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Design of a passive safety system for a nuclear thermal rocket

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ABSTRACT

Long-term high payload missions necessitate the need for nuclear space propulsion. Several nuclear reactor types were investigated by the Nuclear Engine for Rocket Vehicle Application (NERVA) program of National Aeronautics and Space Administration (NASA). Study of planned/unplanned transients and their impact on nuclear thermal rockets is important due to the need for long-term missions. It has been determined that a loss-of-flow-accident (LOFA) is the most serious design basis accident that will affect nuclear thermal rockets. A safety system is needed to respond to a LOFA and to prevent the core from melting. In this paper, a special secondary loop has been designed that utilizes the existing components of the Pewee I reactor. In particular, the tie rod tubes are connected to a secondary loop with radiator tubes. A check valve is also present in the circuit to help facilitate natural circulation in one direction in the absence of gravity. The radiator tube heat transfer surface area was increased to the following specifications: (i) 2 times the heat transfer surface area (HTSA) of the tie rod tubes, (ii) 4 times the HTSA of the tie rod tubes, (iii) 6 times the HTSA of the tie rod tubes, (iv) 8 times the HTSA of the tie rod tubes, and (v) 10 times the HTSA of the tie rod tubes. The following expected results were achieved: (i) during both steady-state operation and post-LOFA decay heat removal, temperature of the tie rod can be kept below the material melting point; (ii) during both steady-state operation and post-LOFA decay heat removal, natural circulation can be facilitated with a decent flow rate; (iii) during post-LOFA decay heat removal, the coolant temperatures in the tie rod tubes decreases and the mass flow rate increases; and (iv) in the secondary system, the heat sinks are able to remove the heat generated by the heat sources, during both steady-state and transient operation. As far as minimum radiator HTSA is concerned, the radiator tubes need to have a HTSA of approximately twice of that of the tie rod tubes. This ensures the tie rod tubes won't melt and there is a decent natural circulation flow rate.

1. Introduction

A nuclear thermal rocket (NTR) is a vehicle, powered by nuclear fission, which travels into space for long-term space missions. Typically, NTRs are open-cycle reactor designs and consist of a propellant tank, pump, and reactor vessel. The reactor core serves as the engine of the rocket and heats the coolant (also referred to as propellant or working fluid) and then releases it an exhaust pressure. The reactor vessel of the NTR houses the core barrel, neutron reflector, control drum mechanisms, and core support plates/structures. Instead of control rods, NTRs have control drums to control the reactivity. These drums are rotated to keep the reactor critical.

Historically, NTRs have used various propellants such as ammonia, nitrogen, and hydrogen. The KIWI reactors of Los Alamos Scientific Laboratory (LASL) used ammonia as the propellant. The Tory reactors of Lawrence Livermore Laboratories used nitrogen as the propellant. The Rocketdyne Division of North American Aviation identified hydrogen as a more suitable propellant than ammonia and nitrogen (Gunn, 2001).

Among the advantages of NTRs as opposed to chemical combustion rockets is that they need less fuel per payload. In addition, they can diminish travel time and cut down on risks to near-earth objects and Mars (Akyuzlu, 2014). NASA anticipates that NTRs can travel to Mars by taking 50% of the time than envisioned (Russon, 2015). The learning experience from NTR studies can be used in improving the design of terrestrial nuclear reactors, especially that of safety systems.

Aside from NTRs, rockets powered by nuclear electric fission reactors (NEFRs) have also been devised. In contrast to NTRs, NEFRs have similar fundamentals to those of nuclear power plants such as a reactor core, an energy conversion system, and a heat rejection

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Abbreviations

BM-PeBR	Bimodal Pellet Bed Reactor
CBC	Closed Brayton Cycle
FSOR	Flexible Solar Optical Reflector
HCC	Hot Coolant Channels
HS	RELAP Heat Structure
HV	RELAP Hydrodynamic Volume
HTSA	Heat Transfer Surface Area
ISNPS	Institute for Space Nuclear Power Studies
ICC	Inner Coolant Channels
ML	Multilayer Insulation
NASA	National Aeronautics and Space Administration
NbC	Niobium Carbide
NERVA	Nuclear Engine Rocket Vehicle Application
NTR	Nuclear Thermal Rocket
P	Pressure (Pa) in Fig. 1
PeBR	Pellet Bed Reactor
PCC	Peripheral Coolant Channels
PVA	Photovoltaic Array
RELAP	Reactor Excursion Leak Analysis Program
SOFI	Spray-On Foam Insulation
Stdy-st	Steady-state problem type declaration in RELAP
T	Temperature (K) in Fig. 1
TDJ	Time Dependent Junction
TDV	Time Dependent Volume
TREAT	Transient Reactor Test Facility
(U-Nb)C	Uranium-Niobium Carbide
VCHP	Variable Conductance Heat Pipe
W	Mass flow rate (kg/s) in Fig. 1
WANL	Westinghouse Astronuclear Laboratory
ZBO	Zero-Boiloff
ZrC	Zirconium Carbide
ZrH	Zirconium Hydride

Symbols

A_c	performance factor in specific impulse equation
α_d	payload ratio
A_{out}	flow area of the nozzle exit
A_t	flow area of the nozzle throat
β_s	structural ratio
C_1	thrust coefficient in specific impulse equation
c_p	specific heat capacity at constant pressure
c_v	specific heat capacity at constant volume
Δu	change in rocket velocity
F_{th}	thrust of the rocket
g	gravitational constant of earth
Isp	specific impulse
M	molecular weight of the exhaust gas
m_d	payload mass
M_e	Mach number
m_f	full mass of the rocket
M_{molar}	is the molar mass
m_p	propellant mass
m_s	structural mass
P_{amb}	ambient pressure
P_0	reactor power prior to shutdown
P_{out}	pressure of the propellant at the nozzle exit
P	time-dependent power
t_0	reactor operation time prior to shutdown
T	temperature of the fluid
T_c	cold surface temperature
T_h	hot surface temperature
T_{in}	exit temperature of the propellant from the core/combustion chamber,
T_{out}	temperature of the propellant at the nozzle exit
t_s	time elapsed since shutdown
u	rocket velocity
v	speed of the fluid
v_{eq}	equivalent exhaust velocity
v_{in}	velocity from the core/combustion chamber
v_{out}	exhaust velocity at the nozzle exit

system. NEFRs generate electricity to operate the instruments pertaining to the vehicle and also for the electric propulsion system. The following NEFRs have operated in space: (i) the BUK and TOPAZ reactors of Russia, and (ii) the SNAP-10A reactor of the United States. (Summerer and Stephenson, 2011). Nuclear reactors for space exploration have design criteria that share similarities and differences with those of terrestrial nuclear reactors. According to De Grandis et al. (2004) and Finzi et al. (2007), nuclear reactors for space exploration have the following design criteria: (i) produce required electrical power (most relevant for NEFRs), (ii) need to last for the required time period sans human intervention and refueling, (iii) limited mass and volume of design due to payload, (iv) meet safety requirements of the terrestrial nuclear reactors, (v) less maintenance and repair procedures than terrestrial reactors, and (vi) prevent leakage of fluids and possess safety systems to address these. Summerer and Stephenson (2011) list the following design criteria: (i) sufficient efficiency concerning heat removal in space and launch environments, (ii) very small and compact reactor cores, (iii) very high enrichment ratios, (iv) high core temperatures, and (v) low core power densities to enable long usage times.

The NERVA program of NASA investigated several NTR designs from 1959 to 1973. The first NTR design developed was the KIWI B4D in 1964. The last NTR design developed was the Nuclear Furnace-1. Aside from these, prototype designs of NERVA NTRs include NRX, Phoebus, Pewee, and XE Prime. Out of these designs, the Pewee had the highest operating temperature of greater than 2500 K and the Nuclear Furnace-1 had the longest reactor operation time of approximately 160 min (Houts, 2014).

Nuclear reactors, especially terrestrial nuclear reactors, have active and passive safety systems. Active safety systems are those that require electric/mechanical inputs or human intervention to operate. Passive safety systems are those that depend on natural processes such as gravity or natural circulation and don't need human intervention or electric/mechanical inputs to run. Modern day boiling water reactors and pressurized water reactors have mostly active safety systems. Many of the proposed Generation III+ reactors such as the Westinghouse Advanced Passive 1000 (AP1000), General Electric Economically Simplified Boiling Water Reactor (ESBWR), Molten Salt Reactor (MSR), European Lead-cooled System (ELSY) reactor, High Temperature Gas Reactor (HTGR), and Sodium Advanced Fast Reactor (SAFR) have new passive safety systems. Safety systems that operate in response to an accident have not been designed for nuclear space vehicles. In this paper, we have selected the Pewee I Test Reactor to use for our safety system design. We have assumed the safety system will act in response to a design basis accident such as a LOFA.

In this paper, the following will be presented: (i) a description of the Pewee I Test Reactor, (ii) a description of the fundamental formulae relevant to rockets (iii) a literature review of safety systems in space nuclear reactors, (iv) a literature review of non-forced circulation systems in space, (v) a presentation of the safety