NUCLEAR ENERGY FOR SPACE FLIGHT?

Based Upon and Excerpted From a Speech by

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Central to the theme of lunar missions and exploration is the question of how we are to get to the Moon - and back again. The subject of this discussion provides an answer to this question and suggests how mankind might travel even farther in the future.

It might be best to begin by trying to make a realistic assessment of where we stand now with regard to nuclear energy for space flight and where we might go. What does nuclear energy offer for space flight? Does it offer anything at all, and, if so, what are its promises? How much can we hope for some great advances beyond current levels of technology as exhibited in the laboratory and by scale reactor test? To answer these questions, let us first review some of the basic types of nuclear heat exchanger and nuclear electric propulsion systems and try to make an assessment of these systems. Although no mathematical proof is provided for the conclusions reached, these conclusions may be substantiated by going through the literature on the subject.

First in engineering practicality, first in interest, and first in funding (a more practical point of view) is the solid core reactor. This is nothing more than a chemical rocket combustion chamber that somebody has stuffed full of a neutron moderator impregnated with a fissionable fuel and punched full of holes. Pump it full of hydrogen, and you have a rocket reactor. From an external point of view it is like a chemical rocket engine but is heavier than a chemical rocket engine. In it, we have replaced the chemical fire with a nuclear fire and, from this description, it is obvious that it suffers from many of the problems chemical rocket engines have. It obviously suffers

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from temperature limitations; it is a solid structured system, and we must keep the walls operating at as low a temperature as possible. Of course, the system will not produce useful performance unless the walls operate at as high a temperature as possible, and therein lies the difficulty in solid core reactor development. This is a materials problem, one that ceramicists have been trying to solve for three thousand years, and it is doubtful whether they are much more ahead of the game now than they were in the days of the Egyptian Empire.

Still, even at essentially room temperature, liquid hydrogen, because of its low molecular weight, gives a specific impulse comparable to LOX/H_2 combustion systems. The switch to low molecular weight propellant allowed by use of nuclear energy gives rather marked increase in specific impulse even without forcing operation at extremely high temperatures. Such straightforward heat exchangers today seem as though they will be able to give us specific impulse values of 750 to 800 sec reliably, probably within the decade, and may in time, with sufficient funding and development, yield up towards 1000 sec specific impulse.

Although this is mostly a result of using a low molecular weight propellant (hydrogen) at the higher temperatures that eventually may be possible, it is partly because dissociation energy comes in to help boost exhaust speeds. By operating the system at somewhat lower pressure at extreme temperatures, it will run in such a way that some of the dissociation energy comes back in recombination in the nozzle flow.

A less practical way to replace the chemical fire with nuclear fire is to fill the "combustion chamber" with a liquid fuel (liquid uranium in some appropriate compound form), immerse the whole thing in a big tank of heavy water, spin it around to plaster the liquid fuel up on the sides of the chamber, and then heat the propellant by bubbling it radially through the molten fuel. The heavy water around the core cavity is for the purpose of making it a true neutron reactor, one that conserves neutrons and shoves them back into the core to make fissions. The obvious advantage here is the ability (in principle) to operate above melting points of solid fuel structures. Of course the disadvantage is that no one as yet has studied and solved all of the flow stability, start-up, and shut-down problems that are obvious in this concept. If these kinds of problems are solved, other ones arise: specifically, vapor entrainment from the vapor pressure of the fuel-bearing material and liquid entrainment of fine filaments of liquid trapped by the motion of the bubbles expanding into the central core. With considerable development effort, it looks as though such a system might be made to yield specific impulse of up to 1300 sec if everything turned out very well. This is an interesting level of performance but will not be achieved very soon; nor is there any guarantee that it could be done at high thrust to weight ratio. It seems likely that these liquid core reactors are not going to solve propulsion problems for some time.

Last in the direct heat exchanger system, although it is almost the oldest concept in the business, is the gaseous reactor. Here gaseous U^{235} replaces the liquid in that chemical combustion chamber, and the whole thing is again dipped in a bath of D2O. We pump gaseous uranium fuel through an injector into one part of the chamber, and pump hydrogen propellant into another. They mix in the cavity, the system goes critical and fission takes place, the nuclear fire heats them both, and both of them exhaust through the nozzle. Of course, this is exactly the problem: how to keep the fissionable fuel trapped within the very turbulent mixed gas region in the core, while allowing the propellant to escape. The obvious reason people are interested in such things is that, hopefully, one can run the central gas temperature at levels much higher than the walls, possibly even to temperatures of 10,000 deg or so.

We can picture the problem of such systems in a graphic way. Most of us have seen Atlas engines or Titan or F-1 engines running at full thrust. Picture one of these engines going with full flow of full thrust. Now inject some lead sulfide vapor into the combustion chamber. The problem is how to keep the lead vapor from coming out the nozzle with the rest of the propellant. To date there really is not any workable scheme demonstrated which can solve this problem. There is no scheme extant which offers any real hope for the solution of this problem. In a sense, this is in the same category as the Sherwood program to achieve controlled fusion power. There may be a way to do it, and, by looking at it on a research basis, we may find it; but we may not.

The oldest nuclear propulsion scheme is that of propulsion by nuclear explosives. In effect, this is just a variation of the gaseous reactor. Here the gaseous part of the system is located at the base of the rocket vehicle. We set off a nuclear bomb far behind the rocket and intercept some of the expanding bomb material, for example, by the base of the vehicle. Presto! Momentum exchange, and the rocket is impulsively accelerated. with a very high effective specific impulse. The rocket **is**, in fact, very impulsively accelerated, and this of course is the great problem--how to avoid accelerating it to a thin film. However, it appears that there are ways to go about this; people have devised schemes that lead them to believe that there may be solutions to this problem of the tremendous impulsive load, but the whole concept suffers from the great disadvantage that it has never been tested with nuclear explosives systems. Until recently this could not even be considered; the United States is a peace-loving nation full of nuclear test bans. But now we are testing once again, and the Russians tell us they are going to keep right on testing as well. It would be tragic if a test ban descends upon us again before we have a chance to try out this system.

This is not to imply that great numbers of people have great hope that it will work. But suppose there is even a very small chance that it does; can the United States afford not to try it? Suppose that we do not and another country does, and it does work and gives 6000 sec I_{sp} in vehicles that weigh a few million pounds. Although perhaps this is not very useful tomorrow, such performance might be a very good thing to have available for an era of large scale space flight.

We can summarize solid core heat exchanger propulsion systems by saying that we know both how to do it and how well it will perform. We know how, but not how well, for liquid fuel reactors and for explosive propulsion; and we do not know either for gaseous reactors.

Turning now to nuclear electric propulsion; it often has been pointed out that the principal acceleration methods--arc jets, hydromagnetic accelerators, and electrostatic systems--cover an I_{sp} spectrum that goes from about 1000 to 10,000 sec or so. Thermal arc jets are electric "gaseous reactors" that may yield 1000 to 2000 sec, with some development in specific impulse. Hydromagnetic neutral plasma accelerators might possibly cover from 2000 to 5000 sec with diligent development. Questions of efficiency loom large here and are unsettled. Electrostatic systems (ion accelerators) seem to offer promise for use in the region from 5000 to 10,000 sec or thereabouts. Since the system thrust-to-weight ratio varies inversely with specific impulse, all other things being equal, electrostatic systems will tend to give lower accelerations than arc jets. But crucial in the performance of all such systems are questions of overall energy conversion efficiencies, both in the source and in the sink (the accelerator) components.

Efficiencies of thermal radiation and maximum practical radiator temperatures remain to be explored and developed. It appears that overall efficiencies on the order of 20% might be possible today with fairly straightforward technology.

To summarize as before, it can be said that we know HOW and HOW WELL about electrostatic accelerators and arc jets, and about turbo-electric and solar cell sources, and that we know HOW, but not HOW WELL, direct conversion devices and hydromagnetic accelerators will perform.

This higher performance, the higher I_{sp} that is offered by nuclear propulsion, of course means a greater payload or a greater velocity than from an equivalent chemical vehicle. The doubling of I_{sp} in heat exchanger systems gives striking cost advantages for high acceleration vehicles used in Earth orbital flight or for maneuvering Earth orbital systems. This is mostly because of the low mass of system required in-orbit; therefore you pay less in boosters to get it up there. In addition, if used in certain special ways and in combination with chemical boosters, it even appears that large cost advantages may accrue if you use nuclear propulsion for a large fraction of the ΔV to boost from Earth to orbit. Results of some analyses give hope, reasonable hope, for costs of $30/lb or so to orbit. Such a cost is between 4 and 10 times lower than many estimates of chemical rocket delivery capabilities, and it is only an order of magnitude greater than present trans-Atlantic air fares.

The extremely large I_{sp} obtainable from nuclear/electric systems essentially eliminates any competition for all but probe type interorbital missions. If you are going to carry heavy payloads, you are driven to nuclear electrical systems.

Now let us look at the other side of the coin - a much more gloomy side. So far, and in most talks of this sort, everyone cavalierly ignores that awful creature, radiation. The pilot of a manned nuclear vehicle, however, is not so fortunate; he can not ignore it; there it is sitting behind him. How are our conclusions going to be compromised by a proper assessment of radiation problems? First, we find that the only really troublesome problem is that due to fission product decay after shutdown. Power-on doses all seem to be small enough that they can be handled by the shielding, which is needed for protection against solar flares and other natural space radiations. It is only when considering manned maneuvers in space with nuclear vehicles, terminal maneuvers, rendezvous, and transfer of people that a real problem arises.

To illustrate this, we have made a simple calculation comparing a LOX/H_2 system using 440 sec I_{sp} with a nuclear hydrogen rocket using 800 sec. We have taken 5% for structure in the LOX/H_2 system and 10% in the nuclear system. We have taken a LOX/H_2 engine thrust-to-weight ratio of 70:1. You will grant that these assumptions are not biased in favor of the LOX/H_2. We find that for equal gross weight a single-stage nuclear system can carry a dead load larger by about 20% of the gross weight than can a LOX/H_2 rocket. If the LOX/H_2 can carry 5%, it turns out the nuclear system can carry 22%. If the LOX/H_2 can carry 20% (to smaller ΔV), the nuclear system can carry nearly 40%. Now, suppose we take that extra dead load capability and put it into shielding around the reactor. Let us, for illustration, shield that reactor so well that the pilot, when he has accomplished rendezvous, can get out and walk all around his vehicle. If he joins with an orbital vehicle in space, we will shield the reactor to the point that the rendezvous station receives only laboratory tolerance dose rates at 30 ft from the reactor, at 20 min after shutdown. Now, this is a real situation you can think of as occurring in a close **rendezvous**. Since the shield mass depends on the reactor power, and the power is proportional to the thrust, our answer will depend on the vehicle acceleration we choose. It turns out that, if we take 0.38 acceleration, the minimum size at which the nuclear hydrogen vehicle completes with LOX/H_2 (carries the same payload for the same gross mass) is $1\text{-}1/2 \times 10^6$ lb. Clearly, this is not a good way to try to exploit nuclear energy; we should stick with LOX/H_2.

Suppose we do not fight the radiation problem this way. Suppose we throw the source away instead, so that we do not have to shield. If we throw the reactor away after one use, then we do not need this shutdown shielding, and we can exploit the higher I_{sp} advantage of nuclear propulsion in all sizes of rocket vehicles. Of course, this leaves us without an engine to come home on and it also raises the cost, especially if the reactor has ten million dollars worth of uranium in it. Better still, suppose we use a refuelable reactor--develop one in which we can push the fuel elements out after one use, but keep the rest of the reactor system there. Here the cost would be high unless the fuel elements themselves contain very little uranium, which argues for use of well-moderated reactors. In this concept, the fuel elements might be viewed as analogous to slivers in solid rocket engines used in a solid rocket for test purposes, where we just keep the case and reload it for reuse. If we do this, again no special shielding is needed.

Another solution, and possibly the best one, is to use a distant rendezvous (ca., 10 to 30 miles) and controlled vernier docking with chemical engines--chemical rockets-- so that we can carefully control the orientation of the vehicle as well as its relative velocity to the rendezvous point. This would allow the use of shadow shielding covering only a fraction of all space. Instead of 4π space, let us cover 1/50 of 4π space and rendezvous carefully with chemical engines. Although it sounds rather fearful, this may be no more difficult than docking the Queen Mary in New York harbor. Still, it is well that chemical rockets will be made to rendezvous one of these days, because all of the experience gained in chemical rendezvous will be useful here as well. If we allow the use of shadow shielding, we can once again exploit nuclear energy to the fullest extent.

For nuclear electric propulsion, similar problems arise. In some ways they are worse, because nuclear electric systems must run longer and therefore will build up more fission products. But in some ways they are better, because some of those built up in early times have already decayed by the time the vehicle terminates its flight. Again, these radiation problems are soluble either by disposal of the reactor or the fuel elements, and refueling, or by careful oriented docking from distant rendezvous.

Consideration of this whole situation shows that what we really need are several different types of nuclear rocket propulsion systems, if we are to take maximum advantage of the I_{sp} offered to us. If nuclear rockets are to be used in quantity in the future, we should have cheap and disposable reactors, high power density shielded reactors, and refuelable reactors.

Although we cannot expect miracles from nuclear energy for space flight, it is important to emphasize that the potential improvement in cost which has been mentioned, about a factor of 4 to 10, comes at a rather crucial point in the cost per pound scale. At $300/lb to orbit, and an equivalent cost for interorbital transport, it would take us on the order of 50 years to establish a Martian colony of something like 1000 people at currently feasible rates of expenditure (i.e., the order of several billion dollars a year). A Martian colony of 1000 people may sound far out today, but probably many of us will live to see such a thing transpire. One thousand people is about the number that set sail in 1634 to establish the Massachusetts Bay Colony. It has been pointed out that those prople, when they got off in Massachusetts, did not step into a vacuum; they could breath the air and eat the fish and so on. But neither did they carry nuclear reactors with them, nor all the modern technology that we have today. At $30/lb to orbit, and comparable cost for interorbital flight, the time required for such a thing is only about 5 years, and this becomes a reasonable goal. The nation that develops the cheapest propulsion system, significantly cheaper by factors of 2, 3, 4, or 5, certainly stands the best chance to own Space.

The needs here, the long term needs, are clear. Figs. 1 and 2 show the solar system, iviting to us, ready for the plucking, with a useful area about 63 times the area of North America. Someday the people from this Earth are going to own it all, and the owners will be those who have moved first and fastest into the future of the propulsion system spectrum, the future that belongs to nuclear energy.

Fig. 3 is a picture, in a way, of how the future belongs to nuclear energy. On the left-hand scale is the specific impuse required from a heat exchanger nuclear rocket to complete with chemical rockets, and with nuclear electric propulsion for different missions marked along the bottom scale. The three curves each represent a different state of the art of nuclear electric propulsion . The region of superiority of nuclear electric propulsion is that to the lower right of the triple point, chemical rocket superiority is that to the lower left, and heat exchanger nuclear rockets fill the area above. Of course, this graph is very subjective, because there is no really rational way to assess what is best and what is worst, but we will go through some simple missions. Consider the shaded region on the left. If we examine ground missions of a few thousand miles range, we see that the curve lies between 1200 and 1500 sec I_{sp}. This is equivalent to saying that heat exchanger nuclear rockets are not going to compete with chemical rockets for ground-bound missions on the Earth until they can do better than something like $I_{sp} = 1200$ sec. This does not mean that you could not make them lighter, or cheaper, or carry bigger payloads. What it means is that we are going to have warehouses full of Atlas missiles and warehouses full of Titan missiles, and nobody is going to throw them away as long as they will do the job. There is no point in spending money to develop a system for a job that is already done and paid for.

As we go up to further, more distant missions, there is a chance that nuclear propulsion can come into its own, just because it will take us so many years before we are ready to attempt those missions; these jobs are not yet done and paid for. If nuclear electric propulsion must stagger along at 100 kg/kw electrical power, as on the lowest curve, then nuclear heat exchanger propulsion at $I_{sp} = 650$ sec would seem to be superior to nuclear electric for all missions beyond the Moon, up to or slightly beyond the orbit of Mars. Once you go to the outer planets, Jupiter, Saturn, and so on, the ΔV requirements become so great for any useful transit times that even 650 sec is hopeless in comparison with a 100 kg/kw from nuclear/electric propulsion. Now let us suppose we develop nuclear/electric propulsion systems at 10 kg/kw in the exhaust jet. In the fierce competition between nuclear/thermal and nuclear/electrical systems, this has moved the nuclear/electric systems in to the point where heat exchanger rockets must yield 800 sec or better to compete on Martian-Venusian missions. $I_{sp} = 700$ sec just barely competes in a subjective way with nuclear/electric for lunar shuttle missions, and we see that for low Earth orbital missions the pure rocket approach does not compete with chemical rockets until we get up towards 800 and 900 sec. If nuclear/electric systems can be made still better, to k kg/kw in the exhaust (and this does appear to nearly everyone to be the end of the line of all current ideas), then the nuclear/thermal rocket must deliver more than 1000 sec, or there is not any home for it at all on a large-use basis.

The key feature from this graph, however, is not the competition between nuclear/thermal and nuclear/electric; it is the fact that everything to the right on the graph belongs to nuclear energy of one kind or another. It does not belong to chemical energy; we are not going to get to Pluto or do very many Venusian or Martian missions that way. What we need to do is to develop some of these nuclear propulsion systems a little more quickly, so that we can arrive in space more quickly and with the right kind of equipment for further work when we get there. We should not keep fighting among ourselves in the rocket business.

What we should try to do now is to diversify our nuclear propulsion programs. We have one very vigorous program funded at the moment, the Nerva reactor and the Rift vehicle program. This is going to lead to a logical complete development of a flight vehicle using the Kiwi kind of nuclear/thermal reactor as a basis. This is an admirable start, but now we need one other program of comparable size and support to give us a good nuclear/electric system within a decade, a complete working system of high power in the order of many megawatts-- Not just a reactor development, but a complete system using nothing but current technology. Additional effort and support also is needed in a program to provide for a proof test development of more advanced systems, both in nuclear/electric and solid core reactor propulsion. We can name specific items here, such as plasma thermocouple reactors. Although currently in an applied research stage, these are also in a position where funding would allow some simple and crude integrated units to be built. Probably these would not operate a sufficiently long time at present to be directly useful for propulsion, but it would help us to fund such a program and build such a reactor to see what we have to do to go beyond that. In solid core reactor propulsion, one can think about building different kinds of reactors than we are now building with an emphasis on disposability, refueling, and cheapness of construction. What we see at present is that we are still putting most of our money in the chemical bucket, and, although a fair amount is now going into nuclear propulsion, there is only one real program. It seems evident that we need more than one; we ought to diversify now so that within a decade or so we can begin to exploit the region to the right in Fig. 3.

We find in history that, once upon a time--nearly 100 years ago--a similar situation of choice arose in world transport. For over 30 years in the early 1800's, the United States completely dominated the North Atlantic Packet trade by virtue of perfection of that most lovely of machines, the Clipper ship. Then along came a horrible, ungainly thing, belching black smoke. It blew up at intervals and was very hazardous to bring into port. Certainly people would not be so foolish as to ride on it. It was called the steamship. American maritime circles scorned such a creature as uneconomic; it clearly could not compete, it was too expensive, and it was unsafe - people would not entrust it with their cargoes. And so our United States shipyards built more and more Clipper ships. But the steamers turned out to be faster after all, and people did use them. The British, who had built steamships, captured the Packet trade nearly completely, and they held it for almost 40 years, until we in this country could catch up with steamship development and production.

It is very true that this analogy is about an incident in world history which is small and unimportant as viewed from our present point in time. Space flight today is certainly more than just the North Atlantic Packet trade. In fact, it is the major future endeavor of all mankind, and we should not plan to be second best in this great adventure. We must develop the nuclear propulsion systems needed for the long term future of space flight.

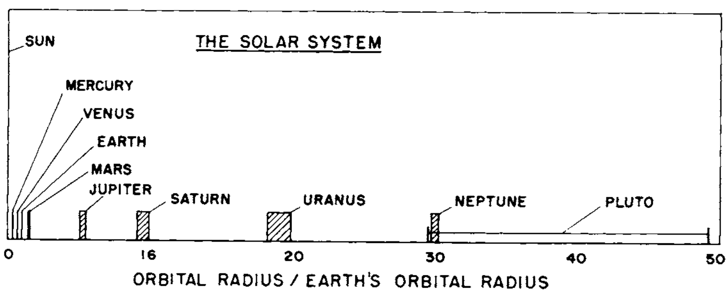

Fig. 1 Solar system; general outline

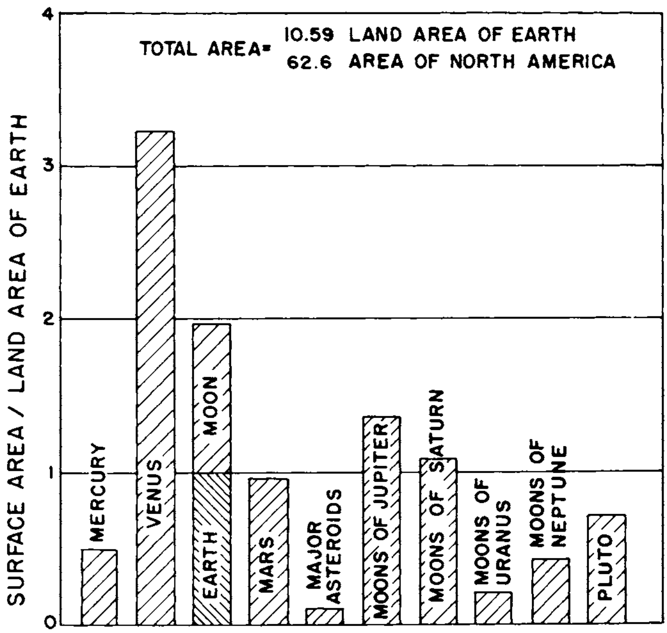

Fig. 2 Solar system; useful area available

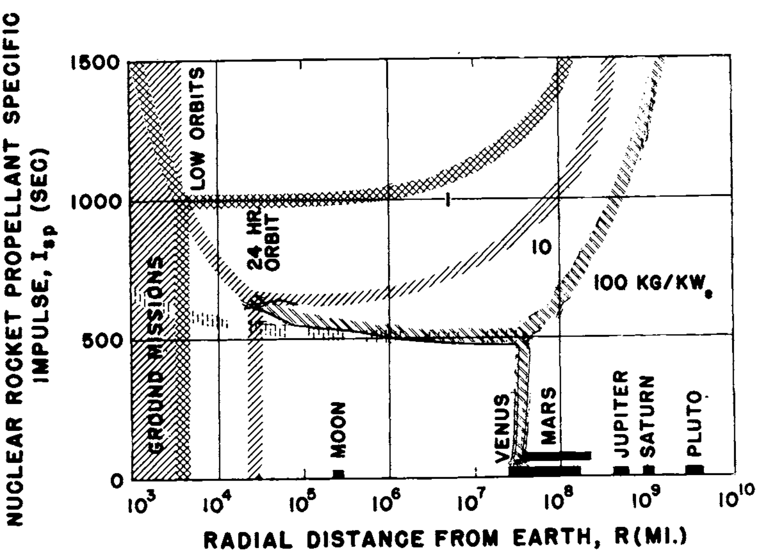

Fig. 3 Relative performance comparison of chemical nuclear-thermal and nuclear-electric propulsion