SNAP 8 Reactor and Shield

C. E. Johnson* and C. A. Goetz†
North American Aviation, Inc., Canoga Park, Calif.

This paper summarizes the SNAP 8 reactor design and shielding requirements. It is hoped that the information will be useful for preliminary design studies of spacecraft employing SNAP 8. SNAP 8 is a 35-kw electrical power supply for use on spacecraft. It employs a nuclear reactor heat source to drive a mercury Rankine cycle turboalternator. The system is being developed jointly by the Atomic Energy Commission and NASA. The power conversion system is being developed by the Aerojet General Corporation under contract to NASA. The reactor is being developed by Atomics International under contract to AEC. The system has been under development for approximately three years. The major performance objectives of the SNAP 8 reactor are 600 kw of thermal power, 1300°F NaK outlet temperature, 10,000-hr endurance, orbital startup and automatic control, high reliability, and low weight. To meet these performance requirements, a 550-lb reactor has been designed and is described in this paper. Use of a reactor imposes restrictions on the spacecraft design. It is shown that shield weight can vary from a few hundred pounds to several thousand pounds, depending on the payload dose tolerance and the spacecraft configuration. Approximate relationships are presented to facilitate shield weight estimates for preliminary design studies of unmanned spacecraft using the SNAP 8 reactor.

Introduction

SNAP 8 is a nuclear powerplant intended to produce approximately 35 kw of electric power output for use in spacecraft. The system, which is being developed jointly by NASA and AEC, employs a nuclear reactor (being developed by Atomics International under contract to AEC) as the heat source for a mercury Rankine cycle power conversion system (being developed by Aerojet General Corporation under contract to NASA).

The purpose of this paper is to provide information on the design of the SNAP 8 reactor and shield which may be of use to spacecraft designers considering applications for SNAP 8. The performance requirements, design, weight, and operating characteristics of the SNAP 8 reactor are summarized, and a typical shield is discussed. The effects of spacecraft configuration and payload dose tolerance on shield weight for unmanned spacecraft are discussed. Approximate relationships are presented to facilitate rough estimates of shield weights for preliminary design studies of unmanned spacecraft employing the SNAP 8 reactor.

Performance Objectives

Thermal power. The SNAP 8 reactor is designed to transfer 600 thermal kw to the NaK coolant. The reactor may be operated at any constant power level desired from approximately 10 to 100% of rated power.

Temperature. The reactor is designed for an NaK coolant outlet temperature of 1300°F with a control deadband of ±30°F. The coolant inlet temperature is nominally 1100°F.

Endurance. The reactor and its associated controls and shield are designed for 10,000-hr endurance.

Startup. SNAP 8 is designed to start in orbit upon ground command. During reactor startup, at least 20% of rated NaK flow must be maintained in the primary NaK loop. Orbital restart is not required.

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* Chief Project Engineer, SNAP 8, Compact Systems Division, Atomics International.

† Supervisor, SNAP 8, Nuclear and Control Analysis, Atomics International.

Control. The reactor control system is designed to maintain the NaK outlet temperature in the range 1300 ± 30°F, whereas the reactor operates at essentially constant power. A rapidly acting, load-following, control system is not required because both the reactor and the power conversion system operate at essentially constant power after startup.

Shielding. It is anticipated that the several shield designs may be required for various spacecraft configurations, payloads, and missions. One such set of shield criteria requires that the shield reduce the direct neutron and gamma dose emanating from the reactor during 10,000 hr of operation at 600 kw to 5×10^{12} fast nvt and 9×10^{6} rad (C) of gammas, respectively, over most of the surface of an 8-ft-diam payload assumed to be 15 ft from the reactor. A relatively small portion of the payload may receive more than 10^{13} fast nvt due to neutron scattering from the NaK pipes and wire harness where they pass around the outside of the shield. It is assumed that the spacecraft will be designed to limit scattering from the power conversion components, radiator, spacecraft structure, etc., to 5×10^{12} fast nvt in 10,000 hr so that the total payload dose due to direct plus scattered neutrons will be $\sim 10^{13}$ fast nvt. Similarly, the total gamma dose to the payload (due to activated coolant outside the reactor as well as to direct and scattered photons) is assumed to be $\sim 10^{7}$ rad.

Configuration. The reactor and shield are designed to be launched with the reactor above the shield.

Reliability. A tentative reliability goal of 93% has been set for the reactor and its associated shield and controls to survive launch, achieve automatic startup, and operate for 10,000 hr. This figure includes failures due to meteorite puncture.

Reactor Design

The forementioned performance objectives have led to the reactor and shield design illustrated in Figs. 1 and 2. Reactor and shield design data, operating parameters, and weights are listed in Tables 1 and 2. The overall size and configuration of the SNAP 8 reactor is illustrated by the SNAP 8 Developmental Reactor Mockup shown in Fig. 3 and by the SNAP 8 Experimental Reactor shown in Figs. 4–6.

Core

A layout drawing of the reactor is shown in Fig. 1. The stainless steel core vessel is 9.214-in. i.d. × 22.4-in. long. The complete core assembly including the vessel, fuel elements, other internal components, and the NaK coolant weighs approximately 300 lb. The core contains 211 fuel elements, 0.56-in. o.d. and approximately 17-in. long. Each fuel element contains a fuel-moderator rod composed of a zirconium, 10 wt % uranium alloy hydrided to a hydrogen concentration of 6×10^{22} hydrogen atoms per cubic centimeter, i.e., near the hydrogen concentration in cold water. The fuel elements are clad in Hastelloy-N, and a hydrogen permeation barrier is applied to the inside of the cladding tube to limit hydrogen loss to an acceptable value during reactor operation.

The space between the hexagonal array of fuel elements and the cylindrical core vessel is filled with internal reflector elements as illustrated in Fig. 7. These internal reflector elements are composed of beryllium oxide clad in stainless steel.

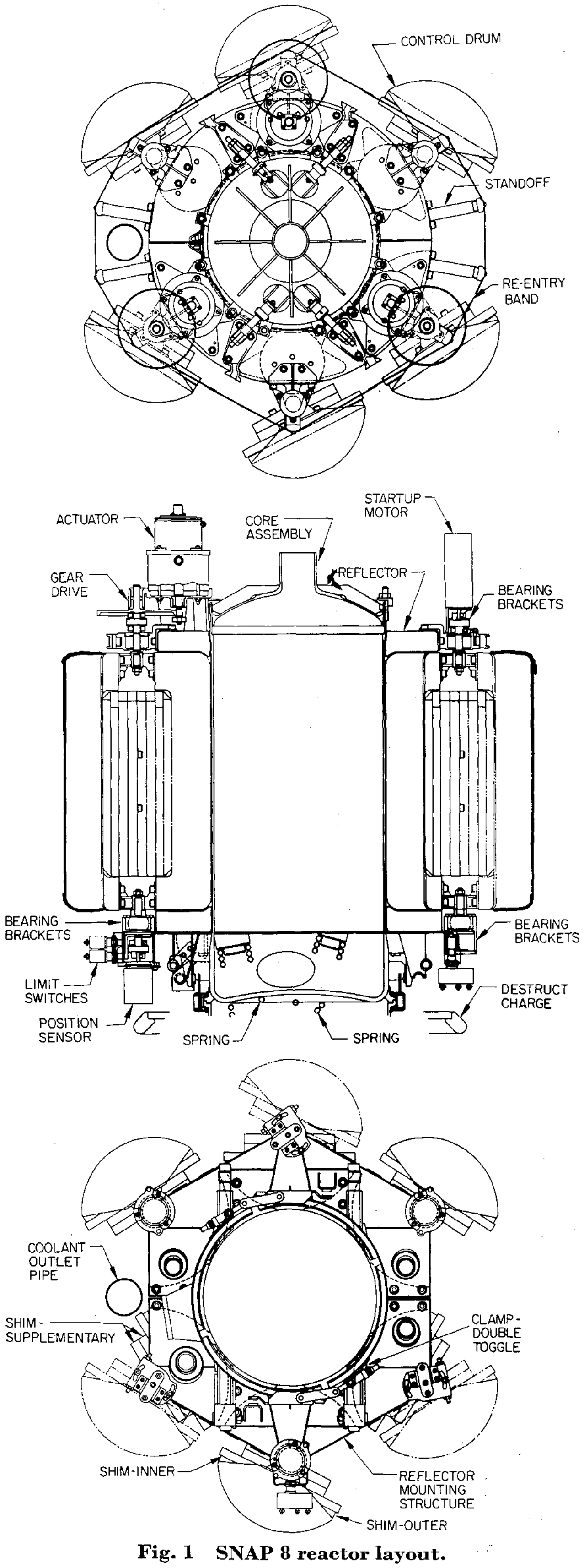

Fig. 1 SNAP 8 reactor layout.

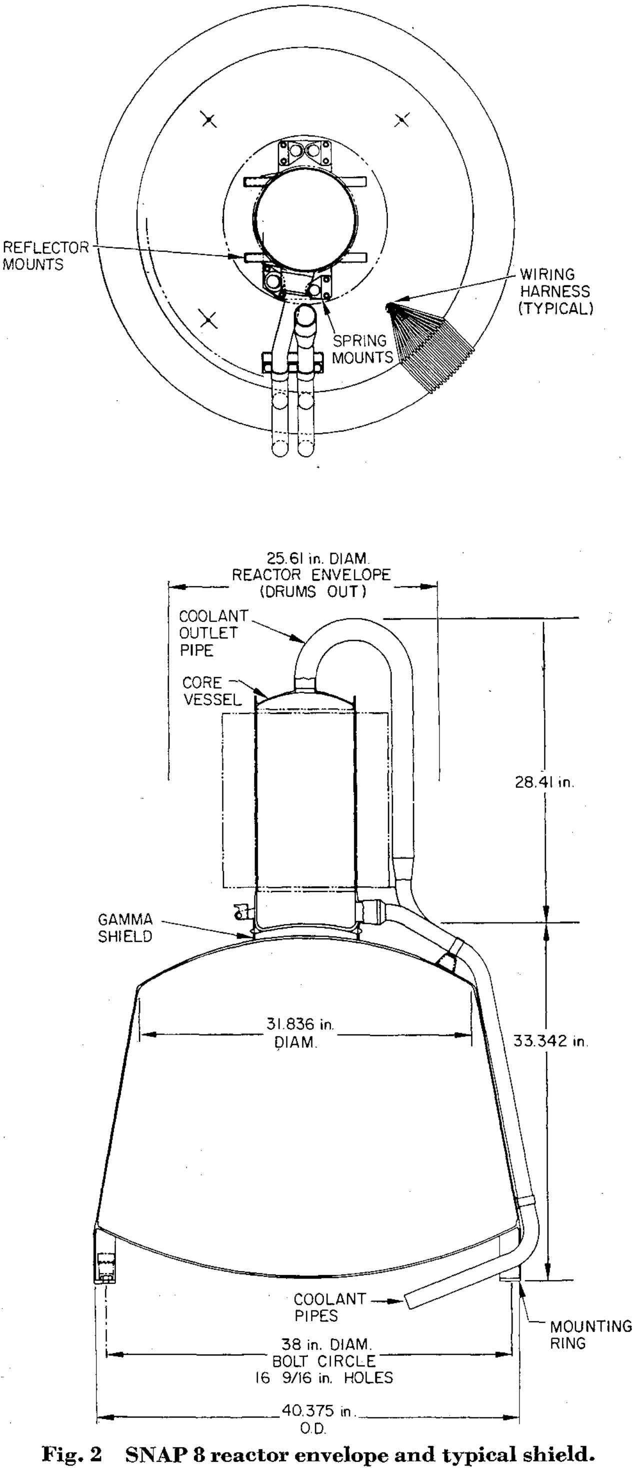

Fig. 2 SNAP 8 reactor envelope and typical shield.

Reflector

Reflector control system

The core vessel is surrounded by an annulus of beryllium approximately 3-in. thick and approximately 17-in. long.

Table 1 SNAP 8 reactor and shield design data

Rated operating conditions	
Reactor thermal power, kw	600
Operating life, hr	10,000
NaK outlet temperature, °F	1300
NaK inlet temperature, °F	1100
NaK operating pressure, psia	40
NaK flowrate, lb/sec	13.3
Average thermal flux, n/cm²/sec	5×10^{12}
Medium fission energy, ev	0.2
Fuel elements	
Number	211
Fuel element o.d., in.	0.560
Degree of hydriding, N_H, atoms/cm²	6.0×10^{22}
Internal reflectors	
Composition	BeO
Cladding material	Stainless steel
Core vessel	
Inside diameter, in.	9.214
Length, in.	22.4
Thickness, in.	0.105
Material	Stainless steel
Reflector	
Composition	Beryllium
Thickness, in.	3 ± 1
Number of control drums	6
Shield	
Composition	LiH
Vessel material	Stainless steel
Vessel thickness, in.	0.109
Vessel o.d. at large end of cone, in.	40.4
Vessel o.d. at small end of cone, in.	31.9
Direct neutron dose at payload 15 ft from reactor, fast nvt	0.5×10^{13}
Direct gamma dose at payload 15 ft from reactor, rad (C)	0.9×10^{7}
Electric power requirements	
3500 w-sec-d.c. pulse to fire explosive pin-pullers to initiate startup	
300 w, 28-v-d.c. for 6 hr during startup	
100 w, 28-v-d.c. for 10,000 hr after startup	

Table 2 Reactor and shield weight summary[a]

Core assembly		
Fuel elements	202	
Core vessel	40	
Grid plates, flow baffle plate, and structural components	18	
Internal reflectors	10	
NaK in core vessel	14	
NaK pipes and NaK in pipes	14	
Temperature sensor switches	2	
		300
Reflector assembly		
Beryllium reflector	155	
Control drum actuators	25	
Drive mechanisms and structure	35	
Shutdown and safety devices	15	
		230
Shield assembly		
Lithium hydride	680	
Shield vessel and structure	310	
Gamma shield	34	
Cable harness	15	
Destruct charge	11	
		1050
Programmer and controller (located in instrument compartment of spacecraft)		20
Total reactor and shield weight		1600

[a] The units are in pounds.

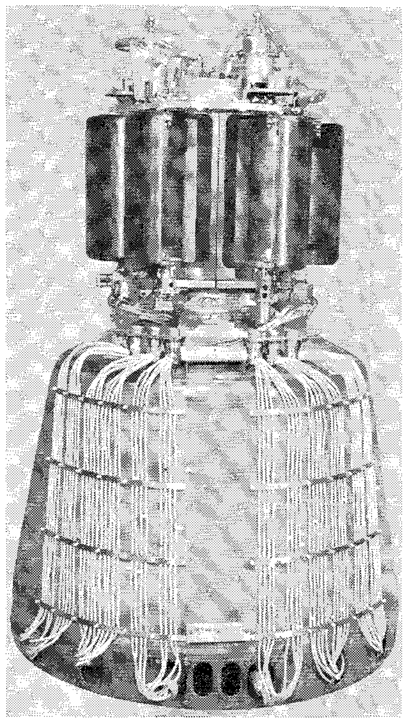

Fig. 3 Model of SNAP 8 reactor.

This neutron reflector contains six movable semicylindrical sections or drums as shown in Fig. 1.

Reactor control is accomplished by rotation of the drums toward or away from the core to increase or decrease the fraction of leakage neutrons reflected back to the core. The reactor control system is designed to maintain the NaK outlet temperature within the range between 1270° and 1330°F. If the coolant outlet temperature wanders out of this range, the controller signals one of the long-term actuators to rotate one of the control drums in or out approximately 0.5°.

Startup

Reactor startup is initiated by a signal to the startup programmer located in the payload compartment of the spacecraft. The startup programmer automatically sequences the disarming of the reactor launch safety systems and energizes the control drum motors to drive the control drums in at a preset rate to take the reactor to critical and to rated operating temperature. NaK coolant flow (at least 10% of rated flow) must be maintained through the reactor during startup. The startup sequence, illustrated schematically in Fig. 8, proceeds as follows: the reactor destruct charge (described later) is ejected overboard. The six control-drum lockout pins are released. The startup programmer energizes all six control-drum actuators. Three "startup drums" are driven in at constant speed and lock full-in in approximately 5.8 min after startup is initiated. Simultaneously, the other three "long-term control drums" are stepped inward fairly rapidly until the reactor is approximately $0.50 subcritical. At this point, the stepping rate is slowed down by a signal to the programmer from a preset position-sensing switch on one control-drum shaft. The control drums continue in until the NaK temperature reaches 1270°F, approximately 3 hr after initiation of startup. The closing of the low-temperature limit switch deactivates the startup programmer, and the control system is switched to the automatic temperature control mode.

During temperature control, for the 10,000-hr life of the system, if the low- or high-temperature (1270° and 1330°F) switches are closed, the control drums are stepped $\frac{1}{2}$° every 4 min until the NaK temperature is within the control band.

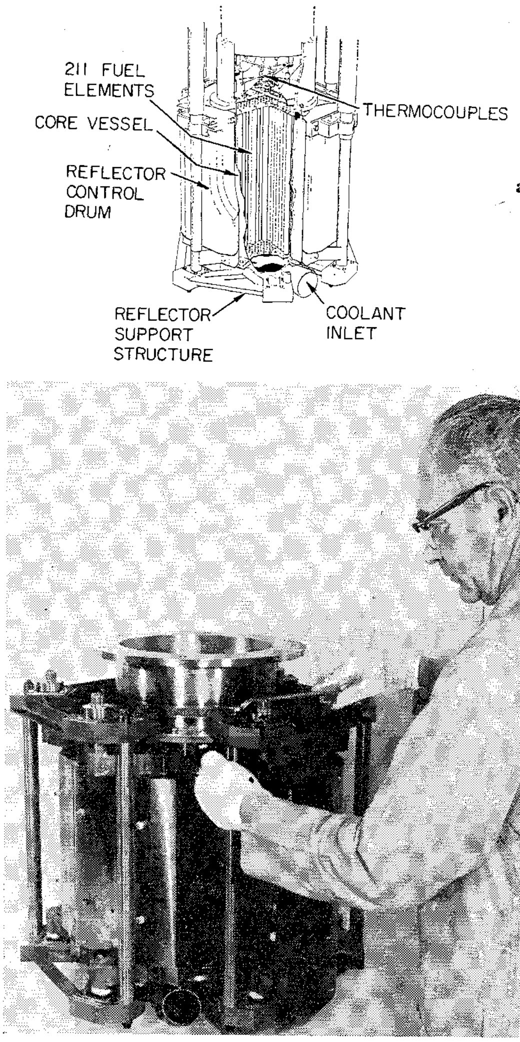

Fig. 4 SNAP 8 experimental reactor.

Safety

During ground checkout and assembly of the spacecraft, the reactor control drums are locked in the least reactive position by both drum lockout pins and by a mechanical lock on each drum which requires a key for removal. The keylocks are used during checkout and would be removed prior to launch through small access holes (about 6 in. in diam) in the vehicle skin. This leaves the drums pinned out during launch. The drums are unpinned during the orbital startup sequence by explosive pinpullers.

If the proper orbit is not reached, the reactor may be destroyed on ground command by the destruct charge located around the inlet plenum of the core vessel. This shaped charge is designed to rupture the core and disperse the fuel elements sufficiently to prevent accidental criticality. The destruct charge is ejected during the orbital startup sequence.

Irreversible shutdown of the reactor is accomplished by spring ejection of the entire beryllium reflector from the core. The reflector is divided axially into two halves that are held together by a steel band around the top of the reactor. This band can be broken by 1) a ground command release actuator, 2) a coolant temperature-sensing actuator to shut down the reactor when the coolant temperature drops significantly at the end of reactor or power conversion system life, or 3) the eat of re-entry into the earth's atmosphere.

Shielding Requirements

Nuclear radiation is obviously a significant factor in the design of a spacecraft that employs a reactor. Maximum

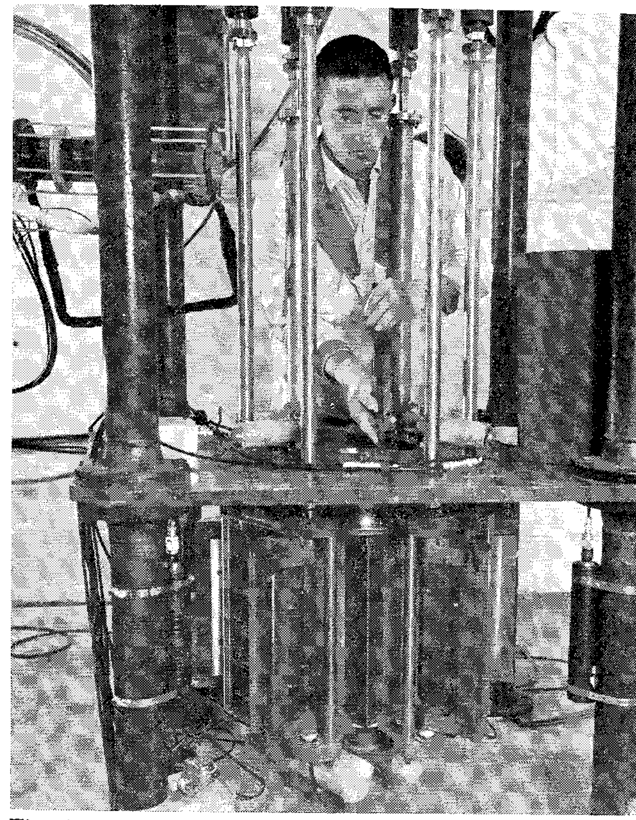

Fig. 5 S8ER dry critical fuel loading. The reactor is attached to the bottom of a table.

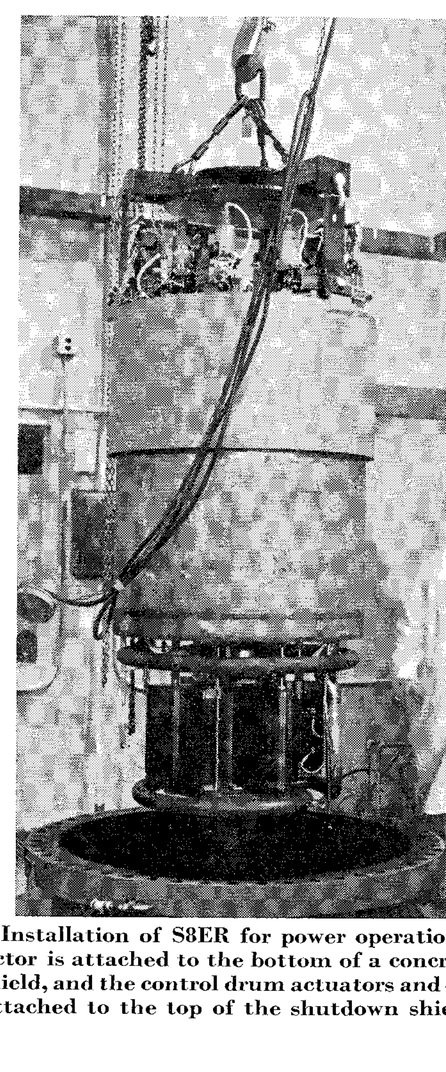

Fig. 6 Installation of S8ER for power operation. Note: the reactor is attached to the bottom of a concrete shutdown shield, and the control drum actuators and drives are attached to the top of the shutdown shield.

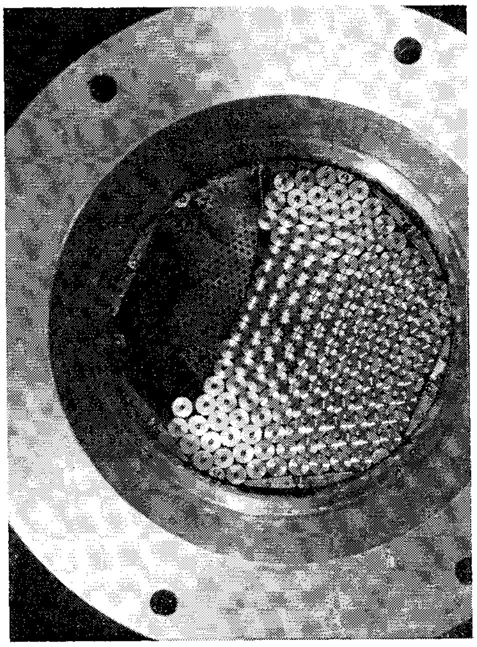

Fig. 7 SNAP 8 reactor core partially filled with fuel elements.

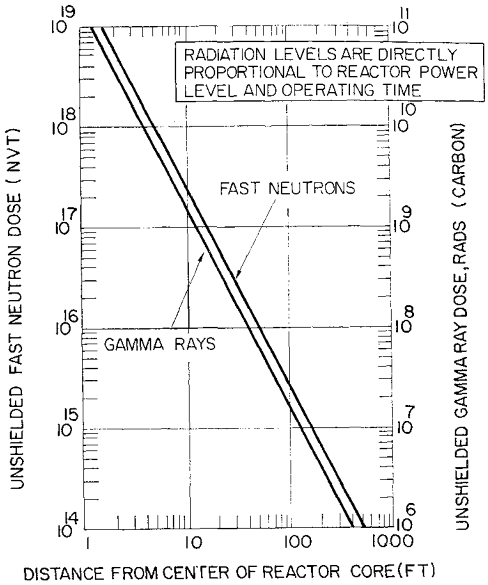

Fig. 9 Nuclear radiation levels outside an unshielded SNAP 8 reactor following 10,000 hr of operation at 600 kw, thermal.

permissible radiation levels always are included in the design criteria. The design dose for an unmanned spacecraft generally is defined by the radiation damage tolerance for the payload equipment. This dose may be met through the combination of good shield design and good system design.

The radiation levels outside a SNAP 8 reactor are presented in Fig. 9. The doses correspond to a 10,000-hr exposure to an unshielded reactor operating at a nominal power level of 600 kw (thermal). The angular distribution of the radiation leakage is approximately isotropic.

Fast neutron radiation dominates shield design for unmanned SNAP 8 systems. This is a result of the relative composition of the radiation environment external to the unshielded SNAP 8 reactor. For typical payload components, the ratio of unshielded neutron dose to design neutron dose is several orders of magnitude higher than the gamma dose ratio.

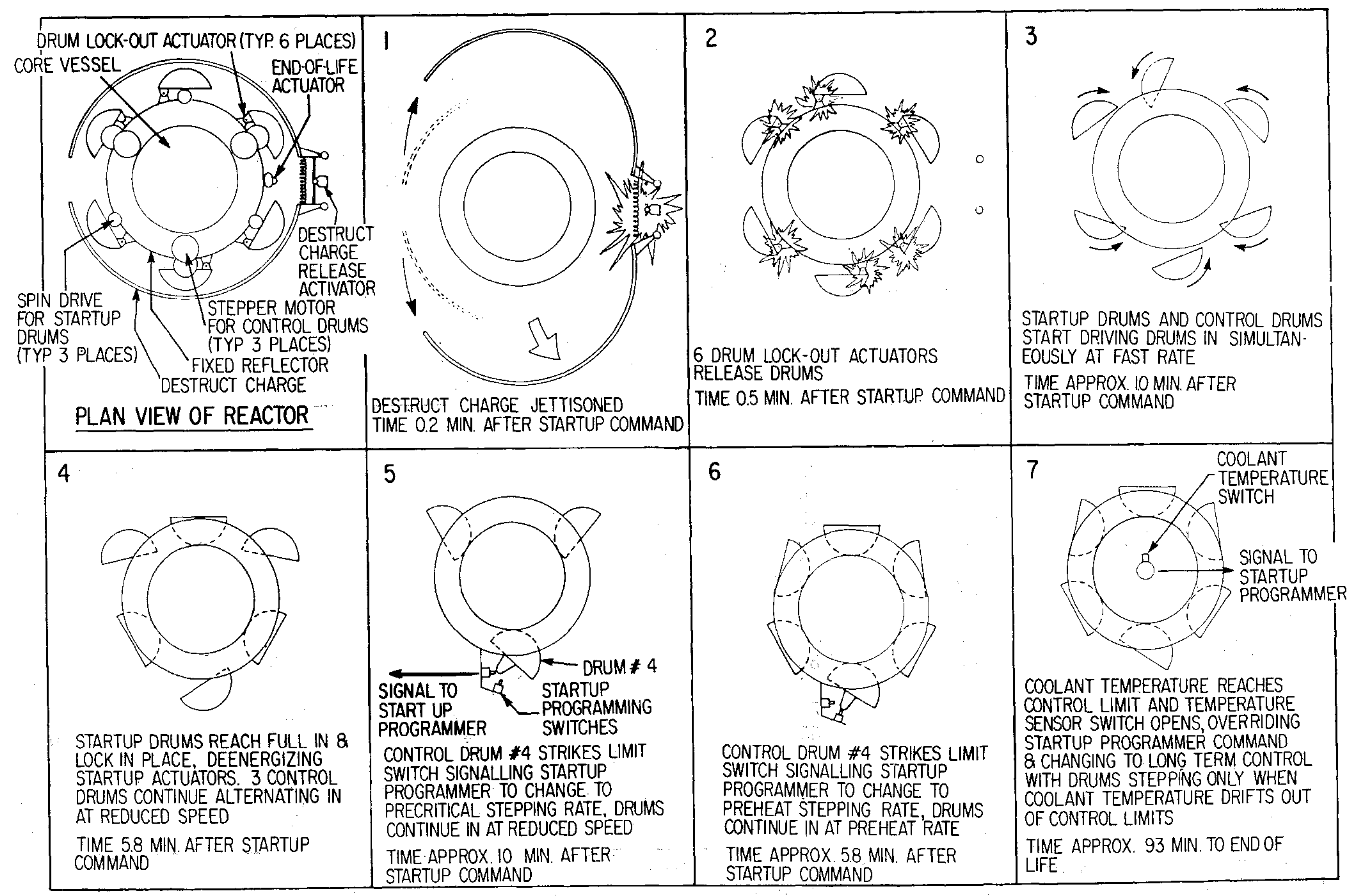

Fig. 8 Reactor startup sequence.

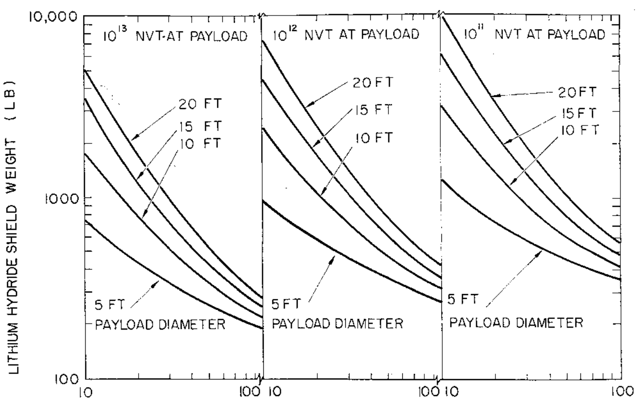

Fig. 10 Weight of lithium hydride required for shadow shields for various shield criteria.

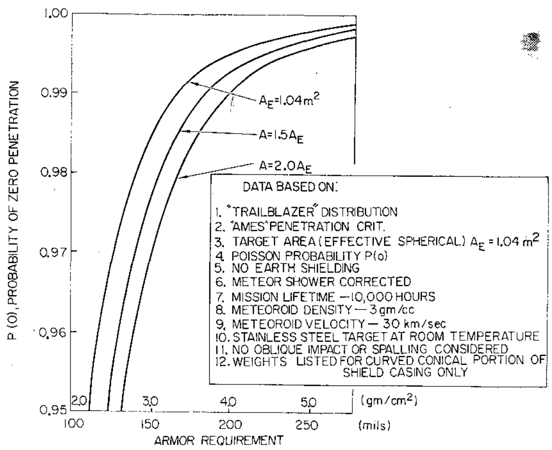

Fig. 11 Shield vessel thickness required for protection against micrometeorite puncture.

For this reason, the SNAP 8 shield is designed primarily on the basis of adequate neutron attenuation. The neutron shield material used is lithium hydride. This material has a very high value of neutron removal cross section per unit weight, and, in addition, it has good thermal and radiation stability.

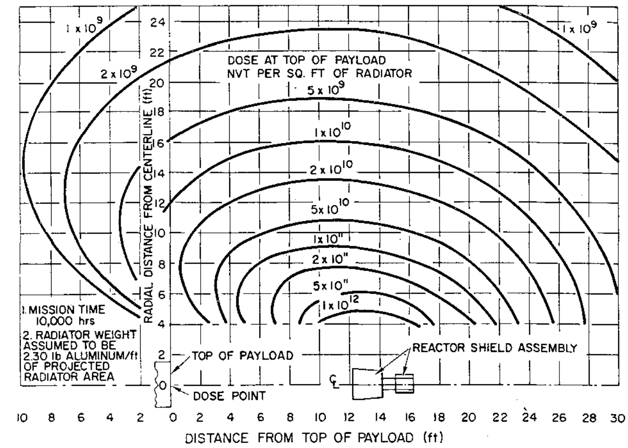

Fig. 12 Neutron dose scattered to a payload 15 ft from the reactor per square foot of flat-plate radiator.

Figure 10 presents the variation of lithium hydride shield weight with three spacecraft design criteria. These parameters are 1) the separation distance between the payload and the center of the reactor core, 2) the permissible fast neutron dose at the payload, and 3) the payload diameter. It should be noted that these weights do not include allowances for shield casing and structural support. The relative importance of these weights may be inferred from Table 2, in which the shield weight breakdown for an actual SNAP 8 shield design is tabulated.

The radial wall thickness of the shield containment vessel is determined by micrometeorite protection considerations. This sort of protection is required, since a rupture of the containment vessel results in a loss of hydrogen from the lithium hydride shield and a consequent increase in radiation damage to the payload. Figure 11 presents the estimated zero-penetration probability vs required armor thickness.

The neutron radiation levels quoted in Fig. 10 refer only to the direct dose (that due to neutrons that come directly from the reactor). Another extremely important source is that due to neutrons that scatter from the vehicle structure and radiators of the spacecraft. Figure 12 presents estimates of the scattered neutron dose at the payload, which is about 15 ft from the center of the core. Each isodose line represents the payload dose due to neutrons that scatter

Table 3 Radiation scattering analysis of several radiator configurations

Radiator type[a]	Radiator dimension[b] Width, in.	Length, in.	Radius, in.	Payload diameter, in.	Reactor-payload distance, in.	Scattered fast neutron dose at payload, nvt[c]
Folding (L), flat plate	120	150	...	114	200	1.8×10^{14}
Folding (L), flat plate	160	112	...	114	162	1.8×10^{14}
Folding (L), flat plate	150	120	...	148	171	1.3×10^{14}
Folding (L), flat plate	150	120	...	214	188	4.8×10^{13}
Folding (T), cylindrical	151	119	...	114	201	7.7×10^{14}
Folding (T), cylindrical	155	116	...	148	206	4.9×10^{14}
Folding (T), flat plate	120	150	...	214	188	1.9×10^{14}
Fixed, flat plate	27	667	...	114	718	2.1×10^{12}
Fixed, flat plate	44	409	...	148	460	1.0×10^{13}
Fixed, flat plate	77	234	...	214	288	2.6×10^{13}
Fixed, flat plate	57	335	...	114	386	6.0×10^{12}
Fixed, flat plate	74	258	...	148	309	1.6×10^{13}
Fixed, flat plate	107	178	...	214	229	7.4×10^{13}
Conical	...	255	22.5 to 74	148	286	$<4 \times 10^{5}$
Conical	...	180	66 to 107	214	210	$<4 \times 10^{5}$
Cylindrical	...	201	57	114	252	2.6×10^{15}
Cylindrical	...	155	74	148	206	6.7×10^{14}
Cylindrical	...	107	107	214	176	8.9×10^{14}

[a] The folding, flat-plate radiators have longitudinal (L) or transverse (T) hinges.
[b] "Width" of radiators refers to radial span, "length" to axial span. All radiators have 500 ft² of radiating surface area.
[c] 10,000 hr of reactor operation at 300 kw (thermal).

from 1 ft^2 of surface area centered at any point along the isodose line.

The scattered radiation characteristics of several possible SNAP 8 radiator configurations have been analyzed. Table 3 presents the results of one such study. In general, the fast neutron dose from unshielded radiators exceeds 10^{12} nvt for reactor-to-payload distances of less than about 40 ft.

One way to reduce the fast neutron dose scattered from the radiator to the payload is to shield the radiator. For most radiator configurations except a conical radiator, however, shielding the radiator requires increasing the solid angle shadowed by the shadow shield, thus increasing the weight of the shield. It should be noted that, in general, the portion of shield which shadows the radiator must be nearly as thick as the payload shadow shield. Otherwise, the neutrons emerging from the surface of the thinner shield constitute a more powerful surface source than the outer surface of the payload shadow shield. Thus, a shield that reduces the radiation incident upon the radiator can be prohibitively heavy if the radiator extends out like wings, for example.

On this basis, it is recommended that the conical radiator concept be given serious consideration for the SNAP 8 spacecraft. This concept has the inherent disadvantage that the radiating area is restricted to the external surface only but retains the extremely desirable characteristic that all spacecraft components and structures can be located behind a relatively small shadow shield.

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Prediction of Interstage Pressure in Multistage Solid-Propellant Rocket Systems

L. D. SMOOT*
Hercules Powder Company, Salt Lake City, Utah

A mathematical model has been developed for accurately predicting the interstage pressure-time transient that exists during the separation of two stages of a solid-propellant rocket system. The system of equations, composed of mass, energy, and force balances for the rocket chamber and interstage region, is solved simultaneously to yield predictions of the time dependence of chamber temperature and pressure together with interstage pressure, temperature, and volume. Sample calculations and prediction-results for a typical multistage rocket system are included.

Nomenclature

a = reaction-time constant in Summerfield equation
a_l = acceleration of lower-stage rocket relative to earth, ft/sec^2
a_r = acceleration of upper-stage rocket relative to lower stage, ft/sec^2
a_u = acceleration of upper-stage rocket relative to earth, ft/sec^2
A_b = propellant burning area, ft^2
A_e = combined cross-sectional area of nozzles at exit planes, ft^2
A_g = variable cylindrical surface-area of interstage gap, ft^2
A_i = cross-sectional area of interstage at gap edge, ft^2
A_t = combined cross-sectional area of nozzles at throats, ft^2
b = diffusion-time constant in Summerfield equation
B = angle of inclination of rocket to earth at time of separation, deg
C = thrust coefficient efficiency; $0.93 \leq C \leq 0.99$
C_d = interstage gap discharge coefficient
C_f = thrust coefficient of upper stage
C_{p_c} = heat capacity of chamber gases, Btu/lb-°R
C_{p_i} = heat capacity of interstage gases at constant pressure, Btu/lb-°R
C_{p_0} = heat capacity of igniter gases, Btu/lb-°R
C_{p_s} = heat capacity of interstage surfaces, Btu/lb-°R
C_{v_c} = heat capacity of chamber gases at constant volume, Btu/lb-°R
C_{v_i} = heat capacity of interstage gases at constant volume, Btu/lb-°R
C_w = rocket nozzle mass flow coefficient, sec^{-1}
C_{w_g} = interstage gap mass flow coefficient, sec^{-1}
d_b = propellant density, lb/ft^3
F_r = residual thrust of lower stage motor, lbf
g = acceleration of gravity, ft/sec^2
g_c = gravitational constant, lb-ft/lbf-sec^2
h_i = heat transfer coefficient of interstage gases to interstage surfaces, Btu/hr-ft^2-°F
k = ratio of specific heats, C_p/C_v, for exhaust
K = fraction of exhaust internal-energy transferred to interstage walls as heat loss (if heat loss equals 80%, K equals 0.80)
L = thrust coefficient correction for divergence angle
m_0 = mass flow-rate of igniter, lb/sec
M_e = effective molecular weight of chamber-gas/condensed-phase mixture, lb/lb-mole
M_l = mass of lower stage, lb
M_u = mass of upper stage, lb
P_c = chamber pressure, lbf/ft^2
P_i = interstage pressure, lbf/ft^2
P_e = pressure at nozzle exit plane, lbf/ft^2
q_i = rate of heat loss from interstage gases to interstage walls, Btu/sec
Q_i = total heat loss from interstage gases to interstage walls, Btu
q_c = heat loss from chamber gases to chamber walls, Btu/sec
r = propellant burning rate, fps
r_i = radius of interstage at gap edge, ft
R = universal gas constant, ft-lbf/lb-mole-°R
S = total surface area of interstage walls, ft^2

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* Presently Technical Specialist, Lockheed Propulsion Company, Redlands, Calif. Member AIAA.