Operational Characteristics of Nuclear Rockets

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The start-up, full-power operation, and shutdown (including afterheat removal from the nuclear reactor) stages of operation of the Nuclear Engine for Rocket Vehicle Application (NERVA) have been demonstrated in the technology program. Start-up is initiated by opening the valve that isolates the engine from the liquid-hydrogen run tank. Two engine systems with unfueled nuclear reactors have been used to investigate this portion of engine operation. A bootstrap technique has been developed that does not depend on auxiliary starting equipment. With the addition of a fueled reactor, as in NRX/EST or XE-P, the energy from the reactor is used to sustain operation or increase to full power. Operation at rated conditions can be sustained for long periods: NRX-A6 has demonstrated a reactor life of 1 hr. Throttling capability allows operation between 60% and 100% thrust at full specific impulse. After shutdown, a period of several days is needed to remove the delayed energy (radioactive decay) from the nuclear reactor by intermittently pulsing propellant through the reactor.

Introduction

THE operational cycles for nuclear rockets differ from those for chemical rockets, in that start-up requires minutes, full-power operation approaches an hour, and shutdown (including the afterheat removal from the nuclear reactor) takes days. This paper presents some of the details of operation and performance of the nuclear technology engine, the Experimental Engine Prototype (XE-P) of the NERVA flight engine system. Test data from the Nuclear Reactor Experiment/Engine System Test (NRX/EST), Cold Flow Development Test System (CFDTS), and Experimental Engine Cold Flow Test (XE-CF) have been used to verify and improve analysis.

Early test configurations of the engine were upward firing systems, but those discussed herein are downward firing systems that closely resemble a flight configuration (Figs. 1 and 2). The propellant feed system comprises a single-stage, radial-exit-flow, centrifugal pump with an aluminum impeller and housing, a power transmission section that couples the pump to the turbine, and a two-stage turbine with stainless-steel rotors. The reactor assembly comprises the reactor core with graphite fuel elements and beryllium reflector. The regeneratively cooled nozzle has a 10:1 expansion ratio, a convergent half-angle of 45°, and a divergent half-angle of 17.5°. Its tubes are formed by brazing stainless-steel U-section channels to a jacket. A hot-bleed port in the convergent section is used to extract turbine drive gas.

The pressure vessel supports components of the reactor assembly to form a pressure shell that contains the hydrogen propellant, and it transmits thrust to the lower thrust structure. The latter is a conical, semimonocoque, titanium structure which transmits thrust, moments, and loads of the pressure vessel to the external shield. The external shield attenuates radiation for nonradiation hardened components and transmits static and thrust loads from lower to upper thrust structures. It is made of an aluminum structure filled with stainless-steel balls and borated water. The upper thrust structure transmits thrust and moments of the test-stand adapter and is a cylindrical, semimonocoque, aluminum structure. A pneumatic actuation system operates the control drum actuators, engine valve, and the remote-assembly drive motors.

At normal operating conditions with the reactor operating at a power level of approximately 1126 Mw, the XE-P engine developes a thrust of 55,620 lb with chamber conditions of 560 psia and 4090°R, a nozzle chamber flow rate of 70 lb/sec, a total engine flow rate of 78 lb/sec, and an overall engine specific impulse (I_{sp}) of 715 sec at an ambient pressure of 1.25 psia. Figure 2 indicates some of the conditions at full power. The hydrogen fluid leaves the tank at 35 psia and 38°R. The turbopump increases the pressure to 994 psia, and 0.6 lb/sec of the flow goes from the pump to the turbine to cool the turbopump bearings. The fluid proceeds through the pump discharge line to the nozzle torus and is then used to cool the nozzle wall. It leaves the nozzle at 748 psia and 141°R and passes through the reflector and to the dome of the pressure-vessel closure. The heat pickup in the reflector increases the temperature to 233°R. At the dome, 5.55 lb/sec of the fluid is extracted to be used for the turbine drive. The rest of the fluid proceeds through the dummy shield (representing the radiation shield of a flight engine) and through the reactor core to be heated to 4090°R. The 70 lb/sec of fluid that leaves the nozzle is at 560 psia and 4090°R. Fluid is extracted from the convergent part of the nozzle through the hot-bleed port to help drive the turbine. The fluid, consisting of 1.7 lb/sec at 4090°R, is combined with the 5.55 lb/sec fluid from the diluent extraction to provide the turbine drive fluid, which flows at 424 psia and 1191°R and is controlled by the turbine power control valve. The gas, after passing through the turbine, is combined with the fluid to cool the turbopump bearings and is discharged through two turbine exhaust lines.

The XE-P engine control system (ECS) provides for safe and stable startup, steady-state operation, and shutdown within the engine operating constraints. It generates predetermined demand signals as required for the initial operation and termination of tests. A rather detailed block diagram was published in Ref. 1. The feedback control loops consist of engine control sensors, signal-conditioning amplifiers, transmission lines, compensation amplifiers, and logic functions.[1] The major loops control drum position, power, temperature, turbine-power-control-valve (TPCV) position,

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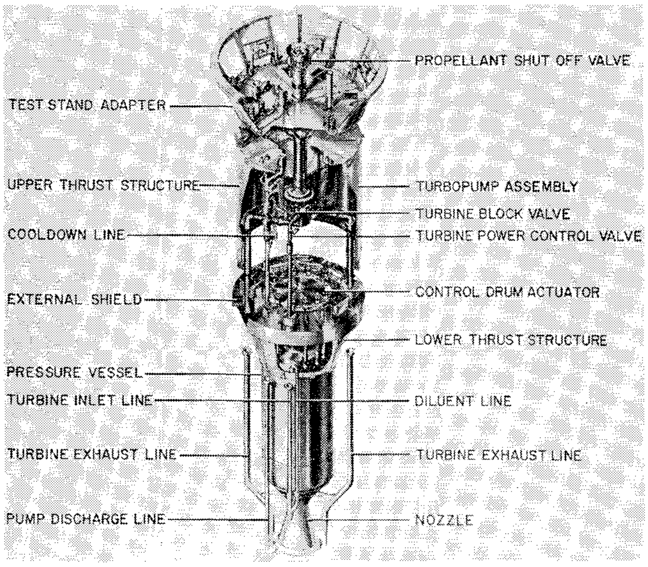


Fig. 1 XE-P engine cutaway view.

and pressure. Each loop can be controlled either manually or automatically.

Start-Up

Start-up is initiated when liquid hydrogen (38°R) is permitted to flow through the ambient engine system (540°R) from a tank that is set at a constant pressure. The technology program uses a tank pressure of 35 psia, though the NERVA engine in flight will have 24 to 30 psia. The higher tank pressure is used primarily because of the limited capability of the test facility altitude simulator to simulate space conditions at low chamber pressure. The flow through the engine is initially very low (1 to 3 lb/sec) and is oscillatory due to rapid heating of the fluid in the turbopump and lines. As the chill progresses, the flow oscillations are dampened if there is no feedback to the turbopump (closed TPCV). As the engine chills, its resistance drops, and flow increases with the constant tank pressure. As the flow increases, the pressure in the nozzle chamber increases, as long as the nozzle chamber temperature remains at, or close to, ambient.

As nozzle chamber pressure increases with the TPCV open, feedback to the turbine initiates operation of the turbopump. At very low speeds, the pump does not contribute any head rise; actually, there is a head loss. Therefore, the rate of speed increase is controlled by the tank pressure forcing flow into the engine to drive the turbine. When the turbopump speed reaches 1500 to 2000 rpm, a positive head rise of sufficient magnitude is obtained to create a self-sustaining feedback of turbine-drive pressure. The acceleration of the turbopump then becomes independent of the tank pressure, and the engine is said to be bootstrapping.

The current start-up procedure evolved because of the desires 1) to start without an auxiliary power source (i.e., without the requirement for a separate venting and cooling system for the turbopump), 2) to achieve predictability, 3) to be able to start and restart the engine over wide ranges of possible initial engine conditions, and 4) to maintain the system within the regime allowed by component operating constraints. Start-up without an auxiliary power source is achieved by using tank pressure and thermal energy stored in the engine. Certain constraints limit the rate at which the engine can be started. The main one relates to the thermal gradients in the reactor core.

This start-up procedure was developed on the basis of knowledge gained in prior testing. Initial startup studies were conducted with the CFDTS test.[2] This engine used an inert core in an XE engine assembly, and 31 tests were conducted to study means of bootstrapping.[2] Effects of tank pressure, back pressure, and prechilling were determined. Then the NRX/EST engine,[3] which included a fueled reactor and a complete engine assembly mounted on a test car in an upward firing configuration, was bootstrapped to operating power eight times. To avoid undesirable flow oscillations, the pump was prechilled in all cases; this is undesirable as a flight procedure, however, because it requires an additional valve and venting system to chill the pump separately.

The phenomenon that can lead to engine oscillations during pump starts without prechilling can be described as follows. When a cryogen enters a warm transfer line, it flash-vaporizes, thereby increasing its volumetric flow rate. If the rate of vaporization exceeds the rate of discharge of fluid from the lines, the line pressure increases. If the line pressure exceeds the reservoir pressure, reverse flow occurs; but simultaneous discharge of the fluid from the line causes the fluid pressure to decrease, and the cycle is repeated. These flow oscillations continue until the thermal energy of the system is sufficiently depleted. Pressure surges in other systems as high as six times the driving pressure have been measured for liquid nitrogen.[4]

From the knowledge gained in CFDTS and NRX/EST testing, the start-up operation has been divided into preconditioning and thrust-buildup stages. The former—from the opening of the propellant shutoff valve to the point where the turbine power control valve (TPCV) is opened—is used to chill the turbopump and sufficiently cool the nozzle to minimize the impedance of the system at the point of initiating thrust build-up. Preconditioning makes it possible to have a predictable flow build-up during the thrust-buildup stage. Also, it permits a hold before thrust build-up so the exact timing sequence can be established.

The initial part of this procedure was tested in the XE-CF. Startup transients for a typical cold-flow test with the pump prechilled are shown in Fig. 3. The pressure traces obtained with warm pump start-up were nearly identical to those in Fig. 3, except that the initial pump pressure drop was smaller, and the preconditioning stage was ~20 sec longer. Both bootstraps behaved similarly with only minor oscillations occurring during the engine chilldown. There were inlet flow oscillations into the turbopump in both runs, but flows leaving the engine were relatively stable. Storage capacitance from within the nozzle to the chamber, where the hydrogen is in the gaseous state, acts to damp any oscillation. During the initial engine chilldown, the nozzle tubes are

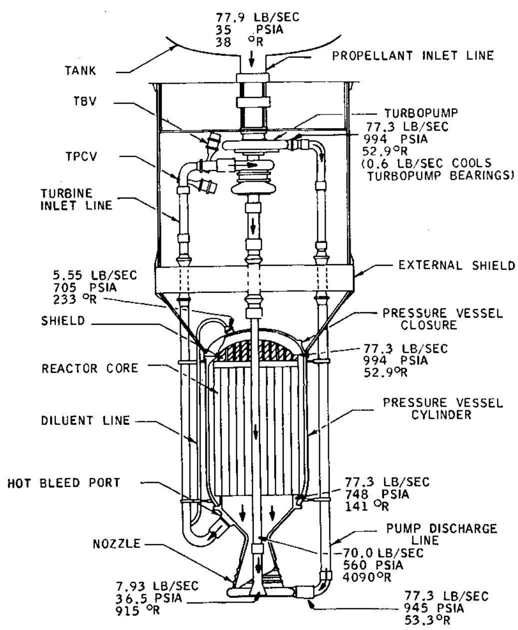


Fig. 2 Schematic of technology engine.

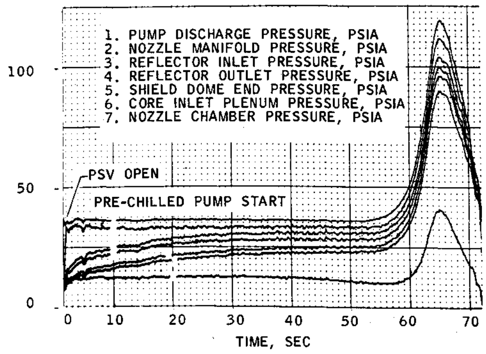


Fig. 3 XECF EP-2 systems pressures from pump to nozzle chamber.

choked, and with the relatively constant pressures, the flow of hydrogen through the engine is held reasonably constant. After the nozzle tubes unchoke, the core inlet orifices are choked, and the flow leaving the engine continues relatively smoothly. In conclusion, with the TPCV closed, the technology engine will chill with negligible pressure oscillations and negligible flow oscillations in the reactor assembly. The flow entering the engine will oscillate until line chilling has occurred.

If the TPCV is opened before the turbopump assembly is completely chilled, major engine pressure oscillations will occur as indicated by test data in the CFDTS. The oscillations are the result of gas formation in the turbopump as it starts into bootstrap. When the pump suction valve (PSV) is opened, the minor oscillations noted with the chilled pump occur initially, and then pressures and pump speed gradually increase as the engine chills. When the pump reaches about 2000 rpm, a positive head rise is obtained. At this point, the pump discharge temperature indicates saturated conditions. However, large portions of the metal parts of the pump are still well above liquid hydrogen temperatures, and the quality of the exit fluid is unknown.

With the positive head rise, a feedback of energy is obtained to the turbine and bootstrapping begins. With the pump marginally chilled, excess gas forms; this is probably a result of either the increased heat transfer or the heat generated by the turbopump assembly itself as speed increases. The excess vapor causes cavitation, and the pumping of liquid ceases. There is still pressure in the engine feeding energy to the turbopump, which accelerates, since the power required with gas in this case is considerably less than it would be if only liquid were in the pump. The result is the out-of-phase relationship between speed and engine pressures shown in Fig. 4. Simultaneously, since the pump is no

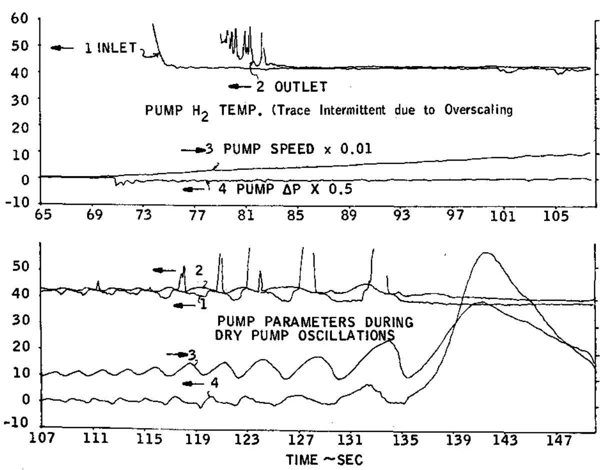


Fig. 4 Pump parameters during oscillations in CFDTS without a prechilled pump.

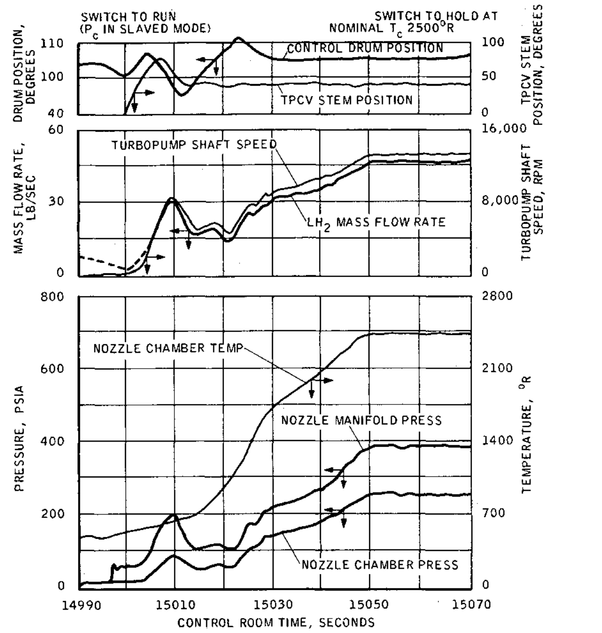
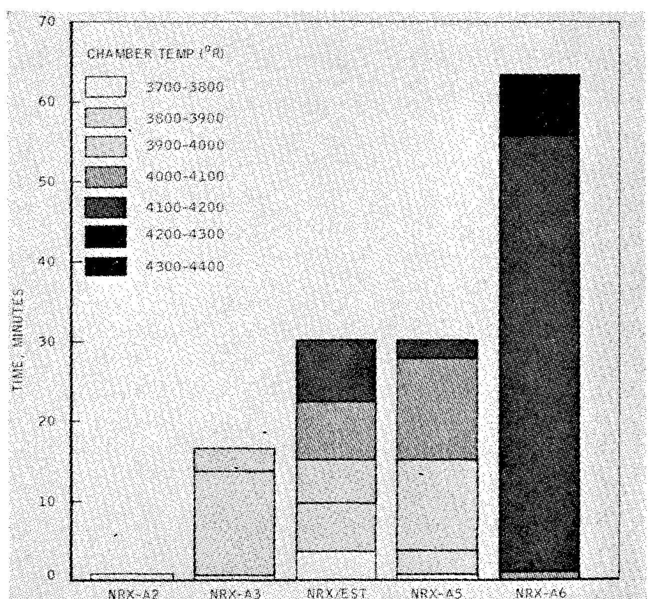


Fig. 5 NRX/EST EP-IIB run 1 start-up transient.

longer pumping liquid, an excess of gas is produced, which rises from the pump inlet towards the propellant tank. This gives the characteristic rises in inlet temperature. When the engine has purged itself of pressure, the feedback to the turbopump drops, the pump slows, and tank pressure forces liquid into it, initiating another cycle. Characteristically, in CFDTS and in XE-CF, the oscillations terminate when the reflector-inlet temperature reaches about 50°R and when liquid is flowing through the nozzle tubes.

Once an appreciable power level has been reached, such as chamber conditions of 60 psia and 1100°R, chamber temperature is increased at 50°R/sec for 60 sec to the design chamber temperature of 4090°R. Though higher rates will probably be used in the NERVA flight engine, the levels will not approach the rates customarily found in chemical rockets because of the thermal-gradient limitations in the reactor.



	NRX-A2	NRX-A3	NRX/EST	NRX-A5	NRX-A6
EQUIVALENT FULL POWER RADIATION (MINUTES) (a) ENTIRE TEST	5.7	26.8	54.4	52.2	66.9
(b) SINGLE RUN	5.1	14.3	14.5	16.4	66.6
MAXIMUM FLOW RATE (LB/SEC)	75.6	73.5	87.9	71.9	72.0
MAXIMUM POWER (MW)	1096	1100	1155	1120	1200
NUMBER OF STARTUP AND SHUTDOWN CYCLES ABOVE 2500°R	1	3	6	2	1

Fig. 6 Technology tests run times.

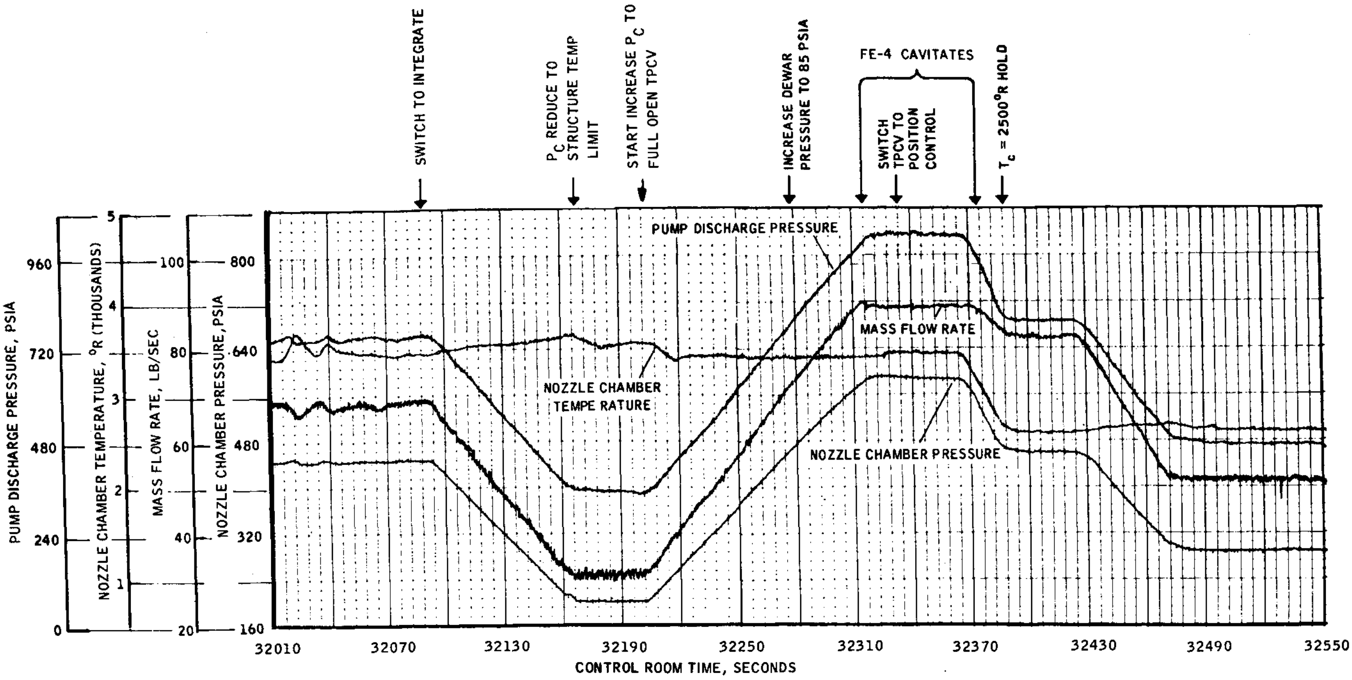


Fig. 7 EP-III mapping run.

A typical thrust build-up is shown in the NRX/EST data, illustrated in Fig. 5. The start-up was to a power hold of 2450°R. The procedure followed was to increase reactor power to 1 mw. Chamber temperature was held at 1000°R for 16 sec with a minimum chamber pressure of 50 psia. With the initiation of bootstrapping the pump discharge valve is opened and the TPCV starts to open. Reactor power increase is limited to a 2.5-sec period. The initial rise in turbopump speed follows that of a typical cold-flow test because of the small amount of power being added to the system. Speed peaks at 8200 rpm, 900 rpm higher than in the cold-flow test, and then drops off. The pressure controller tries to maintain 50 psi. Sixteen seconds after initiation of bootstrap (15015), the temperature is ramped up at 50°R/sec. After 41 sec (15030), the controller errors are at a minimum and a smooth acceleration to the desired hold point is achieved.

Power Operation

A 60-min, full-power test was run December 15, 1967, using the NRX-A6 reactor, which incorporated major design improvements relative to the earlier reactors represented in Fig. 6. The ability to maintain a desired chamber temperature (hence, specific impulse) was demonstrated in the NRX-A6 and NRX/EST tests during the full-power hold where chamber temperatures were held within a band of ±50°R and, with an improved data acquisition system for XE-P, the band was ±10°R.

Throttling a flight engine system may be needed to reduce thrust towards the termination of a burn for the final trim on velocity, to minimize the afterheat removal requirements, or to provide a safe retreat position in case of a component malfunction. This thottling maneuver can be performed with no loss in I_{sp}. Figure 7 shows the performance of the engine during an engine performance mapping test in the NRX/EST. The engine was throttled from 450 psi to 200 psi chamber pressure and then increased to 590 psi, keeping the temperature demand fixed at 3400°R. The chamber pressure was throttled at 4 psi/sec with chamber temperature varying 300°R. The amount of hysteresis obtained during throttling operation is dependent on the control system design as well as the rates of throttling.

Shutdown with Afterheat Removal

Various methods of shutdown have been investigated. The general philosophy used to maximize over-all specific

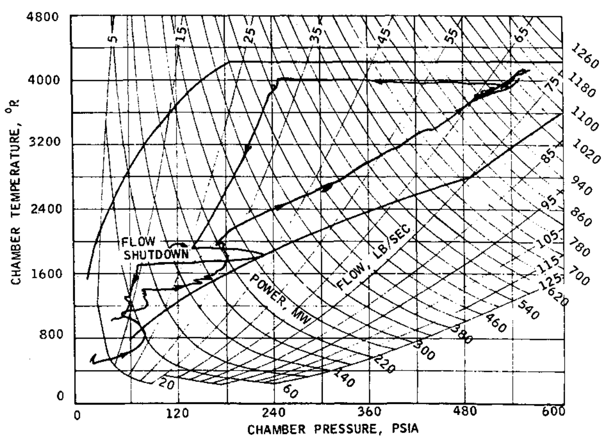


Fig. 8 NRX/EST EP-IV operation.

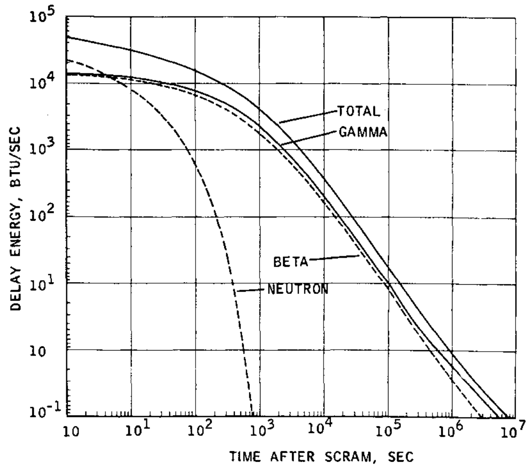


Fig. 9 Steady-state burn time 20 min.

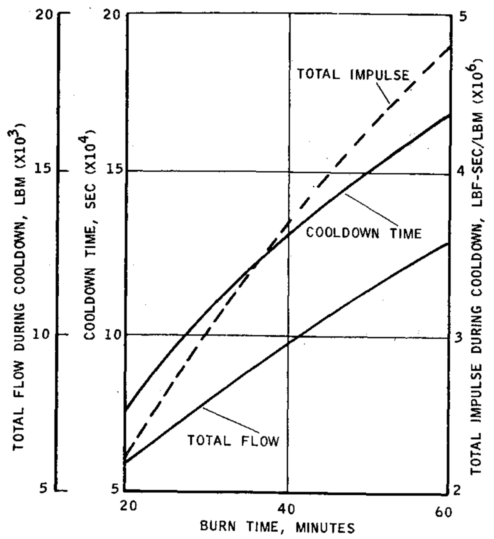


Fig. 10 Afterheat removal performance for various run times.

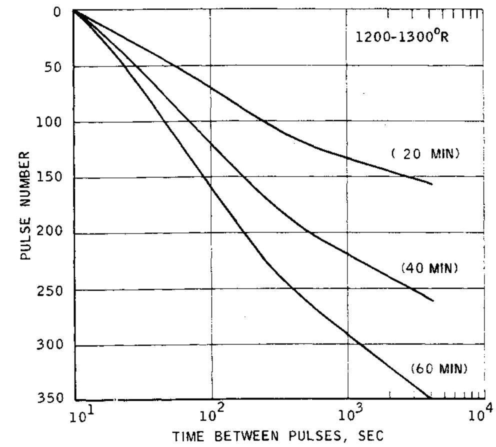


Fig. 11 Time between pulses for various run times.

impulse is to decrease chamber pressure at maximum temperature. Flow rate and power are correspondingly decreased. This procedure will reduce the decay heat products to be removed at lower chamber temperatures (lower I_{sp}'s). Temperature is then decreased at a maximum rate until flow reaches a minimum level. The reactor drums are scrammed (positioned for minimum reactivity) as soon as the operating level is reached where no operating constraints are violated. Chamber temperature is then controlled in a pump tailoff mode using the turbine power control valve. When the TPCV is closed, tank pressure is used. During NRX/EST fullpower operation a demonstration of this type of shutdown was made during EP-IV (Fig. 8). The chamber pressure was reduced from 540 psi to 230 psi at a constant 4000°R chamber temperature. Chamber temperature was then reduced at 50°R/sec. At 1900°R, a switch was made to facility cooldown fluids. The transient performance was smooth.

The heat generated by the decay of radioactivity of fission products is significant, even though it is small compared to the maximum power of the engine. Figure 9 shows the decay heat for a 20-min, full-power burn. After the first 100 sec, the decay heat dominates the afterheat energy that must be removed to prevent damage to the reactor. This energy should be removed in such a way as to create little or no penalty in I_{sp}. When the power levels are very low, the engine itself will radiate the energy to space. However, most of the decay heat that is generated at fairly high power, shortly after engine shutdown, must be removed in another way. The method is to pass propellant through the engine to cool the reactor, and to do this in such a way that the propellant is exhausted through the nozzle at as high a temperature (hence, I_{sp}) as possible. The thrust that is generated contributes to the total velocity increase that the vehicle requires for its mission in space. The afterheat is removed by pulsing the flow through the engine. At the high end of a selected temperature range, such as 1300°R, the flow pulse is initiated. When the reactor is cooled to a lower temperature, such as 1200°R, the flow pulse is terminated. Figure 10 provides a chart of time after reactor scram to remove heat to a level of 25 Btu/sec, total flow and impulse for various run times. Approximately 5% to 4% of the total engine impulse is generated during the cooldown afterheat removal. A 400°R increase in pulsing temperature reduces the afterheat removal flow 30%. Figure 11 shows the time between pulses as a function of pulse number. The final pulses reach an hour apart.

Concluding Remarks

Start-up of nuclear rockets can be divided into preconditioning and thrust-build-up stages. The preconditioning stage provides a means of establishing a predictable startup under a wide range of initial engine conditions for both performance and time. The preconditioning cycle lasted 68 sec in XECF with the turbopump initially at ambient conditions. No external power source is required to start the engine. Thrust buildup, limited in the technology program by the thermal gradients permitted in the reactor to 50°R/sec, results in an additional 60 sec to reach full power. The nuclear rocket offers flexibility at high power having a built-in capability for varying thrust between 60 and 100% at full specific impulse and has demonstrated a life cycle performance at full power of 60 min. Shutdown offers a unique challenge to the mission designer, because thrust is generated at a cyclic specific impulse of several hundred seconds over a period of one to two days. This thrust is predictable and can be utilized by the mission designer for trimming velocity.

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