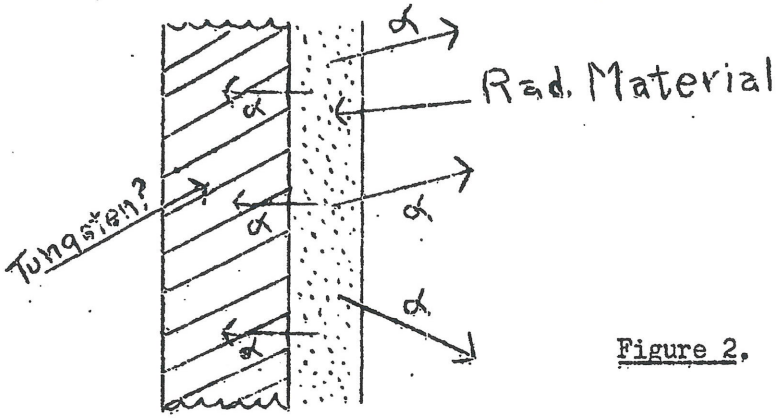

Figure 2.

Assuming 7×10^{-6} erg (ca: 4 MEV) for the energy of an alpha particle we can write the condition:

$$\frac{\rho d}{A \cdot 1.7 \times 10^{-24}} .7 \cdot 10^{-6} \cdot \lambda = 2.10^{11}$$

where d is the thickness of the layer (about $2 \cdot 10^{-4}$ cm), A the atomic weight (about 200), ρ the density (about 20), and λ the decay constant. We find:

$$\lambda = \frac{2.10^{11} \times 200 \times 1.7 \times 10^{-24}}{7.10^{-6} \quad 2 \cdot 10^{-4} \cdot 20} = 2 \cdot 10^{-3} \text{ sec}^{-1}.$$

This suggests the use of an alpha-decaying substance with the mean life of $1/(2 \times 10^{-3}) = 500$ sec. Suppose we can produce such material in a pile by subjecting a stable or semistable element to an intense neutron

beam. Let us calculate now the thrust of a nuclear sail formed by a layer of tungsten 2×10^{-4} cm thick, with an equal thickness of radioactive material. The thrust per cm^2 of the sail-surface will be:

$$\frac{1}{2} \times 1/3 \times \frac{2 \cdot 10^{11}}{10^{-6}} \times 10^{9} \times 6.6 \times 10^{-24} = 200 \text{ dynes.}$$

On the other hand, the mass of the sail per unit surface is:

$$20 \times 4 \times 10^{-4} = 0.008 \text{ gram}$$

so that the total acceleration becomes:

$$200/0.008 \cong 20{,}000 \text{ cm/sec}^2.$$

Since it is 20 times larger than g we can ease up the conditions by taking, for example, a ten-times larger thickness of tungsten-sheet (0.002 cm) and using an alpha-decaying element with a period of 1000 sec.

Fantastic as it looks, such an arrangement appears possible, at least in principle.

APPENDIX 3.

REPORT OF KACHIK, HUMMEL AND HENRY ON HIGH TEMPERATURE MATERIALS

THE PENNSYLVANIA STATE COLLEGE
School of Mineral Industries
State College, Pennsylvania

Memorandum Report No.: 5 Date: June 10, 1946

Government Contract No.: W33-038 ac 13506

Subject: Progress Report on the Metallurgical Aspects of Metal and Metal-Ceramic Bodies for Use at High Temperatures in Jet- and Rocket-Engine Service

I. Purpose

A. To present the data on the physical and chemical properties of high-melting, metal-base carbides, nitrides, and borides as obtained from a literature survey.

B. To outline a program of study by which the applicability of the above compounds for jet- and rocket-engine service will be determined.

II. Factual Data

A. Literature

As a group, five metal carbides, viz., HfC, TaC, ZrC, CbC, and TiC, comprise the highest melting compounds known. Their melting points all lie above 3000°C (5430°F); that of HfC, the highest, is about 3900°C (7050°F). The carbides of tungsten, vanadium, molybdenum, and boron, the nitrides of tantalum, zirconium, titanium, and scandium, and the borides of hafnium, zirconium, and tungsten form a group having melting points between 2500 and 3000°C (4530 and 5430°F).

In general, all of the above compounds resist decomposition at high temperatures. Their resistance to corrosion by various gases at high temperatures has been observed qualitatively to differ according to the position of the basis metal in the Periodic Table. In particular, the carbides of elements in Group IV (Zr, Ti, and Hf) and in Group V (Ta, Cb, and V) are reported to combine the best resistance to O_2, H_2, N_2, and H_2O (vapor) at high temperatures.

Additional data on physical properties, crystal structure, and chemical properties are given in Appendix A, and Tables II and III.

III. Conclusions

A. Although they have been largely overlooked as materials for high temperature service, the metal carbides, nitrides, and borides have extremely high melting points, and consequently, show much promise as materials for jet- and rocket-engine service.

B. The carbides of hafnium, tantalum, zirconium, columbium and titanium are the only known compounds, in either the ceramic or metallurgical fields, with melting points significantly above the calculated rocket-motor flame temperature of 2930°C (5300°F).

C. Quantitative data on thermal expansion and conductivity, strength at high temperatures, and corrosion resistance will have to be obtained before further selection of likely compounds can be made inasmuch as information on properties other than melting point, where available in the literature, is given mainly on a qualitative basis.

IV. Recommendation

A. It is recommended that the metal-base carbides, nitrides, and borides be investigated thoroughly for application in jet and rocket-engine service following the program outlined in Appendix B.

Respectfully submitted,

(Signed) E. A. Kachik
E. A. Kachik, Research Assistant

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Appendix A

II. Factual Data

A. Literature Survey

1. Melting Points and Stability

Table II lists the melting points of the high-melting, metal-base compounds, viz, the metal compounds of carbon, nitrogen and boron. The numbers in the third column of this table refer to the references in the appended bibliography.

Of these, the carbides or carbide mixtures as a class make up the highest melting materials known. HfC, TaC, ZrC, CbC, TiC, 80% TaC +20% HfC, and 80% TaC + 20% ZrC, all have melting points above 3000°C (5430°F). Only TaN and HfB, of the other types listed, have melting points above this temperature. Only three elements--carbon, rhenium and tungsten--have melting points of 3000°C or above (22). Of these, only carbon (M.P. 3500°C) and tungsten (M.P. 3370°C) have melting points that exceed 3000°C appreciably. The latest listing of the melting points of ceramic materials (12) indicates that 3000°C is about the limit for this class of materials.

For rocket tube service, therefore, the carbides, and particularly the first seven compounds and combinations in Table I, appear to offer the most promise. However, for jet engine service, from a melting point basis alone, all of the compounds listed offer possibility for successful application.

The compounds in Table II have not been thoroughly investigated with respect to stability at high temperatures, which property, with melting point, forms the first criterion for their successful application. Pertinent comments, with references, are given in the last column of the tab

Friederich and Sittig (17) reported that titanium, zirconium, and vanadium carbides undergo little or no decomposition on heating below the melting point, but that columbium carbide is decomposed and tantalum carbide partially so by heating below the melting point. However, Becker (9), in his book, "Hochschmelzende Hartstoffe", states that the carbides, with the exception of WC, MoC, and Mo_2C, melt without decomposing in a vacuum or inert atmosphere. Several writers (17,19,28,29) agree that WC is unstable above 2000°C (3630°F). Friederich and Sittig (17) disagree with Ruff and Wunch (28), Sykes (29), and the data compiled by Gregg (19), in asserting that W_2C decomposes below the melting point. The results of the latter investigators have been more generally accepted. It appears agreed (17)(18) that both MoC and Mo_2C decompose below the melting point. Boron carbide was found to have little vapor pressure at the melting point by Ridgeway (16), from which it seems reasonable to assume that the carbide is stable.

The nitrides of zirconium, columbium, titanium, and scandium were reported stable up to their melting points by Friederich and Sittig (16). In reporting on the work of Agte (2), Becker (9) confirms this statement for TiN and ZrN, and adds TaN to the list of stable nitrides. Vanadium nitride on heating evidently partially decomposes (16), although the degree of decomposition or temperature at which decomposition occurs was not specified. The nitrides of boron, silicon, aluminum, and beryllium sublime at high temperatures and could be melted only under pressure (16).

Agte and Moers (4) found that the three borides listed did not decompose before melting.

Of the high-melting compounds listed in Table II all but MoC, Mo_2C, WC, Bn, Si_3N_4, AlN, BeN and probably VN appear stable enough to justify further consideration.

2. Thermal Expansion and Conductivity

The coefficient of thermal expansion for TaC was determined by Becker (8) and found to be 8.2×10^{-6} between room temperature and 2380°C (4355°F). He also determined this property for WC and W_2C. He found that the coefficient of thermal expansion for W_2C was 11.4×10^{-6}, and 1.2×10^{-6} in the (001) and (100) directions, respectively, and for WC was 7.3×10^{-6} and 5.2×10^{-6} for the same directions, respectively. No similar data for the other compounds listed has been published.

Data on thermal conductivity were not found, and evidently determinations of this property have not been made.

3. Strength

Only two measurements of tensile strength were reported. Becker (9) obtained 2-3 kg/mm^2 as the tensile strength at room temperature for dense, polycrystalline, 1.2 mm dia., TaC wires, which had been prepared by carburizing the metal with a gaseous hydrocarbon.

Agte (1) reported that the tensile strength of WC was less than 35 kg/mm^2.

4. Resistance to Corrosion by Hot Gases

Becker, (9) in summarizing the general observations of Friederich and Sittig (16)(17), Agte and Moers (4), and of

Holbling and himself (10), correlated the resistance of the high melting carbides to corrosion by hot gasses with the position of the basis metal in the Periodic Table. He stated that Group IV carbides, (Zr, Ti, and Hf) are stable against oxidation by air at high temperatures, that the stability against attack is less for the carbides of Group V elements (Ta, Cb, and V), and that the carbides of Group VI elements (W and Mo) are readily oxidized. In the way of quantitative data he states only that MoC is markedly oxidized at 500°C, WC at 700°C and TaC at 800°C, but that Group IV carbides show no oxidation at these temperatures. Higher temperatures than this were not mentioned. Friederich and Sittig (17) reported that TaC powder burns readily in air, but that TiC powder was difficult to oxidize at "incandescence". These authors found that a CbC compact decarburized slightly on heating in air.

Against nitrogen at high temperatures Becker (9) classified the carbides of the Group IV elements (Zr, Ti and Hf) as least resistant, and reported that these carbides are decarburized appreciably by nitrogen at temperatures above 1550°C. Group V carbides (Ta, Cb, V), on the other hand, are similarly attacked by nitrogen only near their melting points. Since the Group VI metals (W and Mo) form no stable nitrides, they are completely resistant to the action of nitrogen.

Water vapor and hydrogen, according to the same author, have much the same effect as oxygen. The carbides of Group IV elements are most resistant to attack by water vapor, while those of Group VI elements are least. Group IV carbides show the best resistance to hydrogen and Group VI carbides the poorest. This gas decomposes the carbides at temperatures above 1500°C.

Becker (9) states that the carbides are very reactive with chlorinating agents at higher temperatures forming the respective chloride. When oxygen or sulfur is also present, the corresponding oxide or sulfochloride is formed. The two carbides of tungsten show markedly different reactivity toward chlorine: W_2C is rapidly attacked by the gas at 300-400°C, but WC is almost immune to attack in this temperature range (9).

Against general chemical attack, the carbides show very good resistance, and are dissolved only by the strongest oxidizing acids and fused alkalies (17).

The corrosion resistance of the nitrides and borides has not been as extensively studied. Scandium nitride oxidizes readily at red heat (16) and columbium nitride oxidizes slightly to columbic acid on heating in air (16). Becker (9) states that the nitrides are somewhat more stable than the carbides against attack by oxygen. The borides, he remarks, are very sensitive to foreign gases.

From this information it appears possible to further limit the investigation of materials for high-temperature service to compounds of Group IV or V elements, since these compounds evidently have the most resistance to oxidizing gases, hydrogen, and water vapor. Since the compounds of Group V elements also have good resistance to nitrogen this group appears to provide a good starting point for experimental work.

5. Crystal Structure of the Compounds

Table III summarizes the available X-ray crystallographic data (22) and densities (25)(9) for the compounds in Table II

The cubic NaCl structure predominates although there are several hexagonal compounds. The borides have not yet been fully investigated.

6. Metallography

The interreaction of the various components of the systems making up the carbides and nitrides has been briefly considered by several investigators (2,3,4,9,11,16,29). The results have been collected by Becker (9). A brief resume of features having possible significance for the present investigation follows.

The compounds CbC and TaC show no marked solubility for either carbon or the metal; however, TiC, ZrC, and HfC dissolve considerable amounts of carbon at high temperatures, with corresponding decreases in the melting points of the compounds. This carbon is precipitated on cooling. W_2C dissolves appreciable quantities of both carbon and tungsten at high temperatures. WC apparently dissolves little, if any, of either at any temperature. Small amounts of both Mo and C were found soluble in Mo_2C.

The metal-nitrogen systems are "analogous to the carbide systems" (9). The metal-boron systems have been studied only enough to indicate that they are very complex.

Inter-carbide and nitride reactions have also been studied, chiefly with respect to the liquidus temperatures. Becker (9) gives the following information:

1. TaC and W_2C form a eutectic at about 10% TaC. On either side of the eutectic point the liquidus curve extends in straight-line fashion to the melting point of each component.

2. CbC and W_2C form a eutectic in the range 10-25% CbC.
3. ZrC and W_2C are immiscible in all proportions. As long as any W_2C is present the mixture becomes mushy at the melting point of W_2C.
4. For the CbC-TaC system, the liquidus temperature shows a gradual increase from the melting point of CbC to that of TaC.
5. CbC and ZrC have practically the same melting point and the liquidus line is nearly horizontal.
6. The systems TaC-ZrC and TaC-HfC each show a melting point maximum at the 80% TaC composition (See Table II). The maximum is significantly above the melting point of either component for both systems.
7. The TiN-TiC system has a melting point maximum at the 50-50 composition. This maximum exceeds the melting point of TiC, the higher melting component, by only 45°C.
8. The addition of TaC to TaN apparently results in a gradual increase in melting point for the resulting mixtures, although only the 50-50 composition was investigated.
9. Considerable study has been given alloys of the cemented carbide type which usually consist of hard carbides (usually tungsten or tantalum) imbedded or cemented in a soft matrix or binder (iron, nickel or cobalt). The binder, by alloying with the carbides, secures the compact against disintegration. These

materials have melting points or ranges that are determined by the binder and moreover that are usually relatively low. They are probably of little use for the necessary exposure conditions.

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Appendix B

IV. Recommendations

A. Program of Research on Metal Compounds

As noted under "4" of the Literature Survey, Appendix A, compounds of Group IV and V elements appear to offer the most promise, and should, therefore, be considered first. The carbides, as a class, melt at far higher temperatures than other known materials and, logically, seem worthy of more emphasis than the other compounds, especially for service where temperatures up to 3000°C must be withstood. However, for jet-engine service, where an increase to 1500°C in combustion tube operating temperature would constitute a marked improvement, all of the stable compounds in Table II should be investigated.

TiC, ZrC, VC, TaC, CbC, WC, TiN, and ZrN are supplied by several firms at prices ranging from $0.75/lb. for TiC to $62.75/lb. for high purity CbC. From a practical viewpoint the least expensive compounds, either to buy or to make, should be tested first. It should be borne in mind, however, that fabrication costs of the finished part may be high enough that material cost will be a minor factor. For this reason material cost should not be allowed to become the deciding factor, at least until more information is developed.

The following general program is proposed:

1. The purchase of those compounds available commercially and the preparation of those not available, for testing purposes. It will be necessary to design and construct suitable apparatus for preparing these compounds.

2. Determination of the thermal conductivity and expansion characteristics, strength, and resistance to corrosion by hot gases of the collected compounds. Compacting, sintering, and testing equipment will be needed.

3. If necessary, the determination of other characteristics, such as crystal structure, density, and interreaction with similar or dissimilar compounds and substances.

4. If several materials or compounds are nearly equally promising from the tests in (2) on the previous page, ease of fabrication, cost, and strength/weight ratio will determine the selection of material for final trials.

5. Fabrication of appropriate shapes from suitable compounds or combinations, for simulated service tests and finally actual operation as jet- and rocket-engine parts.

Table II

Melting Point and Stability of High-Melting Metal-Base Compounds

Compound	°C	°F	References	Remarks on Stability
80% TaC+20% HfC	3940 ± 150	7120 ± 270	3,8	Melts without decomposition (9)
80% TaC+20% ZrC	3930 ± 150	7100 ± 270	3,8	" " " (9)
HfC	3880 ± 150	7020 ± 270	3,8	" " " (9)
TaC	3870 ± 150	7000 ± 270	3,8,14,15,17,21,25	Contradictory-see text
ZrC	3530 ± 125	6390 ± 225	3,8,15,17,25	Melts without decomposition (9)(17)
CbC	3500 ± 125	6330 ± 225	3,8,15,17,25	Contradictory-see text
TiC	3140 ± 90	5680 ± 160	8,17,25	Melts without decomposition (9)(17)
WC	2870 ± 50	5190 ± 90	3,5,7,17,19,20,25,28,29	Decomposes at 2600°C (4710°F) (9)(17) (19)(28)(29)
W_2C	2860 ± 50	5170 ± 90	3,5,7,17,19,20,25,28,29	Contradictory-see text
VC	2830	5125	17,25	Melts without decomposition (17)
MoC	2690 ± 50	4875 ± 90	3,17,18,25	Decomposes below M.P. (9)(17)(18)
Mo_2C	2685 ± 50	4865 ± 90	3,17,18,25	" " "
B_4C	2350-2500	4260-4530	27	Melts without decomposition (27)
TaN	2800-3090	5070-5450	4,16,25	Melts without decomposition (9)(16)
ZrN	2930	5300	16	" " " (9)(16)
"	2980 ± 50	5400 ± 90	4,25	
TiN	2930	5300	4,16,25	" " " (9)(16)
ScN	2650	4800	16	" " " (16)
CbN	2050	3810	16	" " " (16)
VN	2050	3810	16	Partially decomposed before melting (16)
BN	3000*	5430	16	Sublimes below M.P. (16)
Si_3N_4	1900*	3200	16	" " " (16)
AlN	2200**	4000	16	" " " (16)
BeN	2200**	4000	16	" " " (16)
HfB	3060	5540	2,25	Melts without decomposition (9)
ZrB	2990 ± 50	5450 ± 90	2,25	" " " (9)
WB	2925 ± 50	5300 ± 90	2,25	" " " (9)

* Under Pressure
** Under 4 atm. Pressure

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Table III

Crystallographic Structures (22) and Densities (9)(25)

Compound		X-ray Data a	c	mol/unit cell	Density-g/cc
HfC	Not listed (cubic NaCl?)				12.2
TaC	Cubic NaCl	4.53		4	14.05
ZrC	" "	4.73		4	6.90
CbC	" "	4.40		4	7.56
TiC	" "	4.31		4	4.25
WC	Hexagonal c.p.	2.901	2.830	1	15.5
W_2C	Hexagonal	2.99	4.72	1	17.2
VC	Cubic NaCl	4.30		4	5.36
MoC	Not given				8.2
Mo_2C	Hexagonal c.p.*	3.004	4.725		8.9
B_4C	Cubic Diamond**				2.51
TaN	Hexagonal ZnO	3.05	4.94	2	14.1
ZrN	Cubic NaCl	4.61		4	6.93
TiN	" "	4.40		4	5.18
ScN	" "	4.44		4	--
CbN	" "	4.40		4	8.40
VN	" "	4.28		4	5.63
BN	Hexagonal Graphite	2.51	6.69	4.2	--
Si_3N_4	Not given				--
AlN	" "				--
BeN	" "				--
HfB	" "				--
ZrB	" "				--
WB	" "				--

* Reference (16)
** Reference (28)

APPENDIX 4. HYDROGEN-MODERATED ATOMIC ROCKET

G. Gamow, F. T. McClure and R. B. Kershner

Since the atomic rockets must necessarily use hydrogen as the working fluid, and since liquid hydrogen represents the best possible moderator for enriched piles, it is reasonable to consider the possibility of an atomic rocket motor in which hydrogen serves both purposes. In this case liquid hydrogen coming from the tank must first stream through the pile-structure with its original low temperature and high density (moderating stage) being later heated up and accelerated to a high velocity on the way to the nozzle (accelerating stage). This end can perhaps be achieved by having a series of channel-systems through the body of the enriched uranium. First, hydrogen entering from the tank is sent through rather broad channels thus receiving comparatively little heat from the hot walls and remaining in the liquid state through the main part of its travel. After having accomplished its moderating function, hydrogen enters the system of narrow channels where it is rapidly heated and accelerated towards the nozzle. The problem of developing a rocket motor of such type splits essentially into two parts:

1) Critical size of hydrogen-moderated pile and
2) The problem of heat-transfer, and the arrangement of channels necessary to keep hydrogen from being heated in the first (moderating) stage, and to heat it up fast enough in the second (accelerating) stage.

A. The muclear Problem

In order to design the smallest possible hydrogen-moderated pile, we can start with the so-called "atomic water boiler" asdiscussed by Dr. Christy in his Chicago paper. Considering a homogeneous solution of enriched uranium salt in water, Christy arrives at the following boiler-characteristics corresponding to the minimum amount of U235:

Radius 22 cm. (for a sphere)

Mass of U235 = 1.5 kg

We subject Christy's model to the following transformations which do not affect its efficiency.

1) Instead of a sphere we take a cylinder of about the same volume, the length of the cylinder being equal to its diameter.

2) Replace water by liquid hydrogen. This will not affect greatly the efficiency of moderator since oxygen atoms in the water molecules are unimportant either in slowing down or in capture of neutrons, and because the atomic density of hydrogen in the liquid state is of the same order of magnitude as atomic density of hydrogen in water (.07g/cm^3 vs .11g/cm^3).

3) Instead of having homogeneous distribution of uranium, introduce it in the form of thin cylinders surrounded by liquid hydrogen. If anything, such transition from a homogeneous to the lattice-pile will improve its efficiency. The new pile will thus be described by the following rough figures:

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Dimensions: diameter ~ 44 x 1.4 = 52 cm
length ~ 52 cm

Volume 1.1×10^5 cm^3

Weight of U235 ~ 4×10^3 gm

Total weight of U (2% concentr. of 235) 200×10^3 gm

Total volume of U (density = 18.7) ~ 10×10^3 cm^3

Fraction of total volume occupied by U - metal: ~ $\frac{1}{11}$

Volume of liquid hydrogen = 1×10^5 cm^3

Weight of liquid hydrogen (density = 0.07) = 7×10^3 gm

B. The Reactor Design Problem

The advantage of the hydrogen-moderated reactor over the carbon moderated reactor may come about in two ways. First, the critical dimensions may be smaller so that the overall reactor size may be more manageable. Second, the use of such a low density moderator might materially decrease the weight of the reactor because of the almost negligible weight of moderator. However, with respect to the latter point it must be remembered that in order to use a liquid hydrogen-moderator, the main body of the hydrogen in the reactor must be protected from the heaters. This implies a multiple honeycomb type of structure in which a series of counter-current heat exchangers satisfy both the heating and cooling requirements simultaneously. This, in turn, implies a considerable amount of "structure" in such a reactor and it appears that the crucial problem is whether this structure weight can be reduced to a value as low or lower than the moderator weight in the other case. Rough analysis shows that this desired requirement is not easily met. Very careful analysis will be required to evaluate the possibilities of the hydrogen-moderated reactor for rocket motors.