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ROCKET ENGINE OPERATIONS - NUCLEAR

REPORT NO. RN-S-0035

NUCLEAR ROCKET ENGINE CYCLE SELECTION (U)

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ABSTRACT

This report is a reprint of a paper prepared by Mr. D. F. Vanica for the Nuclear Propulsion Conference, August 15-17, 1962 at Monterey, California. Acknowledgement is made to the United States Air Force, who supported the work which made this paper possible, under Contract AF 04(616)-6028 for the period June 1960 to June 1961.

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INTRODUCTION

The conversion of a solid-core, heat-exchanger type of nuclear reactor into a thrust-producing rocket engine depends principally on the provision of a system to supply the reactor with coolant or working fluid and a nozzle for extracting the energy from the heated fluid. Aside from the reactor, the major subsystem in the nuclear rocket engine is the propellant feed system. It is defined as that system which transports working fluid from the propellant tank to the reactor, as well as providing the coolant for the reactor pressure vessel, nozzle, and other areas requiring cooling. The propellant-feed system may also supply the working fluid for the engine roll-control system and the reactor-shutdown cooling system.

The design of the propellant-feed system and the integration of this system with the reactor to form the nuclear rocket engine is a major engineering task. The design of the propellant feed system is critical since this system determines the performance of the engine, overall engine configuration, major subsystem configurations, and many individual component specifications. In addition, the type of propellant-feed system employed determines the reliability to be expected and the cost and time required for development.

The fundamental task to be accomplished in the design of the propellant-feed system is to determine the manner in which the energy required to move the propellant from the tank to the reactor is provided - whether from an external source or from the reactor itself - and, if from the reactor, in what manner the reactor supplies this energy.

Extensive engineering design and analysis have shown that there are several approaches to the design of the propellant feed system. These approaches fall into two basic classes, direct tank pressurization, and pumped cycles. All are feasible, all can be developed, and each has advantages and disadvantages. The following pages describe the various propellant feed systems and briefly discuss how their design relates to engine performance, reliability, and relative cost for development. The performance data presented are for the case of an upper-stage nuclear rocket engine based on an upgraded Kiwi-B type of reactor.

These data can be considered as representative for both upper-stage and booster engines. Extrapolation of these performance values to booster engines would, of course, require correction for a smaller-area-ratio nozzle and for sea-level conditions.

ENGINE CYCLES

Gas-Pressurized Cycle

In addition to the reactor, the gas-pressurized cycle consists simply of a gas-pressurization system for expelling the liquid hydrogen from the propellant tank through the flow-control system to the reactor, as shown in Figure 1. The principal advantage of the gas-pressurized cycle is its extreme simplicity and inherent reliability. Since no propellant need be extracted from the propellant flow system, engine specific impulse is the same as reactor-thrust-chamber performance and is the maximum that can be achieved for any reactor exit-gas temperature and pressure. Table 1 presents the pertinent performance data for the gas-pressurized cycle for a 70,000-lb-thrust engine.

Solid-core, heat-exchanger nuclear reactors for nuclear rocket engines are generally designed to operate at relatively high pressures. This permits the use of as small a reactor core and void fraction as possible. Operating pressures range upward from 500 psia. In turn, this requires the propellant to be supplied from the tank at approximately 800 psia to overcome system pressure drops, and to provide the propellant to the reactor and nozzle at the proper pressure and mass flow rate. The propellant tank must be thick-walled to contain the pressure and, consequently, is very heavy. For space-travel applications where the thrust-to-weight ratio is less critical, the gas pressurized cycle affords an excellent choice for the nuclear rocket engine. In most applications, however, the weight of such a tank would limit, if not eliminate, the use of a nuclear rocket engine based on the gas pressurized cycle.

Chemical Gas-Generator Cycle

The weight of the thick-walled, pressure-vessel propellant tank is overcome in the gas-generator cycle, and in the other pumped cycles that follow, using

a turbopump to deliver the propellant at the desired pressure and mass flow rate. Thus, the tank need only be strong enough to contain the mass of propellant, the inlet pressure required by the pump, and any additional loads imposed by flight. Very light tanks can be employed. This cycle, shown in Figure 2, is unique in that the energy for driving the turbopump is supplied by a chemical gas generator operating on liquid oxygen and liquid hydrogen. The propellant flows from the tank through the pump, into the nozzle and reactor moderator cooling passages, through the main core, and is then exhausted through the nozzle.

Since the chemical gas generator serves as an independent power source for the turbopump, no special design features of the reactor are required. The performance of this cycle as a 70,000-lb-thrust engine is summarized in Table 1, where it is shown to yield 93 per cent of the thrust-chamber specific impulse.

The use of a separate chemical gas generator to drive the turbopump adds a third, independent control system which must be integrated into the overall engine control system. In addition, since liquid oxygen as well as liquid hydrogen must be supplied to the gas generator, the engine design becomes further complicated by the necessity of carrying either a pressure vessel for the storage of liquid oxygen or an auxiliary pump drive to supply gas-generator propellant. In either case, extra weight is added to the engine. The number of components increases and the engine design becomes more complicated. This adversely affects reliability or increases the cost required to attain the same degree of reliability.

The development of the chemical gas-generator cycle would be complicated by the necessity to develop and demonstrate the reliability of the gas-generator system. The cost for engine development would be correspondingly higher. In addition, it does not inherently provide for the future flexibility in mission endurance which other systems can provide.

The performance potential of this cycle can be achieved by a considerably less complicated and potentially more reliable cycle, to be described later. Therefore, this cycle does not appear to be a logical choice for the nuclear rocket engine.

Topping Cycle

The topping cycle shown schematically in Figure 3 is characterized by a series flow of the propellant through the major components of the engine. All of the propellant contained in the tank flows through the pump, through the coolant passages of the nozzle and the reactor reflector, and into the low-pressure-ratio turbine. From the turbine the entire propellant flow is ducted into the reactor core where it is exhausted through the nozzle at the maximum specific impulse, thus yielding the optimum engine performance for any given reactor exit temperature. The performance of the topping cycle as applied to a 70,000-lb-thrust engine is summarized in Table 1.

Thermodynamic analyses have shown that, when utilizing the total propellant flow for the turbine working fluid, the required pumping horsepower can be obtained at turbine inlet temperatures in the region of 300 to 800°R at turbine pressure ratios ranging from 1.2 to 1.8. The exact pressure ratio depends upon the turbine inlet temperature. The energy extracted by the propellant in cooling the nozzle and reactor reflector, however, is insufficient to raise the propellant to the desired turbine inlet temperature. Consequently, additional energy must be extracted from the reactor to supply the necessary horsepower. This additional energy can be conveniently obtained by loading the reactor reflector with additional fissionable material to generate energy in this region. This addition can be made without unduly affecting either control of the reactor or the radial power distribution. Approximately 6 per cent of the core power would be extracted in this region.

Since all of the propellant leaving the tank passes through the entire engine-reactor cycle and is exhausted through the nozzle at reactor exit temperature, the topping cycle permits the construction of an engine that yields the maximum specific impulse that can be obtained from any reactor. In addition, since the engine performance (I_{sp}) of the topping cycle is not degraded by pumping-system turbine-bleed requirements, performance is independent of turbine and pump efficiencies. The topping cycle possesses additional very desirable advantages over other cycles powered by high-gas temperature turbines:

[REDACTED]

1. The low operating temperature for the cycle permits the use of a light alloy such as aluminum for the turbine housing, rotor, ducting, and power-control (bypass) valve, thereby reducing weight to a minimum. The light weight, and consequently low metal density, greatly alleviate radiation heating and thus permit greater latitude in turbopump placement with respect to the reactor. The susceptibility of aluminum to neutron damage and irradiation is minor.

2. Because of the low operating temperature of the turbine, the thermal gradient along the common impeller shaft is relatively small, thus minimizing the thermal stresses imposed on the assembly. By the same token, the radial stresses in the turbine rotor are kept small. The near-ambient operating temperature of the turbine avoids the usual problems caused by thermal expansion of the turbine components. The ability to operate at low pressure ratio simplifies turbine design. A single-stage turbine will suffice to drive the pump to supply system pressures in the range from 800 to 1000 psi.

3. The topping cycle derives most of its operating energy from an auxiliary, nuclear heat exchanger located within the reactor pressure shell. Since the source of thermal neutrons to activate this heat exchanger is the main reactor core, the auxiliary heater produces power in a direct ratio to the power produced by the main core. The net effect of change in the auxiliary-heater power output is to vary turbine-inlet temperature and, consequently, turbine horsepower output is directly controlled by the main reactor control system. Thus, the minimum control devices suffice for cycle operation. Because of the simplicity of the design, the topping cycle possesses a basically high reliability.

4. Thermodynamic analyses, (Reference 1)* which have been confirmed experimentally, have shown that there is sufficient energy in the engine metal components at ambient conditions to permit a "bootstrap" starting procedure for the cycle. Thus, there is no requirement for auxiliary equipment to rotate the turbopump to start engine operation.

The combination of high performance and high potential operational reliability, makes the topping cycle the ultimate choice for the nuclear rocket.

* List of references preceeds Table 1.

Utilization of the topping cycle requires special design features to be incorporated in the nuclear reactor. These design features are, principally, the inclusion of an auxiliary heater (i.e., heat exchanger tube banks) within the reactor pressure vessel and a reactor designed to account for the pressure difference which would exist between the auxiliary heater and the main core. The present design for the Kiwi-type reactors under development does not accommodate these features. The utilization of the topping cycle therefore would require an extension in the state of the art for nuclear rocket reactors.

BLEED CYCLES

The bleed cycles are so called because pumping horsepower for the cycle is obtained by bleeding off a portion of the hydrogen propellant flow and utilizing it as the turbine working fluid. This fluid is then ducted overboard through a nozzle (or nozzles) for thrust recovery and for providing vehicle directional and/or roll control. There are a number of variations in the bleed-cycle concept, each of which differs in the manner and position within the propellant flow path which the turbine working fluid is extracted. These differences also extend to the differences in temperature and, consequently, the mass flow rate at which the turbine working fluid is obtained. Since the turbine bleed flow cannot normally be returned to the reactor and must be dumped overboard, the various bleed cycles also yield engine specific impulses less than the basic nozzle expansion specific impulse; the amount being roughly proportional to the turbine flow requirements. The three variations in the bleed-cycle concept which appear most promising for nuclear rocket engines are the hot bleed cycle, the cold bleed cycle, and the heated bleed cycle. Each of these cycles will be discussed individually.

Hot Bleed Cycle

The classical hot bleed cycle, shown schematically in Figure 4 obtains the turbine working fluid by extracting a small flow of hydrogen from the plenum just below the reactor-core exit (the entrance section to the nozzle). This gas flow is in the range of 4000 to 5000°R. The bleed flow is cooled to 1760°R either in a secondary heat exchanger or by the addition of liquid

hydrogen. In the latter case, the bleed flow plus cold diluent constitutes the turbine working fluid. The working fluid is ducted to the turbine, then exhausted overboard through a nozzle system.

The working fluid for the hot bleed system is at high temperature and high pressure and requires the use of a high-pressure-ratio turbine for the pump drive. Because of its low molecular weight, hot hydrogen when expanded through high pressure ratios achieves very high translational velocities. Therefore, in order to stay within permissible tip speeds, several turbine stages are required to efficiently extract the energy from the gas. For hydrogen at 1760°R and a turbine pressure ratio of 10, a multi-stage axial-flow turbine would require a flow rate of 5 to 6 per cent of the total flow to provide the necessary pump horsepower for an 800 psi pump discharge pressure. This loss of flow from the reactor, when the residual thrust recovery of the exhausted working fluid is accounted for, results in a decrease of overall engine specific impulse of approximately 2 to 3 per cent from that obtained from the topping cycle. The relative performance for a 70,000-lb-thrust engine is shown in Table 1.

The turbine horsepower is controlled by regulating the mass flow rate of the turbine working fluid. The regulation is achieved by placing a hot-gas throttling valve upstream of the turbine inlet. In addition, a means of controlling the temperature of turbine working fluid is necessary to prevent exceeding the material temperature limitations of the turbine assembly. Aside from these complications, the major subsystems for the hot-gas bleed are essentially the same as for the topping cycle.

Dynamic analyses (Reference 2) conducted on the analog computer, covering both steady-state and off-design operation of the bleed-cycle nuclear rocket, have shown that control of the engine presents no appreciable problem. The extent to which control can be achieved (i.e., variation in thrust and the complications involved therein) depends primarily on the operating characteristics of the hydrogen pump employed.

While the use of a high temperature for the turbine working fluid necessitates only a small gas-flow rate, the turbine must be constructed of relatively dense, high-strength steels. These materials have approximately twice the heating rate of aluminum when subject to nuclear radiation.

Because of its high performance potential, the hot bleed cycle represents a good choice for the nuclear rocket engine. The difficulty with the hot bleed system lies in the necessity to penetrate the nozzle and/or pressure vessel and extract high temperature hydrogen gas, to be cooled, to drive the turbine. Another area of development is the size and placement of the diluent orifices. Experience has also shown that the turbine bleed duct must be cooled to prevent burnouts. The design of the hot bleed mechanism is critical in that failure of the system causes cessation of propellant flow and eventual loss of the reactor.

Cold Bleed Cycle

In contrast to the hot bleed cycle, the cold bleed cycle shown schematically in Figure 5 extracts turbine working fluid from a region of relatively low temperature in the engine propellant flow loop. Cold hydrogen is bled through the shield from the reactor-core inlet plenum and ducted directly to the turbine inlet. After expansion through the turbine, the working fluid is then exhausted overboard for thrust recovery and roll control. For the Kiwi-type reactor, the hydrogen-gas turbine-inlet temperature would be in the range of 200 to 300°R.

The performance of the cold bleed cycle depends on the amount of fluid for turbine drive extracted from the propellant flow system which is, in turn, governed by the number of stages employed in the turbine drive. At these low temperatures, a four-stage turbine with a 10:1 pressure ratio is satisfactory. Approximately 15 per cent of the pumped flow rate will produce the necessary pump horsepower for 800 psia pump discharge pressure. The net performance of this cycle is shown in Table 1.

Turbine horsepower is controlled by the simple means of placing a low-temperature throttle valve upstream of the turbine inlet. Thus, a very simple flow-control system can be utilized. Because of the low cycle-temperature and extremely simple control system, the cold bleed cycle possesses most of the operational advantages and the reliability potential of the topping cycle.

Despite the advantages of the low cycle-operating-temperature, the low turbine inlet temperature has one disadvantage. The weight flow rate for

turbine working fluid is relatively high, thus decreasing the engine specific impulse. It has been previously stated that a four-stage turbine may be used to minimize the bleed-flow requirements, and thus optimize the performance for the cycle. The requirement for a multi-stage turbine, however, does not complicate turbine design, since the low operating temperature permits the use of lightweight materials for the turbine rotor. Materials such as aluminum permit the rotors to be overhung on the shaft.

The performance potential of this cycle can be greatly increased without compromising reliability by another form of the bleed cycle described below. Therefore, this cycle does not appear to be a logical choice for the nuclear rocket engine.

Heated-Bleed Cycle

The heated-bleed cycle shown in Figure 6 is a variant of the cold bleed cycle. Although the turbine working fluid is extracted from the same position at the same temperature in the propellant flow loop as in the cold bleed cycle, the hydrogen is routed to the nozzle, where it is used to cool the expansion skirt before it is ducted to the turbine inlet. By this process, the temperature (and consequently the energy) of the turbine-drive hydrogen is increased. The performance of this cycle as applied to a 70,000 lb thrust engine is summarized in Table 1.

Heating the turbine-drive fluid by passing it through tubes in the nozzle expansion skirt increases the performance potential of the basic cold bleed cycle, with a minimum effect on reliability. The performance gains achieved become strictly a function of the area of the nozzle expansion skirt to be cooled. For example, if the coolant is ducted to the nozzle skirt at an area ratio of 4 and cooled to the exit at an area ratio of 40, the turbine gas is heated to about 1100°R before entering the turbine. At this temperature, only 6 to 8 per cent of the total hydrogen flow is required to yield pump horsepower for 800 psia discharge pressure; this is a significant decrease over the cold-bleed cycle, turbine-bleed flow rate.

The heated-bleed cycle may be considered a modified cold bleed cycle. With the exception of the cooled nozzle skirt and the propellant ducting

required, the heated-bleed cycle possesses the same advantages of simplicity and potential reliability as the cold bleed cycle. In most cases, identical hardware may be employed.

The heated-bleed cycle yields a 70,000 lb thrust nuclear engine with an overall specific impulse of only about 4 per cent less than the topping cycle, and within 98 per cent of the hot bleed engine. By utilizing the nozzle skirt as a heat exchanger for heating the turbine working fluid, the problems of heat-transfer in this engine are considerably less than for the hot bleed. The fundamental principle on which this cycle is based, that is, extracting a cold gas and heating it, has less of a malfunction potential than the hot bleed. A failure of the expansion cone of the nozzle serving as the cycle heater could result in loss of turbine working fluid and, consequently, loss of the reactor. The probability of this occurring because of structural failure or heat transfer is remote.

The development testing of the heated-bleed cycle is complicated because of the requirement that there be full flow in the nozzle skirt to achieve proper heat transfer rates. All ground testing will require a duct aspirator to simulate altitude firing conditions. The necessity to test under altitude conditions is not as complicated or costly as it may first appear. One possibility of testing exists if an aspirator is not available. This can be accomplished by the use of a special low altitude cylindrical nozzle skirt designed to simulate the heat transfer but to exhaust to sea level conditions. A special skirt would involve its own development problems, but would maintain engine development progress if an aspirator were not available.

The heated-bleed cycle is also an excellent choice for the upper-stage nuclear rocket engine. The growth potential of this cycle is limited by the maximum turbine operating temperature because of the heat transfer limitations in the nozzle skirt. However, by loading the reflector or incorporating an auxiliary heater in the turbine inlet duct, any desired turbine inlet temperature may be attained.

CYCLE RECOMMENDATIONS

Development of the nuclear rocket engine presents technical tasks not heretofore encountered with chemical rockets. Because the presence of the

nuclear reactor could constitute a hazard if a vehicle malfunctioned and came to earth in other than designated areas, a nuclear rocket must complete its development phase and reach operational status with an unprecedented high total system reliability. Therefore, high reliability must be the governing factor in the selection of any design concept for the engine, with high performance a desirable but secondary goal.

It has been shown that the cycle selected for a nuclear rocket potentially affects the reliability to be expected from the engine. All of the cycles previously discussed can be developed into an operational nuclear rocket engine. There are, however, differences in time and cost required to reach the same state of reliability. These differences are implicit in the nature and complexity of the cycle design and the consequences to the engine if parts of the engine system fail.

The topping cycle, the cold-bleed cycle, the heated-bleed cycle, and the hot-bleed cycle offer the best chance of providing a nuclear rocket engine of high reliability and good performance. Of these, the topping cycle, because of its simplicity, low turbine and manifold operating temperatures, and maximum performance, is the best cycle and represents the ultimate choice for the construction of an operational nuclear rocket. Only with this cycle can high reliability and maximum performance be achieved simultaneously - an unusual combination for mechanical devices.

The selection of the topping cycle, however, must be tempered with practical considerations. The calendar time at which engine development begins, the size of the engine, and the current state-of-the-art in the development of the nuclear rocket reactor all affect the selection. For example, the current development of the nuclear rocket reactor by the AEC at the Los Alamos Scientific Laboratory is proceeding through the Kiwi-B series of reactors and the extrapolation of this series to the Phoebus concept. Each of these reactor experiments represents a definite extension in reactor technology and the program is following a logical route to nuclear rocket engine advancement. Unfortunately, the Kiwi-B reactor series cannot accommodate the topping cycle because these reactors do not have auxiliary heaters in the design. The design could be modified, however,

at the expense of development time and additional funding. Therefore, to become operational during this decade, nuclear rocket engines utilizing the Kiwi-B series of reactors will have to employ either the hot or heated bleed cycle; the final selection depending on the result of heat transfer and hot bleed port studies conducted in support of the NERVA program.

CONCLUSIONS

The foregoing discussion leads to the following conclusions and recommendations for selection of nuclear rocket engine cycles:

1. For upper-stage nuclear rocket engines from 50,000 to 100,000 lb thrust to be operational during this decade, either the hot-bleed or the heated-bleed cycle is recommended.
2. For upper-stage engines of 100,000 to 180,000 lb thrust employing the Phoebus reactor, the topping cycle is recommended if the reactor design can be modified early enough. Otherwise, the reactor will not accommodate the topping cycle, and the hot-bleed cycle or the heated-bleed cycle would be employed.
3. For upper-stage engines of greater than 200,000 lb thrust and for all booster engines where in each case new reactor development is required, the topping cycle is the unqualified choice for the engine cycle.

REFERENCES

1. "Dynamics of Topping Turbine," NASA Contract NASw-48, Aerojet-General Corporation Report 0307-01, Confidential.
2. J. H. Beveridge and D. F. Vanica, "Off-Design Operation of a Pump-Fed Nuclear Rocket Propulsion System," SAE Preprint, No. 422-C, 1961.

TABLE 1
PERFORMANCE SUMMARY, 70,000 LB THRUST NUCLEAR ENGINE

Propellant Feed System Cycle	Gas Pressurized	Chemical Gas Generator	Topping	Hot Bleed	Cold Bleed	Heated Bleed
Reactor Power, mw	1500	1500	1500	1500	1500	1500
Chamber Weight Flow Rate, lb/sec	83	83	83	83	83	83
Nozzle Expansion Ratio	40:1 *	40:1 *	40:1*	40:1 *	40:1 *	40:1
Nozzle Efficiency	0.97	0.97	0.97	0.97	0.97	0.97
Stagnation Temperature, °R	4500	4500	4500	4500	4500	4500
Chamber Specific Impulse, sec	833	833	833	833	833	833
Turbine Weight Flow Rate, lb/sec	NA	8.5	83 **	4.2	16	5.7
Turbine Exhaust Specific Impulse, sec	NA	275	NA	431	152	327
Turbine Exhaust Thrust, lb	NA	2340	NA	1810	2440	1860
Overall Engine Specific Impulse, sec	833	778	833	812	720	800
Chamber Pressure, psia	680	680	680	680	680	680
Turbine Inlet Temperature, °R	NA	1760	300 - 600 +	1760	275	1100

* Thermal Radiation Cooled 9:1 - 40:1

** Includes Turbine Control Bypass, Turbine Exhausts to Core Inlet Plenum

+ Gas Temperature Leaving Reflector

Table 1

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Figure 1

Gas-Pressurized Cycle

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Figure 2

Chemical Gas-Generator System

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Figure 3

Topping Cycle

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Figure 4

Hot Bleed Cycle

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Figure 5

Cold Bleed Cycle

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Figure 6

Heated Bleed Cycle

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