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Cryogenic Technology in the Nuclear Rocket Program*

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Since several different methods of utilizing nuclear energy for space vehicle propulsion are currently under investigation, it is important at the outset to state that the particular nuclear rocket program which will be discussed in this paper is the so-called Project Rover. This undertaking is being conducted jointly by two United States government agencies, the Atomic Energy Commission and the National Aeronautics and Space Administration. The objective of the program is to develop a satisfactory upper stage rocket powered by a nuclear reactor. The Los Alamos Scientific Laboratory has been assigned responsibility for the development of the nuclear reactor. When the development of the reactor is completed it will be incorporated into a suitable rocket engine system by the Aerojet General Corporation and the Westinghouse Electric Corporation. Following that, Lockheed Missiles & Space Co. will incorporate the engine system into a suitable upper stage vehicle.

The test reactors under development at the Los Alamos Scientific Laboratory have been called Kiwi reactors, not only because of their relationship (operational) to the New Zealand bird which does not fly, but also because, for reasons of convenience, the reactors to date have all been tested upside down, and hence cannot fly. In principle a Kiwi

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reactor and the operation thereof is quite simple. The device consists of a high power density nuclear heat exchanger reactor in which energy generated by fission is imparted to a suitable propellant passing through the reactor core. The heated propellant then exhausts through a de Laval type nozzle by means of which its thermal energy is converted into kinetic energy, and a thrust is imparted to the rocket system in the usual manner. A schematic diagram of such a system is shown in Fig. 1.

Since the specific impulse obtainable from a nuclear rocket system is inversely proportional to the square root of the molecular weight of the exhaust gas, hydrogen is by far the most efficient of the various propellants available. For roughly comparable conditions of chamber temperature and pressure the specific impulse of a nuclear rocket using hydrogen as the propellant can be shown to be approximately twice that obtainable from one using any of the high energy chemical fuels presently available. As a result of this increase in specific impulse it can also be shown that, for a given mission (for example, earth escape), it will be possible to increase the payload by a factor of at least four when nuclear propulsion systems become available.

In Fig. 2 a slightly more detailed schematic diagram of one of the reactors currently under development is shown. The reactor core consists of a uranium-graphite matrix. The hydrogen propellant enters the regeneratively cooled nozzle at about 20°K and exhausts from the reactor core at a temperature of the order of a few thousand degrees Kelvin. To date the development problems have resulted primarily from the stringent operational requirements of designing a reactor in which the following

reactor parameters a) core temperature, b) rapid start-up capability, c) ability to withstand extreme temperature gradients, and d) minimum weight are all optimized.

In order to make significant progress in the development of a satisfactory high power density nuclear reactor required for this application, full scale tests have been required to check advances in reactor design. These tests have been carried out at the Nuclear Rocket Development Station in Nevada. The overall facility contains several so-called test cells, some of them operational and others still under construction. Test Cell A, in which all of the tests to date have been performed, is shown in Fig. 3. In Fig. 4 a reactor is shown being installed in its test position at the face of the test cell. During an actual test, shown in Fig. 5, about a thousand data channels transmit to the control station information relating to core and propellant temperatures and pressures, propellant flow, reactor power, vibration, radiation, etc. This information is subsequently analyzed to provide new design criteria. In addition to full scale reactor tests at Nevada, fundamental studies relating to the reactor operation as well as extensive component testing programs are being carried out simultaneously at the Los Alamos Scientific Laboratory in New Mexico and at National Aeronautics and Space Administration laboratories in order to provide additional technical support for the Rover program.

Prior to September 1, 1962, there had been much concern about possible disastrous consequences if, during the start up of the reactor, liquid hydrogen should happen to enter the reactor core in appreciable amounts.

If this should occur, the resultant increase in reactivity caused by the excellent neutron moderating property of high density hydrogen could be expected to cause an uncontrollable reactor power excursion. This in turn might either melt the reactor or otherwise damage it. It was therefore decided to attempt to program the start up in such a way as to increase the reactor power simultaneously with the flow rate in such a way as to prevent two-phase hydrogen from entering the reactor core. This was to be accomplished by adjusting the heat input into the propellant as it progressed sequentially through the various portions of the reactor shown in Fig. 2 (i.e., the nozzle and the neutron reflector) such that the hydrogen entering the reactor core was always maintained well above its critical temperature (33°K) during the period that the core inlet pressure was less than the critical pressure of hydrogen (12.9 atm). Given the necessary transport properties and heat transfer data for fluid hydrogen a complicated but straightforward set of hydrodynamic and heat transfer equations were developed to produce the necessary start-up program for the reactor. There were many uncertainties, however, and of these the most troublesome was the possibility of liquid entrainment by the gas stream and the possibility that thermal equilibrium would not be maintained as the propellant passed through the various passages in the nozzle and reactor.

In order to obtain some information on the validity of these assumptions prior to full scale testing of a reactor, a typical reflector flow passage was constructed and installed in a suitable

liquid hydrogen test flow system capable of simulating start-up conditions in the reactor itself. Both wall and fluid temperatures were recorded during typical reactor start-up programs and compared with the corresponding theoretical information produced by the calculation. These results are being published¹ but since this information is not yet generally available, it is appropriate to note at this time that, in general, good agreement between the calculation and the experiment was obtained only after the fluid had progressed a considerable distance along the flow passage. While the initial transient flow conditions obtained, whenever and wherever the state of the fluid corresponded to either two phase or near critical, very poor agreement between the experimental and the calculated behavior was observed. In view of the inadequate experimental or theoretical transport property data available for this region of the state diagram, it was not possible at that time to determine how much of the disagreement was attributable to the use of erroneous values for the transport properties in the calculation and how much was attributable to the failure to obtain thermodynamic equilibrium in the flow passages. Experiments are currently underway to investigate in more detail the pressure drop and heat transfer phenomena occurring under transient conditions, such as will be experienced in nuclear reactor start ups.

In order to obtain information on the degree to which thermal equilibrium is achieved in the propellant as it progresses along its flow path, a density gauge has also been developed in which the sensing element is a capacitor located in the flow channel. Since the densities

of liquid and cold gaseous hydrogen differ considerably, any variation of the density of the fluid flowing between the plates of the capacitor will correspond, according to the Clausius-Mossotti relation, to a change in the dielectric constant and hence the capacitance of the condenser. If this capacitance is made part of a resonant LC circuit, density changes can then be easily detected by measuring the resulting frequency shift. After preliminary tests several of these gauges were installed in the flow passage immediately upstream of the reactor core inlet in a recent cold-flow* run in Nevada in order to determine the extent to which the attainment of thermal equilibrium produced single phase uniform density hydrogen by the time the propellant reached the reactor core inlet.

Some typical results are shown in Fig. 6. It should be noted that marked fluctuations in the density of the fluid entering the reactor core began when the mean temperature of this fluid was as high as 200°K. Thermodynamic equilibrium obviously was not achieved as the propellant was forced through the warm nozzle and reflector passages despite expectations to the contrary. These expectations were based upon the fact that the design of the flow passages was such that a well-developed turbulence should have been produced in the fluid stream over most of its path.

For unavoidable reasons these data were not available at the time the first hot reactor was ready to be tested using liquid hydrogen. Since other, but far less specific, data did indicate that such a test was feasible, two reactors were actually tested before the information shown in Fig. 6 became available. Although other problems related to the mechanical

* Several cold-flow runs have been performed using unloaded, i.e. no U^{235} in the core, reactors to investigate transient start-up conditions.

design of the reactor were uncovered in these hot runs, it was quite conclusively proved on September 1, 1962, that it is possible to start up a reactor on liquid hydrogen. It thus appears that any reactivity fluctuations due to changes in propellant density are either self-compensating or at least easily controllable. Alternatively, it may be that in a hot run thermodynamic equilibrium is more nearly achieved and that the density of the fluid entering the core is indeed quite uniform. In future reactor tests these questions will be exhaustively investigated. Simultaneously, fundamental studies relating to two-phase flow and heat transfer into two-phase fluids under nonequilibrium conditions are being undertaken with considerable interest.

Of the many cryogenic engineering problems which have arisen in the Rover program thus far, the one described above is but an example. Many other difficult ones relating to the design, construction, and operation of the facility have been met and resolved — at least sufficiently to carry out reactor tests. As the development progresses more will be encountered and hopefully solved as successfully.

Acknowledgement

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References

1. G. P. Watts, A. R. Lyle, and J. D. Balcomb, Proceedings, Nuclear Propulsion Conference, Monterey, California (1962).

Figure Captions

- Fig. 1 Nuclear Rocket Propulsion System
- Fig. 2 Schematic Diagram of a Kiwi Reactor
- Fig. 3 Test Cell A from rear, showing liquid hydrogen dewars, piping, and maintenance; assembly and disassembly building in the background.
- Fig. 4 Kiwi B4-A at the face of Test Cell A being readied for testing
- Fig. 5 Kiwi B1-B Reactor Test at NRDS September 1, 1962, using liquid hydrogen as the propellant
- Fig. 6 The relative density, flow rate, temperature and pressure of the propellant vs time just before entering the reactor core during a cold-flow reactor test.

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