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CRYO-ENGINEERING IN THE NUCLEAR ROCKET PROGRAM*

by

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Among the many remarkable technological achievements which have enriched our lives in the years following World War II, few have been more spectacular or more exciting to the imagination than the development of rocket vehicles with sufficient power to permit mankind to take an initial small step toward an objective probably as ancient as man himself: the exploration of outer space. In order even to accomplish this much however it has been necessary to develop compact, light weight, and extremely powerful rocket engines as well as suitable sources of energy from which these engines can extract the necessary power. To date the requisite energy has been obtained from the carrying out of highly exothermic chemical reactions in the combustion chamber of a rocket engine system, the thermal energy of the reaction products being converted into a directed flux of kinetic energy in the rocket nozzle.

Toward the end of World War II, a new and very efficient source of almost unlimited energy became available from nuclear fission and in the years immediately following, the development of peaceful uses

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of atomic energy has been actively encouraged. It therefore was almost inevitable that the ever-increasing energy requirements of the space program would eventually lead to a joining of forces on the part of the two technologies to produce a nuclear powered rocket and this in fact is what has happened. The potential effectiveness of these new energy sources for rocket

propulsion is shown

in the last column

of Fig. 1 in which

the ratio of

take-off mass to

final or burn-out

mass is tabulated

for a given mission

(earth escape) for

rockets using each

of the indicated

energy sources. The closer this number is to unity the greater is the effectiveness of a given weight of fuel or, putting it another way, the closer this number is to unity the larger will be the fraction of the total rocket weight which can be devoted to payload.

Clearly the development of practical methods of exploiting these potential improvements in rocket performance is essential to any serious space exploration program. It should be pointed out

Fig. 1

however that although there are listed in Fig. 1 a number of different ways in which nuclear energy can be utilized for rocket propulsion, as the efficiency increases so also does the difficulty of what patent lawyers are fond of calling "reduction to practice." Consequently at the present time the major effort of the United States nuclear rocket program is devoted to the development of the first mentioned of these devices, namely, a nuclear rocket in which a propellant, liquid hydrogen, will be heated by a solid core nuclear reactor. The development of such a reactor is the main objective at the present time of the so-called Rover program of the Atomic Energy Commission and the National Aeronautics and Space Administration.

Turning now to a slightly more technical discussion of the nuclear rocket it is well known that the basic equations of rocket propulsion are derivable from the principle of momentum conservation and Newton's laws of motion. Thus by ejecting a mass (m) of propellant from the rocket nozzle in one direction with a velocity (v) there is imparted to the rocket a mass (M) a velocity (V) in the other direction. The force applied to the rocket is then equal to the rate at which momentum is being imparted to the fluid medium through which the rocket is moving. Neglecting the effect of atmospheric drag, the acceleration imparted to a rocket vehicle by its engine system is thus equivalent to the motion occurring in a small boat moving without friction on the surface of a pond as stones are pitched out over the stern by the occupant.

To evaluate rocket performance, we require some sort of a figure of merit to help us to determine whether pebbles, rocks, or boulders should be pitched out of our rocket nozzle and with what velocity. This quantity is the well-known I_{sp} or specific impulse

of a rocket system which in effect specifies the thrust (in pounds) imparted to the rocket per pound of propellant ejected per second from the nozzle. From elementary mechanics and thermodynamics it is easy to show that I_{sp} is approximately proportional to the square root of T/M where T is the temperature of the exhausted propellant and M is its mean molecular weight. Assuming that an upper limit to the propellant temperature is fixed at about 2500°K by strength of material considerations, it is then obvious that I_{sp} is maximized by utilizing a low molecular weight propellant and clearly the lightest practical propellant (excluding the more exotic materials such as electrons, photons, and hydrogen atoms) is the element hydrogen. From these simple considerations we therefore have in hand a scheme for a nuclear rocket. We simply construct a nuclear reactor, the cooling medium for which must be hydrogen. We transfer the energy generated by nuclear fission to the hydrogen and then cause the heated hydrogen gas to pass through a de Laval type rocket nozzle by means of which the thermal energy of the gas is converted into a directed

Fig. 2

jet of kinetic energy and this in turn imparts a thrust to the rocket vehicle. The nuclear reactor must therefore be designed as a heat exchanger for hydrogen as shown in Fig. 2 and the rocket vehicle must contain a sufficient supply of propellant hydrogen for the specified mission.

If we now ask how one conventionally stores hydrogen, the answer is of course - in heavy walled steel tanks at high pressure; and when one examines the ratio of the mass of contained hydrogen to the mass of steel tank it turns out that for every pound of hydrogen we require about 100 pounds of steel. Obviously then no nuclear rocket is going to take its propellant along as high pressure gas. The only practical alternative appears to be to carry it in thin walled tanks as a low pressure liquid and this means a fluid storage and transfer system which must

operate at temperatures

of the order of 20°K as shown in Fig. 3. The nuclear rocket program is for this reason therefore deeply committed to a very considerable effort in cryo-engineering.

Fig. 3

Work on the development of a nuclear rocket began at the Los Alamos Scientific Laboratory in 1955. Although the reactor itself is in principle just another power reactor, the requisite specifications were orders of magnitude different from anything that had hitherto been built. For example the power density in a nuclear rocket reactor must be increased by a factor of about 10^3 over that found in conventional power reactors. Operating temperatures must be much higher - of the order of 2500°K . The reactor itself must be able to withstand temperatures from 20°K to 2500°K , and pressures of the order of several hundred psi. It must be capable of being brought up to full power in a matter of seconds. And many additional problems arising from other necessary extensions of current reactor technology had to be solved if a successful reactor of this type was to be developed.

Because of expected difficulties in meeting these requirements it was decided at the beginning of this program that emphasis should be initially placed on the problem of designing, constructing, and testing a high temperature and high power density reactor, postponing for the first tests the low temperature aspects of the problem. It was furthermore recognized that a test facility using ambient temperature hydrogen gas as the propellant fluid could be made operative much quicker than one using liquid hydrogen. During this early period therefore a series of reactor tests using gaseous hydrogen (the so-called Kiwi A nuclear rocket reactor test series) was carried out while a cryogenic test facility was concurrently designed and built.

These Kiwi A tests served to investigate the efficiency of a number of different reactor designs and led eventually to a choice of a reactor design suitable for testing with liquid hydrogen.

During this period several other problems were recognized relating to the operation of a nuclear reactor with liquid hydrogen as the reactor coolant. Because hydrogen is an excellent neutron moderator (due to its low mass) and because the density of liquid hydrogen is about 25 times that of the gas at the operating pressure of the reactor or about 700 times as dense as ambient gas at atmospheric pressure, the reactivity of the reactor will increase markedly should the reactor core ever become filled with liquid hydrogen. It will in fact increase far beyond the reactivity counteracting capability of the control rods. Under these conditions the reactor would go prompt critical and melt or otherwise disassemble itself.

The second problem which is closely related to the first, concerns start-up and shut-down procedures. During both these operations the hydrogen will exist at some point in its flow path at subcritical pressures and temperatures, and two-phase propellant flow becomes possible. High density liquid could then conceivably enter the reactor core and if this did not produce disastrous results immediately, it was expected that it would introduce severe local reactivity fluctuations and magnify the reactor control problem.

Pressure oscillations as high density liquid impinges upon hot channel walls were also recognized as a potential problem, not only in the two-phase flow regime, but also at pressures and temperatures higher than critical since there is no assurance that phase equilibrium will always prevail throughout the flow channels.

For these reasons as well as several others, it was initially believed that the first liquid runs should be carried out with the aid of a mixing chamber designed to permit an all-gas reactor start-up which was already known to be possible and safe. Then by adding liquid to the propellant feed line and thoroughly mixing it in the mixing chamber it appeared possible to insure that the mean pressure at the reactor inlet would exceed the critical pressure before the mean temperature of the hydrogen fell below the critical temperature. One possible sequence of equilibrium states which might be traversed as the liquid flow increased is shown in Fig. 4. In this calculation it was assumed that

the initial state of the inlet fluid was at 300°K and 1 atmosphere. The gas flow rate was then to be increased to some predetermined fixed value while the reactor power was adjusted to yield a chamber

Fig. 4

temperature of the order of 2000°K. During this period the pressure at the reactor inlet will rise to about 6 atmospheres. The gas flow rate was then to be maintained at this value while liquid was added at the mixing chamber causing the mean gas temperature at the reactor inlet to decrease and the pressure to increase while the reactor was simultaneously

being brought up to full power. In this way the two-phase region could be successfully avoided provided thermal phase equilibrium was always produced in the mixing chamber.

There were however a number of individuals concerned with the direction of the project who objected to this procedure. They pointed out that a nuclear rocket reactor eventually had to be capable of an all liquid start-up and shut-down and that if this created insoluble problems, the sooner everyone was aware of them, the better. Fortunately their views prevailed and the mixing chamber, although designed and built, has not yet been used.

On September 1, 1962, the first reactor test using liquid hydrogen was successfully carried out by the Los Alamos Scientific Laboratory. Although there were some problems relating to the mechanical design of the reactor core it was conclusively proved that it is possible to start up, control, and shut down a nuclear reactor using liquid hydrogen as the coolant. Any reactivity fluctuations due to changes in propellant density were found to be either self-compensating or easily controllable. On November 30, 1962, a second reactor was tested also using liquid hydrogen. Again although mechanical design problems persisted, no major problems directly attributable to the use of liquid hydrogen were encountered.

At the present time the Rover program work at the Los Alamos Scientific Laboratory is concentrating upon the remaining mechanical design problems relating to the reactor core. Westinghouse, in connection with its responsibilities as one of the NERVA (Nuclear Engine Reactor Vehicle Application) contractors, is concurrently assisting in this effort. It is anticipated that most of the further development of Kiwi type reactors will be carried on by the NERVA contractors, Aerojet-General Corporation and Westinghouse. The Los Alamos Scientific Laboratory will then concentrate

on the next generation of nuclear rocket reactors, the so-called Phoebus systems. Facilities for testing this new series are already in the design stages.

Having outlined the general chronology, some of the accomplishments and the current objectives of the Rover program, we can now become more specific and inquire about the particular role played by the cryo-engineers in this enterprise. Their job, in its simplest form, consisted of designing, constructing, and operating a flow system capable of delivering a controlled mass flow of liquid hydrogen to the reactor nozzle inlet in order to permit rapid start ups, shut downs, steady state operation and stand-by holds. The system was also to be capable of operating at full flow rate, of the order of a hundred pounds of liquid hydrogen per second at approximately 1200 psi, for some 500 seconds.

The way in which this was done is shown in Fig. 5 which is a schematic diagram

of the propellant flow system in Test

Cell C at the

Nuclear Rocket

Development

Station at Nevada.

Two 50,000 gallon spherical dewars

are connected with

vacuum jacketed

piping to a liquid hydrogen pump (built by Rocketdyne) in such a way

Fig. 5

that both dewars may be emptied together or either one separately. The fluid flow is monitored by two venturi meters, one upstream and the other downstream of the pump. Provision is made for a bypass return line to the dewars from the high pressure side of the pump as well as the return flow loop for checking out the flow system up to the last flow control valve. Once the system is checked out, the return line is disconnected and the reactor hooked up as shown by the heavy solid lines which also designate nonvacuum-jacketed transfer piping. (These are insulated however with glass wool blanket.) An aerial photograph of this test facility is shown in Fig. 6. In Fig. 7 the test reactor Kiwi B4-A is shown at the face of one of the test cells.

Fig. 6

Fig. 7

The cryogenic engineering group at the Los Alamos Scientific Laboratory was responsible jointly with members of the reactor design and testing divisions for the initial planning of the liquid hydrogen flow system, preparing the specifications, reviewing its design with the Architect-Engineer (Air Products & Chemicals, Inc.), reviewing the construction of the facility as it progressed, designing and constructing portions of the low temperature instrumentation, checking out the facility with liquid hydrogen and operating some of the cryogenic subsystems of the facility during reactor tests.

The group is also concerned with the establishment of safety procedures, the calculation of thermal and pressure stresses in the cryogenic piping during cooldown, and related projects such as vibration analyses of facility piping during various types of flow programs. Fundamental investigations of two-phase flow, the measurement of heat transfer coefficients, thermal conductivity and viscosity measurements and calculations for liquid hydrogen in the two-phase as well as the high pressure and low temperature fluid region of the diagram of state have been carried out by the group both at Nevada and at the Los Alamos Scientific Laboratory. Studies have been made of pressure oscillations in the two-phase flow region. Quality meters for liquid hydrogen have been developed. Various types of seals for large diameter high pressure liquid transfer piping have been tested. And the low temperature mechanical properties of many materials used in the reactor or the facility have been determined. In some cases these properties have been measured in the presence of a high radiation flux.

To conclude with a few remarks about the economics of operations such as these, it is of interest to note that the unique nature of the task of testing reactors often leads to highly unconventional solutions for quite conventional problems. This often makes the design unusually difficult because it is frequently required that old and well-known operations be performed in the framework of a completely new set of boundary conditions. One of these is the frequency with which a given operation need be performed before its job is done or outmoded. Another is the relationship of a given requirement to future programmatic requirements. Under such circumstances the capital cost of the installation may become a factor which far outweighs considerations of operating cost, efficiency or maintenance costs. Alternatively, a more costly installation at one stage in the development may more than pay for itself if it serves simultaneously as a prototype for a subsequent but far larger installation based on the same design.

As an example consider the problem of providing a gas supply of say 30 lbs/sec of gaseous hydrogen or the equivalent at 800 psi for 500 sec. Such quantities of gas might be needed for operating the turbine of a liquid hydrogen pump, for example.

Fig. 8

Assume further that a need has also been established for an order of magnitude larger gas supply sometime in the near future. Under these conditions what is the optimum method of satisfying the first mentioned requirement? Some of the solutions which are being examined are a compressed gas supply, gas generators, a regenerator, and a heat exchanger to vaporize liquid hydrogen as shown in Fig. 8.

The total amount of gas needed is approximately 15,000 lbs. or about 3×10^6 standard cubic feet. If high pressure gas storage is used the total amount to be stored must be about 4×10^6 SCF since only the contents of each cylinder in excess of about 1000 psi can be utilized. Of the several methods shown in Fig. 8 the first (tank farm storage) is the least expensive and the most reliable, particularly since about half of the required storage already exists installed at the test cell and it has already been used successfully. About 11 pressure vessels will be required, each one of which is capable of storing about 375,000 SCF. A very crude estimate of the cost of six additional tanks installed is about \$600,000. To increase this gas storage by an order of magnitude however scarcely seems feasible. Not only would a tank farm of 120 such vessels cost of the order of $\$12 \times 10^6$ but it would be quite unmanageable practically and would provide no useful information toward the solution of a problem which must ultimately be solved if the nuclear rocket is ever to get off the ground. This is neither the time nor the place to develop the pros and cons of the various other methods shown. They are all being studied at the present time and the final decision when finally made will presumably be based upon minimization of the overall cost once all the necessary parameters have been identified and properly weighted.

In summary, the role of the cryo-engineering in that portion of the nuclear rocket program which has come under the cognizance of the Los Alamos Scientific Laboratory will continue to be a major one. And as the NERVA, RIFT, and other follow-on programs move into high gear, this involvement is certain to increase and increase and increase.

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