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Design of the non-nuclear components of radioisotope system generally follow standard practice for similar components in chemical rocket engines. These are detailed elsewhere in the literature and are not given here. The most important considerations in overall engine design are those concerned with optimizing the choice of design parameters to yield best overall system performance. . . ."

ISOTOPE THERMAL THRUSTERS AND APPLICATIONS

John S. Martinez
Manager, Propulsion Research Department
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I. Introduction.
II. Isotope Heat-Source Technology
III. Thruster Design Details
IV. Stage Design
V. Low Thrust Orbital Mechanics and Mission Analyses
VI. Aerospace Safety Considerations
VII. Summary

I. INTRODUCTION

Within the past two or three years it has become increasingly apparent that there exists a wide range of useful applications for lightwieght, high radioisotope-powered thermal thrusters. The most promising of these thrusters employs radioisotope alpha sources to heat low molecular weight working fluids (such as H_2) which then are expanded through a nozzle to produce thrust. . . . The possiblity of employing isotopes for propulsion purposes has been mentioned several times in the literature[1,2] during the past in connection with high thrust (nuclear rocket scale) application and quickly rejected as ~~imprical~~ impractical for the following reasons:

(1) lack of availability of isotopes (in megawatt quantities)
(2) low specific power (hence, heavy weight of isotopes), and
(3) inability to modulate power level.

Recently it has been established that all these limitations can be overcome through proper design and through appropriate choice of mission and thrust level. . . . Isotope power output cannot be turned on and off. However, simple, single-pass thrusters can be constructed which maintain their thermal and structural integrity under both flow and no-flow conditions. When propellant flows through the thruster most of the isotope heat is absorbed in the propellant and the remainder is radiated by the outer shell of the thruster to its surroundings. When flow terminates, all of the isotope heat is radiated away from the thruster with only slight increase in maximum thruster temperature. Thus, although it is not possible to modulate the heat generation rate it is possible to modulate thrust. . . . there are a large number of missions which radioisotope propulsion systems promise to perform more economically than any other form of chemical, nuclear or electric propulsion system. Included among these are:

(1) Transfer from low to high orbit. . .
(2) Deep space probes. . .
(3) Sustaining low altitude orbits. . .
(4) Special scientific probes(field mapping and micrometeroite measurements while spiraling out from low earth orbits, etc.).
(5) Attitude control of large spacecraft.

One of the isotope thrusters under study in the U.S.A.+ uses a Po-210 alpha source to generate $\frac{1}{4}$ lb of thrust, weighs between 25 and 30 lb and delivers' impulses in the 700 to 800-sec range. . . a miniture version of the direct-cycle nuclear rocket which is under development in the Rover program TRW/STL has dubbed this thruster POODLE.

1 R.W. Bussard and R.D. DeLauer, Nuclear Rocket Propulsion, McGraw-Hill, New York, 1958

2 H.S. Seifert, M.M. Mills and M. Summerfield, The Physics of Rockets, reprinted from the Am. J. Phys., 15, Nos. 1,2 and 3 (1947)

+ By the Space Technology Laboratories (STL) Division of the Thompson Ramo Wooldridge (TRW) Corporation under joint USAEC and USAF sponsorship.

* AGARD (Advisory Group for Aerospace Research and Development) was a scientific panel that advised the NATO (North Atlantic Treaty Organization) on "problems, prospects, and possibilities in the nuclear propulsion field".

In its preface to the book NUCLEAR THERMAL AND ELECTRIC ROCKET PROPULSION Fundamentals, Systems, and Applications AGARD/NATO First and Second Lecture Series in cooperation with the Universite Libre de Bruxelles 12-21 November 1962 28 September-2October 1964 by R.A. Willaume (AGARD Director Plans and Programmes), A. Jaumotte (Faculte des Sciences Appliquees, Universite Libre de Bruxelles), R.W. Bussard (Space Technology Laboratories, Course Director). Published by Gordon and Breach Science Publishers, 1967, it made this tribute to Theodore von Karman:

> "Through the vision and foresight of the late Dr. Theodore von Karman, founder and General Chairman of the Advisory Group for Aerospace Research and Development of the NATO nations, a lecture series was planned and held in November, 1962. . . This first lecture course was concerned principally with the exposition of the fundamentals of nuclear thermal and electric propulsion (italics mine) and was held in order to acquaint a high level technical group from the NATO nations with the basics of a relatively new field which promised much for the future of aerospace propulsion systems. . . The enthusiastic reception with which the material was met by the European technical community involved, prompted both Dr. von Karman and R. Willaume to initiate plans for a second lecture series aimed at exploring more specific features of each class of nuclear propulsion systems. . . ."

The table of contents contain the following subjects:

- Fundamentals of Nuclear Propulsion
- Isotope/Thermal Thrusters and Applications
- Fast and Moderate Reactors and Applications of Low-Power Nuclear Rockets
- Nuclear Rockets Based on Graphite Reactors
- Technology: Applications and Development Status
- Operational Considerations, Radiation Hazards and Safety
- Nuclear Space Power Systems: Reactors, Conversion Equipment and Power Systems Technology
- Advanced Technology for Large Space Power Systems
- Electric Propulsion: Systems, Flight Mechanics, Power Sources, and Mission Applications

Rt Hayward notes Von Karman's Lectures [illegible]

In order to summerize the material covered at the 1962 and 1964 lectures; [redacted]eactors and electric drive systems [redacted] It must be remembered that it was von Karman who pushed the Air Force to utilize nuclear energy as a power source for high speed aircraft and rockets in the mid-forties. Also, he advanced the knowledge gained from the practical applications of flying-wing designs that were more than 50 years ahead of its time. Also another point of note. It was President John F. Kennedy that ~~as well~~ advocated space exploration as no American president did. Again, it was von Karman and German scientists that designed and created the NASA Gemini and Apollo programs that allowed human beings to go to the moon and return.

FUNDAMENTALS OF NUCLEAR PROPULSION--R.W. Bussard, TRW Space Technology Laboratories, Inc., Redondo Beach, California.

OUTLINE

I. PERFORMANCE ANALYSIS
   A. External Ballistics
   B. Internal Dynamics
II. REACTOR NEUTRONICS
   A. Basic Principals of Fission Reactors
   B. Criticality and Time-Dependenc

In light of recent developments & [illegible] to keep this file classified I would suggest deletion from propulsion studies and forge ahead with A.F. work. I do not see any problem with dissemination. R.t. Hayward

III. RADIATION LEAKAGE AND SHIELDING
- A. Radiation Sources and Hazards
- B. Heat Exchanger and Nozzle Performance
- C. Attenuation Mechanics and Shield Design

IV. HEAT TRANSFER AND FLUID FLOW
- A. Heat Transfer Mechanisms
- B. Heat Exchanger and Nozzle Performance

V. MATERIALS REQUIREMENTS AND PROPERTIES
- A. Propellants and Their Performance
- B. Fuel Element Materials
- C. Moderators and Reflectors

VI. REACTOR DESIGN AND ENGINE CYCLE CONSIDERATION
- A. Reactor Design Principles
- B. Engine Cycles and Selection

PERFORMANCE ANALYSIS-

A. EXTERNAL BALLISTICS

1. "the basic equations of motion. . . derived from Hamilton's "principle of least action" "

   "Euler-Lagrange equations for the motion of a conservative dynamical system"

   ". . . include the non-conservative accelerating force F from rocket motor."

2. "In considering the transfer of a rocket vehicle from one planet to another it is not sufficient to consider only the free Newtonian orbits between planetary radii. . . . We must also account for the gravitational fields of the launching and target planets. . . . For high acceleration vehicles the velocity increment requirements at each end of the journey can be taken as the root-sum-square values. Then the total one-way mission velocity requirement will be the linear sum of the two subtotals needed at each end point. . . . For a round-trip mission this must be doubled."

3. "Other losses of interest are those due to atmospheric drag, to atmospheric effects (nozzle back pressure, etc.) and to propellant consumption for turbine drive use."

4. "The types of propulsion systems proposed for low-acceleration vehicles are often such that the exhaust speed may be varied as desired over a wide range. This is particularly true of nuclear/electric ion plasma propulsion systems."

B. INTERNAL DYNAMICS

1. "The rationale of system analysis is to provide guide lines for design of the vehicle and/or engine. This can be done only if ways are found to connect internal engine parameters with external performance parameters of the vehicle. In rocket flight this can be done because the size or mass of most of the internal components is set by either the power or energy cost of the vehicle flight, and these in turn determine the external behavior. . . . These are the tank and structure, propellant, dead load, nuclear rocket motor, and turbo pump plant. . . Tank and structure mass is related to propellant mass and density. . . Turbo pump mass is related to discharge pressure and volumetric flow rate by where the second equality is derived by use of the rocket thrust equation. Nuclear rocket motor mass is roughly linearly proportional to power output."

2. "Ground launching. . . poses more difficult reactor design and development problems than does launching from free-fall. . . . Another feature of interest in use of heat exchanger nuclear rocket motor propulsion systems arises from the interrelation of reactor specific mass and propellant specific impulse. . . it is clear that a connection does exist if increased gas temperature is to be gained by varying choice of fuel element materials, since materials which offer highest melting point may be denser than those for lower temperature use."

II. ISOTOPE HEAT-SOURCE TECHNOLOGY

A. GENERAL DISCUSSION

Minimum performance goals and nuclear aerospace safety requirements establish design criteria for the thruster, the isotope capsule and the fuel form within that capsule. For instance, to be useful, isotope thrusters must operate at high temperatures.

In recent years the program conducted by the AEC's Division of Isotopes Development has made great strides toward development of stable, refractory fuel forms capable at the required temperatures. This section discusses isotope heat-source technology which encompasses both isotope technology and capsule technology.

B. ISOTOPE TECHNOLOGY

I. Introduction

Radioisotopes, when they decay, emit thermal energy in a completely predictable fashion and at a rate governed by their half-lives. They, therefore, represent a compact, reliable source of heat which will continue to function independently of the surrounding enviroment. Radioisotpoes aer obtained either as by-products of fission reactor operation or are formed by neutron bombardment of target material in a reactor.

Alpha particles, because of their large mass and high positive electrical charge, have an extremely small range in solid material (measured in microns). For this reason almost 100% of their energy is converted into heat within the fuel capsules. Similarly, beta particles are completely stopped by 1/4 in. of aluminum so that their kinetic enrgy is almost entirely converted into heat within the fuel capsules+.

One disadvantage associated with alpha emmitters is the helium buildup within the conatinment vessel. Upon emmission from the nucleus of the isotope, alpha particles, which are helium nuclei, combine with free electrons and form helium atoms. . . It is not yet known whether the helium gas formed escapes by diffussion is absorbed interstitially, or merely remains as free gas and increases the pressure within the fuel capsiqle.. . No definite conclusion has yet been reached. Pending better resolution of this question all current designs are based on the assumption that the helium appears as a pressure-producing perfect has within the capsule.

2. Selection Criteria

. . . for potential high-temperature heat source application indicates the following possibilities: Sr-90, Pm-147, Pu-238, Po-210, Cm-244, Ru-106, Ce-144, and Cs-147.

The choice of an isotope for a given space application depends on the following factors:

(1) Temperature capability of available fuel forms must stisfy mission requirements.
(2) Half-life must be adequate for mission requirements.
(3) Power density must be sufficient to prevent excessive weight penalties.
(4) Isotope must have a potential availablity which is compatible with mission requirements.
(5) Isotope projected costs must be reasonable.
(6) Radiation levels must be compatible with mission limatations.

+ The beta particles are decelerated by interaction with electronic fields surrounding the nuclei of the material through which they are passing. As a result of this interaction some of the energy of the decelerated beta particle is emmitted in the form of electromagetic radiation known as <u>bremsstrahlung</u>.

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