Cycle Trades for Nuclear Thermal Rocket Propulsion Systems

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Abstract

Nuclear fission has been used as a reliable source for utility power in the United States for decades. Even in the 1940's, long before the United States had a viable space program, the theoretical benefits of nuclear power as applied to space travel were being explored [Humble, et. al.]. These benefits include long-life operation and high performance, particularly in the form of vehicle power density, enabling longer-lasting space missions.

The configurations for nuclear rocket systems and chemical rocket systems are similar except that a nuclear rocket utilizes a fission reactor as its heat source. This thermal energy can be utilized directly to heat propellants that are then accelerated through a nozzle to generate thrust or it can be used as part of an electricity generation system. The former approach is Nuclear Thermal Propulsion (NTP) and the latter is Nuclear Electric Propulsion (NEP), which is then used to power thruster technologies such as ion thrusters.

This paper will explore a number of indirect-NTP engine cycle configurations using assumed performance constraints and requirements, discuss the advantages and disadvantages of each cycle configuration, and present preliminary performance and size results. This paper is intended to lay the groundwork for future efforts in the development of a practical NTP system or a combined NTP/NEP hybrid system.

Nomenclature

c*	Characteristic exhaust velocity
C_f	Thrust coefficient
ε	Nozzle expansion ratio
hp	Horsepower
HTX	Heat exchanger
K	Kelvin
kN	Kilo-Newtons
kW	Kilowatts
lbf	Pounds-force
lbm	Pounds-mass
MW	megawatt
P_c	Chamber pressure
psia	Pounds-force per square inch
R	Rankine
s	Seconds

Introduction

Reliable energy is the key factor in developing and sustaining a permanent presence in outer space. To travel beyond low Earth orbit, one is faced with making larger, higher performing, and more costly versions of the chemical rockets used today. This approach can be taken, or a technology with thirty years of demonstrated development can be considered: nuclear propulsion.

Why nuclear? Nuclear energy offers distinct advantages over traditional chemical and solar power systems. These advantages include: long operating life; operation in adverse environments (e.g. radiation belts, Mars surface); operation independent of the sun; and high reliability. Nuclear power appears to be the only likely option for applications requiring energy in the hundreds of kilowatts to megawatt range over a long mission life.

Nuclear power technology at its simplest level involves the use of a nuclear reactor to produce heat. This heat is released in the decay of radioisotopes (such as plutonium); in the controlled fission of heavy nuclei (such as uranium-235) in a sustained neutron chain reaction; or in the fusion of light nuclei (such as deuterium and tritium). The heat energy produced is directly used in the space propulsion processes or converted into electric power. Current nuclear energy applications are based on radioisotope decay or nuclear fission due to the technical challenges of fusion power.

Why nuclear fission? Nuclear fission is a well-developed and extensively used technology [Curran and Houts].

- Fission power systems have been in operation since 1942.
- Fission reactors are used by a wide range of public and private entities.

- Fission reactors are currently operating at power levels up to 10,000 times greater than what is needed for near-term space applications.
- Nuclear fission power plants are the least expensive source of electricity in the US.
- Fissioning of 12 fluid ounces of Uranium emits 50 times the energy contained in a Space Shuttle External Tank which equates to an energy density of 82 billion joules per gram.

A range of nuclear power options as applied to space applications has been developed by the United States since the start of the space age. These options include nuclear electric propulsion (NEP) and nuclear thermal propulsion (NTP).

NEP systems consist of a nuclear reactor combined with a heat-to-electricity power conversion system, and an electrical propulsion system. Due to the low efficiencies of power conversion (from as low as 5% conversion efficiency for a static thermal to electric conversion system to 25% for a dynamic system such as a Brayton power conversion system), these systems also require heat rejection systems to necessary to radiate significant waste heat to space [Angelo and Buden]. The electrical propulsion system generally falls into three main classes of thrusters: electro-thermal, electro-static, and electro-magnetic.

Current state-of-the-art NEP technology is the SP-100 reactor. This reactor is sized for 2.5 MWt, with a 1350 K temperature at the power conversion interface [Gilland and Oleson].

Due to the number of subsystems required, NEP systems have significant dry mass. This can result in a propulsion system that has a mass comparable to the payload or even the propellant. However, the specific impulse of

NEP systems ranges from 5000 to 10,000 seconds thus reducing the required propellant mass, resulting in an overall low vehicle initial mass [Gilland and Oleson]. The acceleration of the vehicle is a function of both the amount of power that can be generated as well as mass of the system. The vehicle acceleration in turn determines the mission trip time. Higher NEP performance is achieved by increasing peak temperatures in the reactor and power conversion systems thus giving higher system efficiency. These higher temperatures and efficiencies require advanced materials, a common feature for all versions of nuclear fission power systems applied to space.

A NTP system is similar to chemical propulsion except that it utilizes a nuclear reactor as a heat source to generate high temperature gases as opposed to chemical reaction. The result is typically a higher thrust system than NEP but one with lower specific impulse performance. The effort to improve specific impulse performance as much as possible requires the use of extremely high temperature, which can affect component life and reliability. This is one area worthy of significant study in the future.

NTP state-of-the art is considered to be the Nuclear Engine for Rocket Vehicle Applications (NERVA) systems of 30 years ago which attained specific impulses of 825 seconds, at thrust levels of 330 kN in ground test [Gilland and Oleson].

Several hybrid concepts involving both NTP and NEP together have been considered for planetary exploration [Gilland and Oleson] [Riehl, et. al.] [Reid]. These concepts combine the characteristics of NTP and NEP to achieve a higher level of performance for a given mission. This higher level of performance could potentially reduce radiation exposure time, reduce zero gravity exposure (for manned missions), and allow

experimental data to be received sooner. It is envisioned that such a system might provide thermal propulsion for thrust injection burns, electrical propulsion for orbital transit and electric power conversion for mission electrical requirements.

If the NTP, NEP, and hybrid concepts are to be developed for actual space application they will at some point require demonstration and certification testing on the ground. Unfortunately, ground testing nuclear engines if often limited or severely restricted by state or federal safety regulations. NASA Marshall Space Flight Center (MSFC) has recognized this fact and is leading a Safe Affordable Fission Engine (SAFE) test series, designed to demonstrate a 300 kilowatt (kW) flight configuration system using non-nuclear testing.

The SAFE-30 test series is a full core test capable of producing 30 kW using resistance heating to simulate the heat of nuclear fission. The 30 kW core consist of 48 stainless steel tubes and 12 steel/sodium heat pipes welded together longitudinally to formulate a core similar to that of a fission flight system. Heat is removed from the core via the 12 heat pipes, closely simulating the operation of an actual system [NASA/MSFC]. Non-nuclear testing of engine systems allows component and engine performance to be evaluated without all the safety, cost and environmental issues associated with traditional nuclear engine tests.

It has been proposed that a reexamination of the utility of NTP might be an appropriate undertaking under the umbrella of the NASA emphasis in nuclear propulsion for space. This paper focuses on trades conducted as a first portion of this reexamination and system design effort being conducted at NASA MSFC involving cycle trades for the NTP system. An important and unique element of

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this effort is the direction to take into consideration the ground testing difficulties mentioned above. Thus, the NTP trades were conducted utilizing a scheme of indirect propellant heating that could potentially allow ground testing and system evaluation in the absence of a nuclear heat source. Plans for future work on this effort will be then laid out including comparisons of NTP to NEP and chemical systems and overall system optimization for particular proposed missions.

Engine Cycle Trade Study

The NTP engine cycle uses a single propellant and is similar to the expander cycle of a conventional chemical rocket engine. The high-pressure propellant is heated using either a single heat exchanger or a combination of heat exchangers to absorb heat rejected from the reactor. The resulting high-temperature

To maximize specific impulse using a single propellant, the greatest amount of heat that can be added to the propellant is desirable along with using a low-molecular-weight propellant. However, the propellant temperature is constrained to be within the thermal limits of the turbine components and the injector plate-chamber-nozzle assembly. For the cycle trades conducted, systems with different configurations of heat exchangers were considered with hydrogen used as the propellant.

To select the best-performing NTP engine cycle, several engine cycle configurations were evaluated based on given inputs and appropriate assumptions. These assumptions are derived from existing rocket engine components and current materials and engineering technology. An abbreviated list
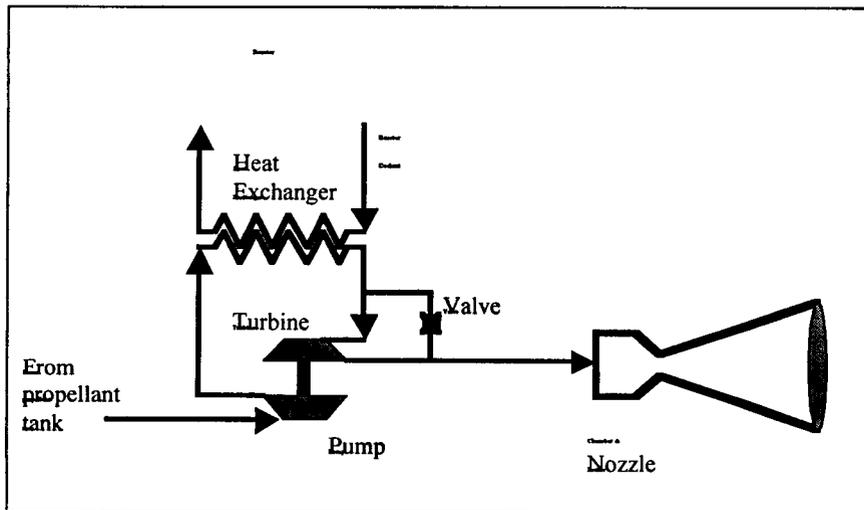

Figure 1. Basic single heat-exchanger NTP engine cycle

propellant gas is expanded through the nozzle to produce a high exit velocity and create thrust. Turbomachinery is used to obtain the high chamber pressure in the evaluated cycles, but a pressurized source propellant, where the liquid propellant is stored in a high-pressure tank and is pressurized by some means, is also a possibility.

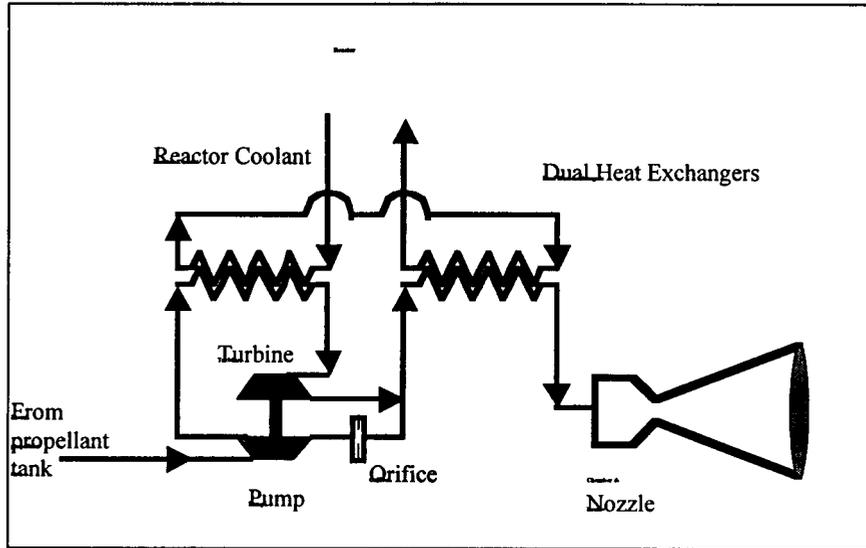of assigned inputs and assumptions are listed in Table 1.

Figure 2. Basic dual heat-exchanger NTP engine cycle

Table 1. Trade study inputs and assumptions

Thrust	1000 lbf
Chamber Pressure (P_{cham})	500 psia
Fuel inlet conditions	25 psia, 37 R
Nozzle area ratio (ε)	75
C* efficiency	98%
C_f efficiency	95%
Reactor	Treated as "black box" heat source

The engine cycles evaluated were variations of either a single heat exchanger configuration or a dual heat-exchanger configuration. The basic single heat-exchanger configuration is shown in Figure 1 and the basic dual heat exchanger in Figure 2.

As can be seen from Figure 1, since the maximum turbine inlet temperature is lower than the maximum possible heat exchanger temperature due to the limitations of the turbine materials and the turbine's thermal limitations, the energy potential of the reactor cannot be fully utilized in this single cycle configuration

From Figure 2, with the addition of the second heat exchanger downstream of the turbine, the total available reactor energy may be utilized. The first heat exchanger exit temperature is still limited to the maximum turbine inlet temperature, but the second heat exchanger exit temperature may more closely approach the reactor coolant temperature and is only limited by the heat exchanger and injector materials/design requirements. However, this performance increase for the dual heat-exchanger cycle, as compared to the single heat-exchanger cycle, comes at the price of increased weight and complexity.

To minimize the temperature constraint limitations of the basic single heat-exchanger configuration and eliminate the complexity of adding another heat exchanger, the concept of a dual-bypass, single heat-exchanger cycle was created. This cycle is shown in Figure 3.

Based on variations of these single and dual heat-exchanger engine cycle configurations, a field of various engine cycles was generated. Among the variations in this field of cycle configurations, engine cycles including a kick-pump, turbine dump flow (similar to gas generator engine dump flow in chemical
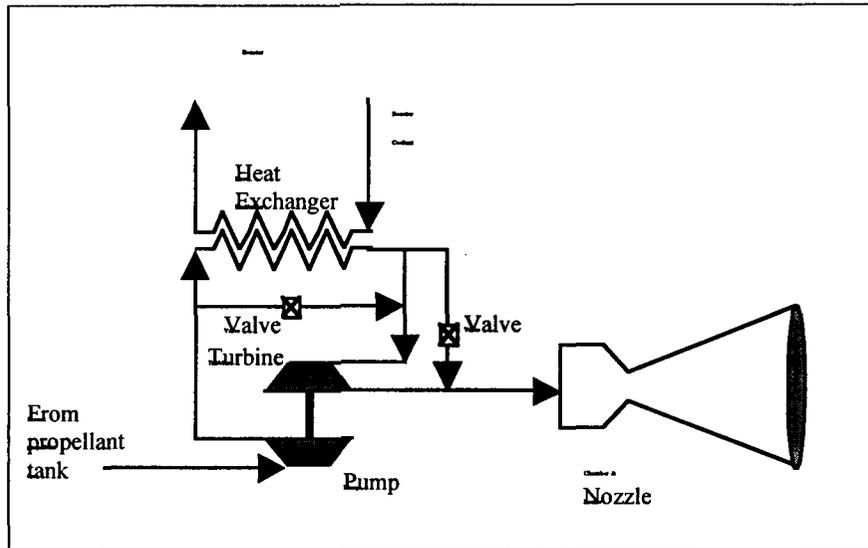
Figure 3. Dual bypass, single heat-exchanger NTP engine cycle

propulsion cycles), and bypass ducts in various locations were considered.

The first phase of analysis involved rating the benefits and shortcomings of each cycle and performing a top-level comparison. The criteria used to evaluate each cycle configuration included: cycle performance, cycle complexity, and number of flow components. From these observations, the field of competing engine cycles was narrowed down to five.

The second phase of the analysis involved using the inputs and assumptions in Table 1 and applying the conservation laws, fundamental thermodynamic relations, fluid properties for hydrogen, the Chemical Equilibrium for Applications (CEA) computer program [Gordon and McBride] for the hot gas rocket performance properties, rocket engine turbomachinery relations, and engine performance definitions to predict the engine cycle performance. From this field of five cycles, the analysis of only the three best-performing cycles is detailed in this paper.

Figure 4 details the power-balance of the cycle shown in Figure 3. In this cycle, the full flow is pumped up to pressure but does not entirely pass through the heat exchanger nor through

the turbine. Because of the heat exchanger bypass and turbine bypass, a higher heat exchanger temperature and chamber temperature are realized than in the pure single heat-exchanger cycle (as in Figure 1) while remaining within the turbine inlet temperature constraint.

In the dual heat-exchanger cycle power-balance shown in Figure 5, the full flow is pumped up to pressure and passes through the first heat exchanger, where the exit temperature is limited to the turbine inlet temperature constraint. The flow is then split upstream of the turbine where the majority of the flow (roughly 70%) bypasses the turbine and goes directly to the second heat exchanger. This lowers the power requirement of the second heat exchanger to raise the entire flow to the maximum heat exchanger exit temperature.

Figure 4. Single full flow heat exchanger with heat exchanger bypass and turbine bypass

Figure 5. Dual full flow heat exchanger with turbine bypass

Figure 6. Dual heat exchanger with split flow turbine

In the dual heat-exchanger cycle power-balance shown in Figure 6, the full flow is pumped pumped up to pressure. The flow is then split downstream of the pump, with the majority of the flow (again, roughly 70%) bypassing the first heat exchanger. The cycles in Figures 5 and 6 have the same power requirements since they are identical except for the location of the bypass. The difference lies in the split of power input between the two heat exchangers. In Figure 6, a smaller amount of power is required by the first heat exchanger in the cycle to bring the smaller amount of flow up to the maximum turbine inlet temperature. The second heat exchanger is then required to add a greater amount of power to the raise the temperature of the flow that bypassed the first heat exchanger and the flow exiting the turbine up to the maximum heat exchanger exit temperature.

Table 2. NTP Engine Cycle Performance Summary

Engine Cycle	Vacuum Specific Impulse (s)	Engine Flow Rate (lbm/s)	Total HTX Power (MW)	Pump Power (hp)
Single full flow HTX w/ HTX bypass and turbine bypass	563.4	1.78	15.27	162
Dual full flow HTX with turbine bypass	568.5	1.76	15.45	177
Dual full flow HTX with split flow turbine	568.5	1.76	15.45	177

Table 2 summarizes the performance of the engine cycles detailed in Figures 4 through 6. As the table shows, the dual heat-exchanger cycles are the best performers if gauging

specific impulse only. However, the dual-bypass, single heat-exchanger cycle is similar in specific impulse, has lower heat exchanger and pump power requirements than the dual heat exchanger cycles, and does not have the complexity that an additional heat exchanger introduces. Conversely, the dual bypass configuration will add to the complexity of valve sequencing to meet the thermal and flow requirements of the turbine.

Table 3. Single heat exchanger NTP engine weight summary

Reactor	482
Shield	478
Heat Exchanger	1630
Nozzle & Hardware	69
Pump	8.5
Tank	228
Structures	289
Propellant	1453

Total System Mass   4638 kg
(10,224 lbm)

Table 3 is a preliminary weight breakdown for the single heat exchanger NTP engine cycle.

Figure 7 show the envelope that the single heat exchanger NTP engine cycle might occupy.

The results of this brief trade study are the identification of several viable NTP engine cycles each with slightly different attributes. Further study along the lines of system sizing, component design, and system reliability considerations will be necessary before any one cycle can be labeled as singularly the best.
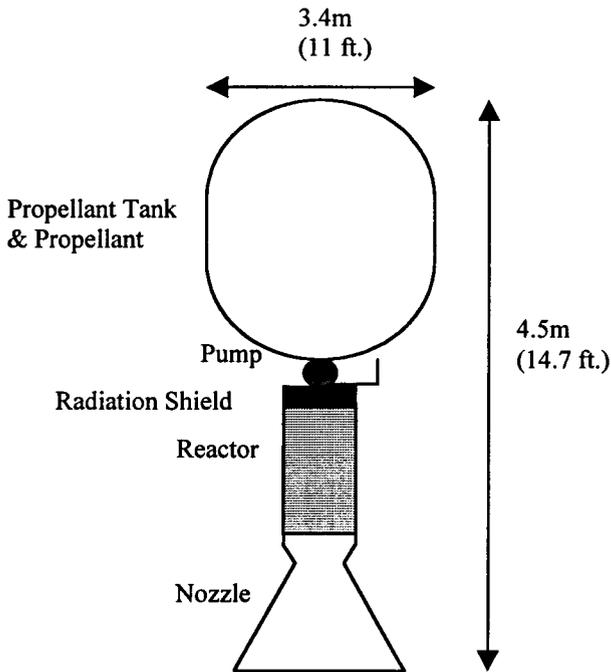
3.4m
(11 ft.)

Propellant Tank
& Propellant

Pump

Radiation Shield

Reactor

4.5m
(14.7 ft.)

Nozzle

Figure 7. Single heat exchanger NTP engine size envelope

Future Work

The work presented in this paper represents only one particular portion of the design of a traditional NTP system, cycle performance trades. This preliminary study sets the groundwork for a much more involved effort. In the long term, the technical utility and feasibility of the promising NTP system will be assessed in regards to emerging space exploration missions.

Literature Search

Numerous NTP systems have been investigated and documented. A broad literature search will be used to identify key technologies required to successfully design and build the NTP propulsion systems.

Baseline Mission Definition

Possible missions of interest to be investigated in the future might include robotic space

exploration missions employing NTP and competing NEP and chemical propulsion engine concepts. Candidate exploration missions to Mercury, Venus, Saturn, Mars, Pluto or their associated moons will be considered. Thermal power levels in the 16 to 20 MW class will be considered with mission launch opportunities starting in the 2010 time frame.

Conceptual Nuclear Propulsion System and Component Design and Analysis

The proposed NTP concepts will be defined and evaluated. Areas that will investigated include:

- Engine cycle performance (specific impulse)
- System mass
- Propellant tankage and valving options
- Structures
- Vehicle subsystems
- Packaging
- Payload
- Radiation shielding
- Launch vehicle requirements

Concept Assessment

Based on the results of the system design and analysis phase of the study, key aspects of the system as it relates to the mission will be evaluated. These will include:

- IMLEO – Initial mass lower earth orbit
- Mission trip time
- System size, packaging and integration
- Key technologies required

Conclusions

As an initial phase of this long-term project, various NTP cycles were examined. Of these, the larger, full-flow, dual heat exchanger cycles were found to be the highest performers in terms of specific impulse. Heat exchanger sizing varied with the engine flow arrangement and dual heat exchanger cases will definitely weigh more and add a complexity factor to the propulsion system. Component materials limit system performance, which is a direct function of the propellant operating temperature. New material technology development could relax such limits but the cost and time to develop such materials are issues to be considered.

The work outlined for the future will build on this study and attempt to define appropriate destinations, missions and power levels where NTP systems can prove to be advantageous.

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