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NUCLEAR THERMAL ROCKET CONTROL

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This paper presents the historical methods of control of nuclear thermal rockets (NTR), with a focus on the state of the technology, with the most recent NTR control experience being the United States Rover program. Gaps in control technology are identified and next steps in developing controls for nuclear thermal rockets are proposed.

I. INTRODUCTION

Revived interest in manned missions to Mars has again prompted the study of nuclear thermal rockets as a viable propulsion option. Since the end of the original efforts of the Rover program, studies consistently mention the need to address nuclear thermal rocket (NTR) controls, however significant activity in this area continues to be deferred. This paper provides some introductory background material about nuclear thermal rockets for historical and technological context. Based on this context, the state of the technology of nuclear thermal rocket engine control as of the end of Rover development efforts is presented. Some control technology gaps are identified and paths forward are proposed.

II. BACKGROUND

NTRs are a propulsion technology similar in concept to chemical rockets. Chemical rocket engines rely on combustion reactions to heat a working fluid called the propellant. The heated propellant is accelerated through a converging-diverging nozzle, resulting in the desired reaction force referred to as thrust. In a typical bi-propellant liquid fueled rocket engine, separate fuel and oxidizer streams such as hydrogen and oxygen are mixed and combusted to produce the heated propellant. In an NTR engine, a single propellant, such as hydrogen, is heated via fission reactions in a nuclear reactor. Figure 1 provides a simple schematic of the engine which consists primarily of a liquid hydrogen storage tank, hydrogen turbopump, nuclear reactor, and a nozzle.

Preliminary investigations of nuclear thermal rockets were first carried out in the 1940's and resulted in classified whitepaper studies provided to the United States government by North American and the Douglas Aircraft Company.[1] Higher efficiency, shorter trip times, larger payload, and potential for high reliability and versatility were among the many proposed benefits that NTR concepts offered over chemical propulsion options also being pursued at the time. Benefits such as these gained nuclear thermal propulsion (NTP) enough interest for the U.S. government to establish the Rover program in 1953 as a backup to the intercontinental ballistic missile (ICBM) program. By 1955, two exploratory reactor research programs had begun. The Los Alamos Scientific Lab (LASL) had the KIWI program, and Lawrence Livermore Lab had the short lived TORY program (redirected to project Pluto). An advanced phase of the Rover program called the Nuclear Engine for Rocket Vehicle Application (NERVA) program was initiated in 1961 in an effort to develop flight style engines capable of withstanding the stresses and extremes of launch and spaceflight while making use of advanced KIWI reactors as a baseline.

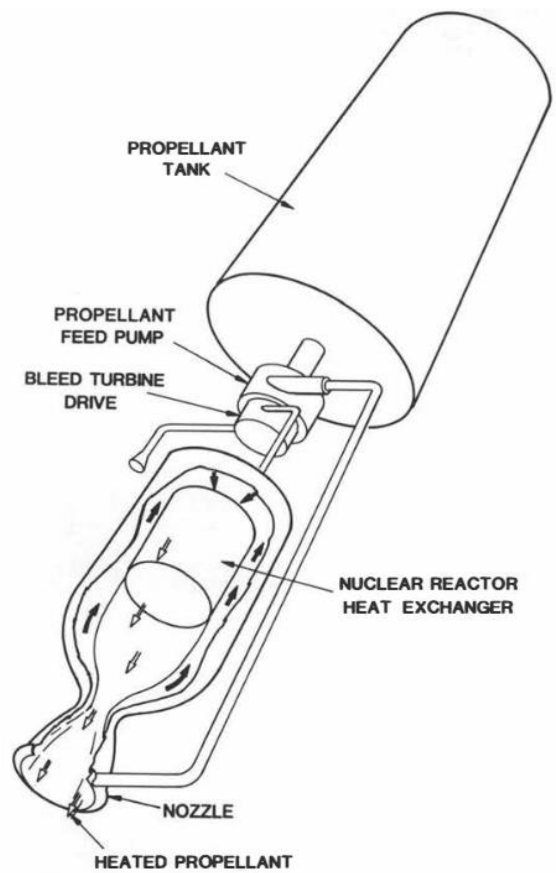

Figure 1. Simple nuclear thermal rocket engine diagram.[2]

Overall, the Rover program produced and tested 21 reactors between 1959 and 1972 (Refs. 2-4) shown in Figure 2:

- 9 KIWI reactors including Transient Nuclear Test (TNT)
- 3 Phoebus reactors
- 1 Peewee reactors
- 1 Nuclear Furnace
- 5 NERVA development reactors (NRX)
- One NRX Engine system test (EST)
- One flight style experimental engine (XE-Prime)

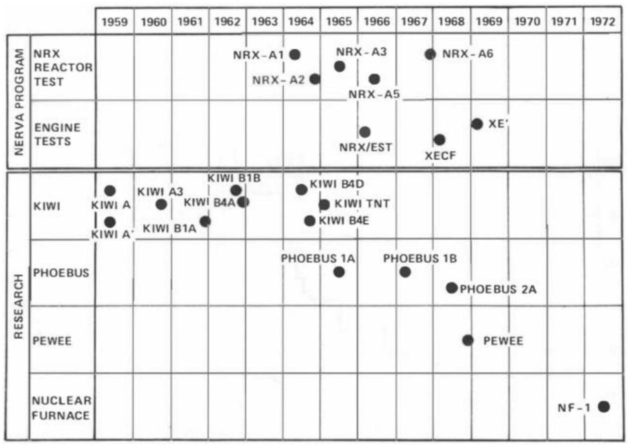

Figure 2. Chronology of reactor and engine tests.[2]

The culmination of testing efforts resulted in the XE-Prime engine test, which was the only nuclear rocket engine to be tested in a flight-type, close-coupled configuration (compact configured components including self-contained propellant pump system with no external power).[5]

Over the years, long lead times and high costs of full sized reactors led to the development of Peewee and Nuclear Furnace reactors for more cost-effective fuels experimentation. Ultimately, economic considerations led to the Rover program being cancelled in January 1973 (Ref. 2).

Recently, revived interest in manned missions beyond the moon has prompted NASA to again consider NTRs as an option for deep space missions.[6] NTRs are a prime candidate for deep space missions because they can significantly reduce transit time, thus minimizing astronaut exposure to solar radiation. NTRs provide the ability to generate high thrust with specific impulse values near 900s, which is about twice that of contemporary advanced chemical rockets.[7] Instrumentation and control of nuclear thermal rockets have long been identified as enabling technologies and high priority development need,[8] and since the end of the Rover program, are finally being addressed with the current efforts. As a starting point, this paper presents the state of the technology for NTR control, with a primary focus on the control description found in the XE-Prime Engine Final Report, volumes I-III (Refs. 5,9,10,11).

III. HISTORICAL NTR CONTROL EXPERIENCE

The XE-Prime engine shown in Figure 3 was the first and only flight type, close-coupled experimental nuclear rocket engine to be built and tested. It weighed 40,000 pounds at 272 inches tall, and 102 inches in diameter. The engine generated about 55,000 pounds of thrust at a reactor power level of about 1140 megawatts. The engine's thermodynamic cycle was referred to as a hot bleed cycle, because hot hydrogen was bled from the propellant system and used to power the turbopump. Due to the low pressure of the turbine exhaust, the gas was then exhausted overboard, resulting in a less than optimum specific impulse of 710 seconds. Greater specific impulse can be achieved with more efficient thermodynamic cycles such as a topping cycle.

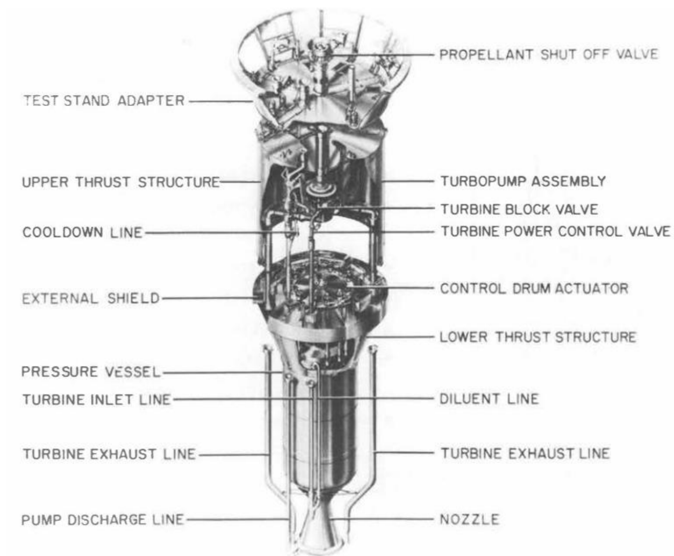

Figure 3. XE-Prime general configuration.[2]

The primary purpose of the XE-Prime test program was to further advance engine technology for the ultimate goal of the development of a true flight engine. The focus of XE-Prime testing fell onto characterizing engine dynamic performance, identifying and demonstrating multiple control methods, and investigating transient operations. Specifically, the experimental plan (EP) general objectives as stated in volume I (Ref. 5) of the final report were:

1. Investigate engine startup characteristics with particular emphasis on different candidate control concepts and startup-restart from different initial conditions.

2. Investigate system characteristics under low-power, low-flow conditions, with and without the turbopump operating.
3. Obtain steady-state and dynamic performance data for selected engine operating conditions and demonstrate the reproducibility of the data.
4. Investigate engine-shutdown and pulse-cooling characteristics.
5. Investigate engine nuclear and non-nuclear component performance, including system controls.
6. Demonstrate the Engine Test Stand 1 (ETS-1) design concept and obtain facility performance data under nuclear firing conditions.
7. Obtain additional experience with remote handling of the engine.

The complete XE-Prime test program took place after cold flow experiments (XECF), and consisted of 40 total runs spread over 10 experimental plans. The tests took place between December 4 1968 and September 11 1969. During the testing program, the engine was successfully started 24 times, and ran for a total of 115 minutes[4,5,6]. Each of the objectives were met or exceeded during one or more of the tests. The XE-Prime test program managed to successfully demonstrate several control modes which amount to the most recent experience with nuclear thermal rocket control, and thus represent the state of the art.

Control of the engine was accomplished manually or automatically via two primary engine components: The turbine power control valve (TPCV), and 12 control drums. The TPCV was actuated to control the nozzle chamber pressure, and the control drums were adjusted to control the neutron population, and thus the chamber temperature. However, feedback mechanisms do not allow for the individual adjustment of a single control parameter without interactions with the other. They are dependent upon each other. The Engine Control System (ECS) compensated for these effects under automatic control modes, however in manual control modes, the operator was responsible for these adjustments to maintain desired operating conditions. The ECS provided six operating modes:

1. Manual drum control
2. Reactor power level control
3. Chamber temperature control with three control mode options
4. Manual TPCV control
5. Chamber pressure control
6. Program control.

In the manual drum control mode, the engine operator commanded the drums to the desired position with a console mounted potentiometer. The operator was provided with indications for all twelve individual control drums, as well as an averaged value. The drums were operated in a "ganged control mode" but individual drums could be removed and adjusted individually. An error signal was generated by comparison between the operator input demand and a measured feedback signal. The control was accomplished by reducing the error signal via control drum servo action.

Reactor power level control is a simple mode where a power level demand was selected by the operator between the limits of 55 and 5500 Megawatts with a selectable period of 2, 5, 10, or 20 seconds. An error signal was calculated between the demand and measured power, and the error was reduced via drum actuation.

Chamber temperature control generated drum position demands based on a desired temperature produced by a temperature demand generator. The operator had the option to choose between three separate temperature control modes. The single range temperature controller used fixed compensation, independent of the engine operating point. The on-off temperature controller provided drum position demands only if the temperature exceeded a preset deadband. The state-program temperature controller made use of one of three compensation networks, automatically selected based on preset chamber pressure values. This was the best chamber temperature control method because it provided more optimal compensation depending upon the engine operating point. The feedback signal used for temperature demand comparison was the average of 5 chamber temperatures, with the option of using the average of 10 in-core temperatures instead.

Manual control was the default TPCV mode unless selected otherwise. Just like manual drum control, TPCV position was manually commanded by the operator via potentiometer. The measured position of the TPCV was provided by an average of three potentiometers housed in the TPCV actuator. The difference between measured position and demand was reduced by actuation of the TPCV servo valve.

Chamber pressure control allowed the operator to manually input a chamber pressure demand, which was achieved at a rate of 1, 2, 5, or 10 psi per second. Chamber pressure was evaluated as the average of three chamber pressure transducers and compared to the operator demand. The difference provided a demand signal to TPCV position control loop.

Program control provided predetermined operating behaviors prescribed by three different plug-in circuit boards. Each circuit board was programmed to follow one of three operating lines within the engine operating map (see figure 3 in Ref. 5, and figure 2 in Ref. 10). The operational choices provided were normal, high thrust, and high specific impulse. Program control provided a direct coupling between pressure and temperature demand generators via temperature-to-pressure demand relationship, where pressure was the primary demand, and temperature was secondary. Thus, a pressure demand was generated first, and the temperature-to-pressure relationship determined the temperature demand. This was unique to program control, because any of the previously discussed TPCV control modes can be combined with any of the drum control modes. The other major difference with program control, is that it could only be selected once the engine has been started (temperature loop closure and pressure null achieved).

Engine startup was a primary point of investigation for the XE-Prime test series, and two primary automatic engine start methods were successfully demonstrated, though several startup methods were investigated:

1. Nuclear autostart
2. Wet temperature autostart
3. Dry temperature autostart
4. Damp temperature autostart
5. Manual open loop start
6. Closed temperature loop start

Nuclear autostart was performed using nuclear measurements for power determination. First the control drums were rotated to a predetermined position past the critical angle. The reactor was considered started when predetermined power was achieved. Then, power control mode was initiated and the system was ready to continue engine startup with hydrogen flow. Bootstrap was initiated by opening the TPCV after completion of pump chilldown. Pump chilldown was performed because the cold flow tests revealed flow oscillations could be avoided with reflector inlet temperature below a certain value. Fluid impedance and system energy balance are also primary reasons for chilldown. Although possible, nuclear power control was not considered to be an optimal bootstrap control mode due to large variation in bootstrap timing.

Temperature autostart was performed without the use of nuclear instrumentation by using temperature control instead of power control, and consisted of two primary start sequences. Wet temperature autostart (WAS) initiated hydrogen flow at the same time as drum rotation. When the reflector inlet temperature dropped below a certain point, power was added by further turning the drums. Heating was sensed by nozzle chamber thermocouples. Once the desired nozzle chamber temperature was reached and pump chilldown achieved, the TPCV was opened and pressure control activated till bootstrap was complete. Dry temperature autostart (DAS) initiated hydrogen flow at either the same time as drum programming, or when a preset core temperature was achieved. Though typically, the propellant flow was initiated once the preset core temperature was reached. Heating was sensed by in-core thermocouples for this method. Again, once chilldown was complete, pressure control was activated and primary propellant flow was initiated via TPCV opening, initiating bootstrap. The damp temperature autostart was a combination of WAS and DAS. Similar to WAS, damp temperature autostart initiated control drum motion and propellant flow at the same time. However, like DAS, the in-core temperature measurements were used to detect heating.

The manual open loop start sequence began with pre-programmed drum movement, quickly followed by TPCV ramp to a preset value. The drums were stopped at a predetermined condition, and eventually turned back a few degrees to stop power increase at a predetermined value. Bootstrap was then initiated as soon as chilldown was complete. The engine was then manipulated within the operating map via fixed rate drum and TPCV ramps.

Closed temperature loop startup was performed by manually adjusting power till a temperature was reached which could be maintained by some flow condition. Once the temperature was maintained using a steady flow rate, the temperature loop was considered closed and bootstrap was initiated.

Although the engine design for the current development activity is still conceptual and the startup requirements have not yet been defined, the demonstration of these startup methods over a wide range of operating conditions is useful for providing experience in automated startup control, and data for modeling startup transients of a general NTR, which will be necessary for designing a new control system and startup sequences.

IV. TECHNOLOGY GAPS AND NEXT STEPS

To provide the necessary mission assurance, a nuclear rocket engine must be able to respond to rapid events and adapt to evolving or degraded conditions. Immediate human intervention for repairs or refurbishment is unlikely for a manned mission to Mars due to issues such as radiation danger to astronauts. Communications delays and blackouts also present problems for timely ground based assistance in assessment of anomalies or failures during a mission. Thus, some autonomous features such as signal validation, diagnostics, mode selection and decision making capabilities are highly desirable for providing additional operational robustness. Ultimately, operational autonomy is highly desirable for nuclear thermal rocket engines and is considered to be a critical design issue for NTR development.

Previous experience with control of nuclear thermal rocket engines required constant human oversight and input. The knowledge base provided by the Rover program is on par with the nuclear industries' experience in controlling light water reactors, as the technologies were largely developed in the same time frame. Some modern improvements in commercial power reactor instrumentation and control are not considered to be adequate to support advanced space reactors for manned missions[12]. While significant advances in control theory have been made since the Saturn program, none has been demonstrated on a reactor system[12]. Thus, the logical steps forward for developing adequate control for nuclear thermal rockets include an incremental approach to developing a new NTR control system. First, a digital automatic control system which is at least capable of the same achievements in startup capability and reliability reported for the XE-Prime engine control system is required. Next, autonomous features such as diagnostics, signal validation, and control mode selection, are to be added to improve reliability and reusability, while reducing the necessity for intensive human oversight. Continual performance assessment, improvement, and additional autonomous features will allow for the evolution of control systems with greater autonomy. Additionally, to allow for the design and testing of a control system, accurate NTR dynamic simulation capability will need to be developed and validated using test data provided by the Rover program.

V. CONCLUSIONS

In summary, the state of the art of nuclear thermal rocket engine control is inadequate for manned deep space missions. The culmination of the Rover program with the experimental nuclear thermal rocket engine, XE-Prime, is the United States' most recent experience with instrumentation and control of an NTR. Thus, a step by step approach is proposed for developing an NTR engine control system. First, advances in control theory since the end of the Rover program should be applied to developing simple automatic control to a validated digital model of an NTR. This control system should then be improved to provide for greater operational robustness via addition of autonomous features. Iterations of the control system can be incrementally improved by addition of more autonomous features. Simulation of the system can provide the capability to test the control system in ways such as modeling degradation of components and other off normal conditions. Ultimately, full autonomy of a nuclear thermal rocket engine is desired.

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