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POTENTIALITIES OF THE RADIOISOTOPE ELECTROSTATIC PROPULSION SYSTEM

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DISCLAIMER

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ABSTRACT

Anticipated availability dictates the choice of cerium-144 as fuel for radioisotope electrostatic propulsion systems. With appropriate vehicle design, the gamma dosage can be acceptable for unmanned probe vehicles even without shielding. Good mission performance can be obtained with vehicles small enough for convenient mating with existing chemical boosters. Although launch-pad and boost-phase radiation hazards are serious problems, practical solutions may be possible. Manned interplanetary missions that require solar-flare absorption shielding appear to be feasible with this propulsion system.

INTRODUCTION

For electric propulsion to be markedly superior to other space propulsion systems such as the nuclear rocket, the electric powerplant must be very light weight, about 10 lb/kw or less. The radioisotope electrostatic propulsion system has promise of specific weights as low as 0.5 lb/kw (ref. 1). In addition to the promise of very light weight,

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the radioisotope electrogenerator has optimum theoretical performance at voltages in the range of 500,000 to 1,500,000 volts. This very high-voltage direct-current power is ideally suited to integration with the colloidal-particle electrostatic thrustor. With such high-voltage power, the colloidal-particle thrustor has promise of high efficiency throughout the specific impulse range of interest for interplanetary missions (ref. 2).

In considering the practical feasibility of the radioisotope electrostatic propulsion system, a number of problems arise such as radioisotope availability, radiation hazards, and mating with chemical boosters. It is the purpose of this paper to assess these problems, to discuss possible solutions, and to estimate the potentialities of the propulsion system for future space missions.

ELECTROGENERATOR OPERATION AND DESIGN

In previous conceptual design studies, the general principles of operation of the radioisotope electrogenerator have been discussed in detail (refs. 1 and 3). This preliminary analysis established that the radioisotopes polonium-210 (Po^{210}) and cerium - praseodymium-144 (Ce^{144}-Pr^{144}) have properties best suited for electrogenerators intended to produce power for electrostatic propulsion. The diagram shown in figure 1 illustrates the proposed operation of an electrogenerator that uses Ce^{144}-Pr^{144} fuel. The radioisotope emits negative beta particles with a continuous energy spectrum that has a maximum energy of 2.98 Mev. The net positive charge produced in this decay process raises the emitter potential to $+\Phi$ volts above space potential. In steady-state operation, beta particles with insufficient radial energy components cannot reach the collector, so they fall back to the emitter where their energy is lost as heat. Other beta particles will reach the collector and be stopped in the foil. Still others may pass through the foil and travel on into space. The current of negative beta particles that passes through the collector must be compensated for by an equal current of positive charges ejected to space. In the scheme shown in figure 1, this compensating current of positive charges is supplied by positive ions ejected to space (e.g., hydrogen ions). As discussed in reference 1, the collector foil (or screen) maintained at space potential is required in order to shield the emitter from the plasma of space

The flow of negative charge carried by the beta particles through an adverse change in potential constitutes direct-current electric power. This electric power could be converted to thrust with a colloidal-particle electrostatic thrustor as shown in figure 1. Maintaining the emitter at a desired potential in steady-state operation requires electrons to be supplied to the emitter to replace the beta particles that have reached the collector. These electrons would be supplied from the charging chamber where in effect, they are removed from the colloidal particles in the formation of positively charged propellant particles. The charging chamber is at $+\Phi$ volts, so the positively charged propellant would be accelerated to the desired exhaust velocity by controlling the colloidal-particle mass. The charged-particle beam would be neutralized with electrons drawn from two sources, the beta particles that have been stopped in the collector and the electrons removed from the compensating gas atoms.

Operation of the Po^{210} radioisotope electrogenerator is illustrated in figure 2 and is similar to the Ce^{144}-Pr^{144} electrogenerator except for a reversal of voltage. Alpha particles are emitted with a discrete energy of 5.3 Mev. Free electrons remaining after the decay process lower the emitter potential to $-\Phi$ volts below space potential. In steady-state operation, these electrons would be used for form negatively charged colloidal particles, for example, by electron attachment. Positive ions would be used to neutralize the exhaust beam of negatively charged propellant particles. Electrons removed from the neutralization-gas atoms would flow to the collector. Some of this electron current would match the current of positive charge resulting from alpha particles stopped in the collector. The remainder of this electron current would be ejected to space to compensate for the current of positive charge carried by alpha particles that pass through the collector.

The previous conceptual design study (ref. 1) emphasized the Po^{210} system with a concentric spherical configuration shown in figure 3. Electrogenerator specific weights of less than 0.5 lb/kw and powerplant efficiencies of 25 percent were predicted. Since alpha particles have a relatively short range, the radioisotope fuel layer thickness would be very small so that the emitter and the collector diameters would be large for electric power outputs of interest for space propulsion. Such large sizes would require assembly or erection in orbit with attendent complex problems in handling, packaging, and launching. In addition, optimum cell voltage was found to be about 1,500,000 volts, which certainly suggests electric breakdown problems. Another problem anticipated in reference 1 is that of delta rays (electrons knocked out of the emitter by emerging alpha particles). These electrons could constitute a devastating short circuit unless a suppressor grid were employed, which of course would increase the powerplant specific weight. Recent data reported in reference 4 show that as many as ten delta electrons can be ejected by alpha particles emerging from Po^{210} covered with a very thin gold film. Although the preceding problems all appear solvable, the low availability and high cost of Po^{210} provide strong arguments in favor of the heavier and less efficient Ce^{144}-Pr^{144} system.

As discussed in reference 1, the exact theoretical calculation of electrogenerator performance is laborious because of complex range-energy relations and the interrelation of the many geometric and design parameters. The effect of design parameters on performance is valuable information for a number of reasons, so a parametric study has been completed, which is reported in reference 5. The results of that study are used in this paper to provide the basic design of a Ce^{144}-Pr^{144} electrogenerator.

In the conceptual design study reported in reference 1, the Ce^{144}-Pr^{144} electrogenerator design had a specific weight of about 4 lb/kw, and the components were at high temperatures (emitter, 924° C, collector, 706° C). With the additional information provided by the parametric study of reference 5, it is now possible to design Ce^{144}-Pr^{144} electrogenerators with specific weights and temperatures approaching those of the Po^{210} electrogenerator. Because of the advantages of greater availability of Ce^{144}-Pr^{144} fuel and the smaller physical size of Ce^{144}-Pr^{144} electrogenerators, it is appropriate to use the Ce^{144}-Pr^{144} system to illustrate the potentialities of the radioisotope electrostatic propulsion system.

The electrogenerator design used herein was chosen on the basis of conservative component temperatures and is not necessarily an optimum design. The various design parameters are as follows:

Radioisotope fuel	pure cerium-144
Fuel layer thickness	35 mg/cm^2
Fuel support foil thickness	25.9 mg/cm^2
Collector foil thickness	5 mg/cm^2
Collector to emitter radius ratio	2.0

Various other design parameters were determined from the results of reference 5:

Electrogenerator specific weight	0.53 kg/kw 1.17 lb/kw
Electrogenerator efficiency	16.2 percent
Emitter radioactivity	121 curies/cm^2
Electric power output per unit emitter area	0.14 w/cm^2
Emitter foil thickness (for molybdenum)	1 mil
Collector foil thickness (for aluminum)	3/4 mil
Emitter temperature (for 0.75 emittance)	410° C 770° F
Collector temperature (for 0.75 emittance)	240° C 463° F

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RADIOISOTOPE AVAILABILITY AND COST

The radioisotope Ce^{144}-Pr^{144} is a fission product, so its availability as a by-product depends on the national reactor power level. The following estimate of the by-product availability of Ce^{144}-Pr^{144} is given in reference 6:

Year	1963	1964	1965	1970	1980
Ce^{144}-Pr^{144}, megacuries/year	1	1	100	115	1150

Ce^{144}-Pr^{144} has a 285-day half life, so it has a power decay as shown in figure 4. In one month, Ce^{144}-Pr^{144} has a negligible decay, so monthly production serves as a measure of availability for electrogenerators. The availability of Ce^{144}-Pr^{144} estimated in reference 6 is shown in figure 5 in terms of thermal kilowatts per month. Radioisotope electrogenerators have theoretical efficiencies from 10 to 30 percent, so it is evident that radioisotope electrostatic propulsion systems of 10 kw electric power are possible, with regard to radioisotope availability, as early as 1965. By 1980, the estimated availability would permit electrogenerators with output powers of over 100 kw. By accumulating the radioisotope over a period of months, these power levels could be increased by a factor of five or ten but would result in increased powerplant specific weights if final refinement were not done just before launch of the spacecraft. Since the powerplant specific weight is roughly inversely proportional to the power reduction fraction (ref. 5), the increase in powerplant specific weight would not be great. In any event, the cost of the decayed radioisotope would be charged against the system if final refinement were not done, and even greater cost would result if final refinement were done.

The cost of the separated Ce^{144}-Pr^{144} radioisotope is estimated in reference 6 as 4 cents per curie (about $5000 per thermal kilowatt) for the estimated 1965 production rate.

Some further comments regarding the availability and cost of radioisotopes are appropriate at this point. The availability and cost estimates listed in reference 6 are based on anticipated increases in the national ground-based nuclear-electric powerplants. The viewpoint taken is that of radioisotope availability as a by-product of national electric power production. It is evident that if the demand for radioisotopes became great enough from the viewpoint of space propulsion, reactors could be built primarily for the production of radioisotopes. For example, a preliminary estimate of the cost of Ce^{144}-Pr^{144} produced in a reactor especially built for that purpose is about $28 per thermal watt of Ce^{144}-Pr^{144} (information received in a private communication with A. F. Rupp of AEC Oak Ridge National Laboratory). Certainly some of this cost would be covered by the simultaneous production of other radioisotopes and also by the ground-based electric power that would be a by-product in this case. Similar comments are valid regarding Po^{210}. This radioisotope is produced by neutron bombardment of bismuth. If the demand became great, it seems possible that more ground-based reactors could be operated with bismuth coolant in order to produce sufficient quantities of Po^{210} for space propulsion.

PAYLOAD RADIATION DOSAGE

High energy gamma radiation is emitted from Ce^{144}-Pr^{144} particularly in the praseodymium decay. The important gamma energies and occurences are given in reference 7 as follows:

Gamma energy, Mev	Number of gammas per decay (average)
0.081	~0.035
0.134	0.106
0.691	0.016
1.49	0.0026
2.18	0.0078

From this tabulation, the total gamma radiation is 0.049 Mev per decay (average of many decays). Bremsstrahlung radiation and low-intensity gammas are negelcted herein. It is of interest to determine the radiation dosage of payloads that might be carried with radioisotope electrostatic propulsion systems.

Expressions are derived in the appendix for the radiation dose rate around an electrogenerator that has a coaxial cylindrical configuration. As shown in the appendix, the radiation dose rate depends only on the radioactivity per unit area on the emitter cylinder, the gamma radiation energies and their occurrence per decay, the length to diameter ratio of the cylindrical configuration, and the position of the payload with respect to the electrogenerator. The gamma radiation dose rate along the electrogenerator axis is shown in figure 6 for the Ce^{144}-Pr^{144} design specified previously. For these calculations, the factor K (see appendix) was determined to be 2.39×10^5 mr-cm^2/curie-hr using the information given in references 7 and 8. For an electrogenerator length to diameter ratio of 5, the radiation dose rate is 0.011×10^{7} r/day at one cylinder length away from the axis. At this separation distance the radial profile of dose rate is fairly flat.

A typical probe mission to the planet Mars has a trip time of 200 days, which would result in a total dose of about 2×10^{7} r at the payload. This dose is below the damage level of most materials and, in fact, is a typical allowable dose specification for payloads. Longer missions may require greater payload separation distances or longer electrogenerators, both of which are feasible design changes.

SPACECRAFT DESIGN

The detailed design of spacecraft with a radioisotope electrostatic propulsion system poses a number of unusual electromechanical problems. Solutions to many of these problems were suggested in reference 1, but the problem of packaging for boost into orbit with chemical boosters remained mostly unanswered. Large spherical electrogenerators such as that shown in figure 3 might be packaged by folding and then expanded into shape after reaching the satellite orbit about Earth. A consequence of packaging by folding might be excessive temperature due to increased local heat release rates in the emitter. An alternative approach is that of boosting the spacecraft with the radioisotope fuel in a specially cooled container and depositing the radioisotope on the emitter support foil after reaching the satellite orbit. The cooling during boost would require about 0.5 lb of water per thermal kilowatt in a 15-min boost, which is not a particularly serious loss in overall mission payload capacity.

However, the problems involved in depositing radioisotope fuel in uniform layers a few mils thick while in orbit may be difficult to solve.

An alternative to the packaging problem is possible with the cylindrical electrogenerator because of its smaller diameter. Electrogenerator cell diameters for the design specified in the INTRODUCTION are shown in figure 7 for a range of output power levels. It is evident from the figure that, for $L/D = 5$, electrogenerators up to 25 kw would fit into the payload shroud of the Atlas-Agena booster, and electrogenerators up to 100 kw could be mated with the Centaur booster. As will be shown later, these power levels are commensurate with probe vehicles for Mars and Saturn orbiter missions. If higher power electrogenerators are required, the payload shroud might be made larger in diameter than the upper stage, or the electrogenerator might be made smaller by using a less conservative design than that used for figure 7. As shown in reference 5, the electrogenerator size could be reduced with little sacrifice in performance, but higher component temperatures would result.

In the preceding section, it was shown that unshielded payloads will require a separation distance from the Ce^{144}-Pr^{144} electrogenerator to avoid excessive gamma radiation doses. This separation might be provided with an extensible boom, as shown in figure 8. During the boost phase, the boom could be nested into the hollow support column, and would be extended after reaching the satellite orbit about Earth. (Other details of spacecraft design are discussed in ref. 1.)

LAUNCH-PAD AND BOOST-PHASE RADIATION HAZARDS

The gamma radiation levels near unshielded Ce^{144}-Pr^{144} electrogenerators are much too high for man. For example, some generally accepted allowable gamma dose rates and dosages for man are listed below (RBE is assumed to be 1 for gamma radiation):

Maximum laboratory weekly dose	300 mr (up to 5 r/yr)
Maximum acute dose	25 r
Maximum chronic lifetime dose	200 r, at 5 r/yr

Gamma radiation dose rates at substantial distances from Ce^{144}-Pr^{144} electrogenerator cells of various output power levels are shown in figure 9. For example, a man 1000 ft from an unshielded 50-kw electrogenerator would receive his allowable weekly dose in 1.5 min and would use up his yearly allowance of 5 r in 25 min.

It is evident that the Ce^{144}-Pr^{144} electrogenerator would require shielding up to a few minutes before launch. Gamma radiation dose rates at the outer surface of lead shields are shown in figure 10. Although these dose rates were calculated from a formula with an approximate correction for buildup (ref. 9), the shield thicknesses are accurate enough to illustrate the fact that a considerable thickness of lead would be required to maintain a dose rate of 2.5 mr/hr. The attenuation factors were based on data for lead given in reference 8.

The shield configurations shown in figure 11 indicate that working space next to the booster payload appears to be adequate. An additional disc-shaped shield would be required between the electrogenerator and the booster up to the time of final assembly of the spacecraft to the booster. From this cursory examination of launch-pad radiation hazards, pre-boost operations appear awkward but feasible.

Boost-phase radiation hazards have not been evaluated as yet and appear to be complex. If a boost-phase abort occurred at a low altitude, it is possible that special construction of the electrogenerator could prevent a serious radiation hazard. For example, if the Ce^{144}-Pr^{144} were alloyed, sandwiched, or well contained in some manner, the radioisotope debris might remain in fairly large pieces. A boost abort above the atmosphere might require a special reentry device at least for the emitter. It might also be possible to vaporize the emitter deliberately and depend on very large mean free paths to keep the Ce^{144}-Pr^{144} aloft for many decay half-life periods. All that can be definitely said here is that boost-phase aborts constitute a major radiation-hazard problem. Furthermore, it seems advisable to delay the detailed study of the boost hazard problem until the practical feasibility of the radioisotope electrostatic propulsion system is more fully established.

INTERPLANETARY PROBE MISSION PERFORMANCE

The preceding discussion has been concerned primarily with electrogenerator power levels appropriate to interplanetary probe missions. The performance of a Mars orbiter probe with the electrogenerator design specified previously is shown in figure 12. These performance calculations were made as described in reference 1. With an Atlas-Agena booster, a total spacecraft weight of 4000 lb starting from a 300-mile Earth satellite orbit is possible. As shown in figure 12, substantial payloads are possible even with a 10 kw system. For example, a 10-kw system could place 1500 lb in a 500-mile satellite orbit about Mars in 260 days. With power levels of 30 kw or 50 kw, payloads of 2500 or 3000 lb are possible. With two H_2/O_2 chemical stages on the Atlas-Agena booster, only 550 lb could be placed in orbit about Mars.

From figure 12 it can also be seen that payloads of 6200 lb could be delivered to the 500-mile Mars orbit in 260 days with a 100-kw radioisotope electrostatic spacecraft that weighs 8000 lb and is boosted with a Centaur. In contrast, an all-chemical Centaur system could deliver an 1100-lb payload into orbit about Mars.

Although the radioisotope electrostatic propulsion system has an impressive theoretical performance for interplanetary orbiter missions to near planets such as Mars, it is possible that these probe missions would already have been accomplished with chemical rockets by the time the radioisotope system became operational. If this situation were to develop, the justification for the radioisotope electrostatic propulsion system might rest on its performance in probe missions to more distant planets. The estimated performance of the radioisotope system in a Saturn orbiter mission is illustrated in figure 13. The payloads shown in figure 13 are only estimates, since a computer program with allowance for the power decay of the radioisotope was not available. The payload estimate was made by using an arithmetic mean value of output power for the heliocentric portion of the trajectory.

With a Centaur booster, a 100-kw radioisotope system with the design assumed herein might place a 500-lb payload into orbit about Saturn in

500 days. A 500-kw radioisotope system might place 2000 lb into orbit about Saturn in 500 days. A Centaur booster with two additional upper stages could deliver 600 lb on a 6-yr Saturn fly-by mission. With three upper stages, a 40-lb payload might be placed into a 3500-mile satellite orbit about Saturn. These mission performance estimates indicate the theoretical superiority of the radioisotope electrostatic propulsion system for long distance probe missions.

MANNED INTERPLANETARY MISSIONS

At first sight, the Ce^{144}-Pr^{144} radioisotope electrostatic propulsion system might appear impossible for use in manned interplanetary missions because of the intense gamma radiation level illustrated in figure 6. If a gamma dose of 5 rem from a 1-Mw Ce^{144}-Pr^{144} radioisotope system were allowable for a 500-day trip, an unshielded crew cabin would have to be separated from the electrogenerator by a distance of 140 miles. If the crew cabin were placed at three cylinder lengths from an electrogenerator that has a length to diameter ratio of 5, 32 cm of lead would be required to shield the crew from a 500-day dose of 5 rem. The emitter in such an electrogenerator would have a diameter of 11 ft (using the design assumed in this paper). Then the shield would have a weight of 70,300 lb. Since the shield weight would be charged against the power generation system, the powerplant specific weight would be 70 lb/kw, which would considerably reduce the attractiveness of the radioisotope system. As mentioned previously, the electrogenerator might be smaller in size if higher component temperatures could be tolerated. Although a reduction in electrogenerator size would require a corresponding increase in fuel layer thickness, the shield attenuation factor is such that substantial reduction in shield weight might be accomplished. Another possibility is that of using the propellant as part of the shield mass.

The preceding discussion has assumed that the crew cabin is unshielded. As shown in a number of papers (e.g., ref. 10), crew cabins on interplanetary spacecraft will require shielding against solar-flare and cosmic radiation. It is suggested in reference 10 that cosmic radiation shielding might not be needed for 500-day trips, since the chronic dose of 25 rem from such exposure might be allowable. In order to reduce the radiation received from a giant solar flare to a 25-rem acute dose, it is shown in reference 10 that a 165-g/cm^2 carbon shield may be required. If it is assumed that a 3 by 6 by 5.5 ft shelter would be adequate for shielding a three-man crew during a solar flare lasting about a day, a mass of 92,000 lb of carbon would be required. By changing the geometry, this mass could be used for shielding the crew from the electrogenerator except during the solar-flare emergency. The mass absorption coefficients of carbon and lead are nearly the same for gamma radiation in the 1 to 2 Mev energy range, so a carbon shield of this mass would be more than adequate. For a 1-day stay in the solar flare shelter, the crew would receive an additional 30-rem gamma dose from the electrogenerator through the 165-g/cm^2 carbon wall of the solar flare shelter. As pointed out in reference 10, a total dose of 80 rem might be acceptable; if not, an additional 1900 lb of lead shielding would reduce the 1-day gamma dose to 3 rem.

From the preceding discussion, it appears feasible to use a $Ce^{144}-Pr^{144}$ radioisotope electrostatic propulsion system for manned interplanetary missions. This feasibility has been roughly established through the use of solar flare shielding assumed necessary for manned interplanetary spacecraft.

CONCLUDING REMARKS

The anticipated availability of the cerium-144 radioisotope as a by-product from ground-based power reactors is sufficient for propulsion systems of 10 to 50 kwe (electric) in 1965 and 100 to 500 kwe in 1980. The cost of cerium-144 is estimated to be $30,000/kwe as a power reactor by-product in 1965. Reactors could be specially built for cerium-144 production at a cost of $200,000/kwe. Radioisotope availability and cost should not be deterrents to the radioisotope electrostatic propulsion system.

The payload radiation dose caused by cerium-144 electrogenerators has been shown to be within acceptable limits even without shielding. The radioisotope electrostatic propulsion system has been shown to be of sufficiently small size for convenient mating with chemical boosters such as the Atlas-Agena and the Centaur. The theoretical performance of the radioisotope system on space probe missions such as Mars and Saturn orbiters is much superior to other propulsion systems.

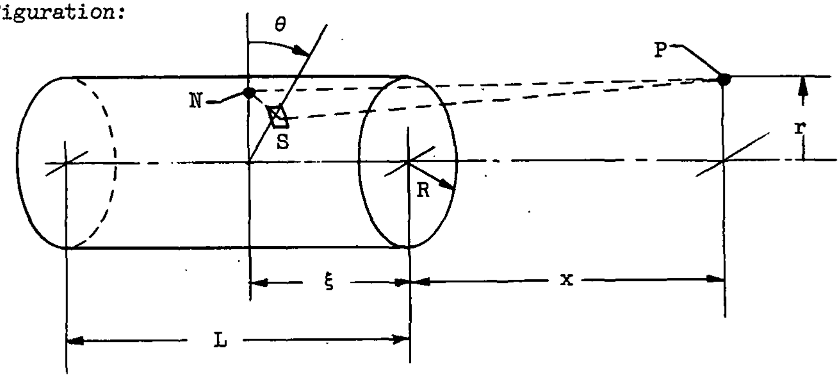
Ground handling and launch-pad radiation hazards are serious problems, but it appears that the radiation dosage can be reduced to safe levels with simple shielding. Boost-phase radiation hazards are serious and have not been examined in detail.

A cursory analysis has shown that the use of the cerium-144 system for manned interplanetary flight may be possible. Massive components such as solar flare shelters and/or propellant appear to be adequate for shielding the crew from the cerium-144 gamma radiation.

The analysis and discussion presented in this paper by no means demonstrates the complete feasibility of radioisotope electrostatic propulsion systems. However, the inherent simplicity, and therefore expected reliability, and the potentially superior mission capability justify further research on this propulsion concept.

APPENDIX - RADIATION DOSE FROM HOLLOW CYLINDERS

The radiation source to be considered here is a very thin-walled (e.g., metal foil) hollow cylinder uniformly coated with a radiation emitter. It is assumed that there is no loss in radiation intensity due to the thin wall or the thin coating. The sketch illustrates the configuration:



The differential radiation dose rate $d\mathfrak{R}$ at point P which is due to the radiation source $R\,d\theta\,d\xi$ located at S is:

$$d\mathfrak{R} = \frac{Kc}{l^2}$$

where K is a factor computed from the radiation energies and occurrences per curie, c is the source activity per unit area, and l is the distance from S to P. In consistent units (ref. 9), $\mathfrak{R}$ = mr/hr, K = mr-cm^2/curie-hr, c = curies/cm^2, and l = cm.

From the geometry, the length l can be obtained from:

$$l^2 = \overline{NS}^2 + (\xi + x)^2 = r^2 + R^2 - 2rR\cos\theta + (\xi + x)^2$$

The total radiation dose at the point P is then:

$$\mathcal{R} = Kc \int_0^{\pi} 2R \, d\theta \int_0^{L} \frac{d\xi}{r^2 + R^2 - 2rR \cos\theta + (\xi + x)^2}$$

By setting $y = \xi + x$, this expression reduces to:

$$\mathcal{R} = 2RKc \int_x^{L+x} \frac{dy}{\sqrt{\left(r^2 - R^2\right)^2 + 2(r^2 + R^2)y^2 + y^4}}$$

The expression has solutions for various regions as follows:

$$\mathcal{R} = 2\pi Kc \left[\text{arc tan}\left(\frac{L}{R} + \frac{x}{R}\right) - \text{arc tan}\left(\frac{x}{R}\right)\right] \qquad (\text{for } r = 0)$$

$$\mathcal{R} = \pi Kc \ln\left\{\frac{\frac{x}{L}}{1 + \frac{x}{L}}\left[\frac{\sqrt{1 + \left(\frac{L}{2R}\right)^2\left(1 + \frac{x}{L}\right)^2} - 1}{\sqrt{1 + \left(\frac{L}{2R}\right)^2\left(\frac{x}{L}\right)^2} - 1}\right]\right\} \qquad (\text{for } r = R)$$

$$\mathcal{R} = \frac{2\pi Kc}{\left(\frac{r}{R} + 1\right)}\left[F_2(\Phi_2, k) - F_1(\Phi_1, k)\right] \qquad (\text{for } 0 < r < R \text{ and } r > R)$$

Where $F_2(\Phi_2,k)$ and $F_1(\Phi_1,k)$ are incomplete elliptic integrals of the first kind with the modulus and amplitudes as follows:

$$k = \frac{2\sqrt{\frac{r}{R}}}{\left(\frac{r}{R} + 1\right)}$$

$$\Phi_2 = \text{arc sin}\left[\frac{\left(\frac{r}{R} + 1\right)}{\sqrt{\left(\frac{r}{R} + 1\right)^2 + \left(\frac{x}{R}\right)^2}}\right]$$

$$\Phi_1 = \text{arc sin}\left[\frac{\left(\frac{r}{R} + 1\right)}{\sqrt{\left(\frac{r}{R} + 1\right)^2 + \left(\frac{L}{R} + \frac{x}{R}\right)^2}}\right]$$

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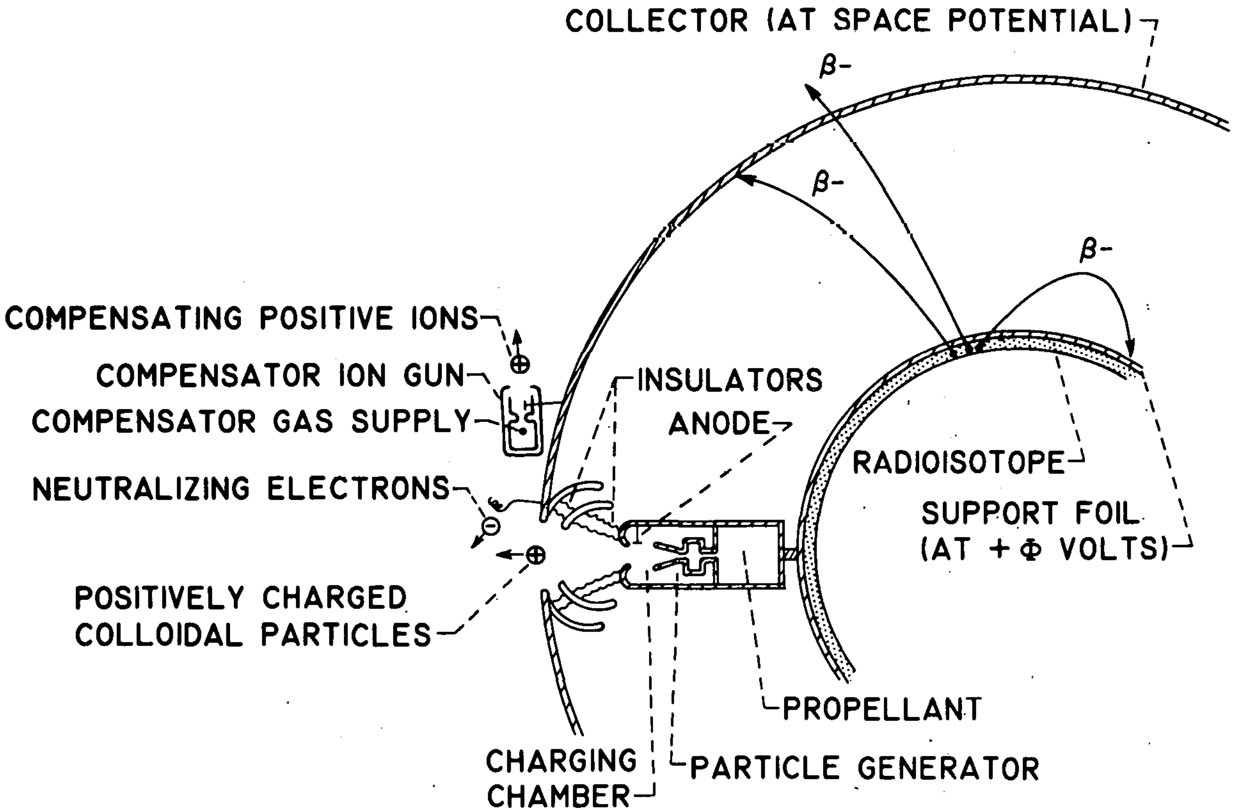

Fig. 1. - Electrostatic propulsion system with electrogenerator using beta-emitting radioisotope fuel.

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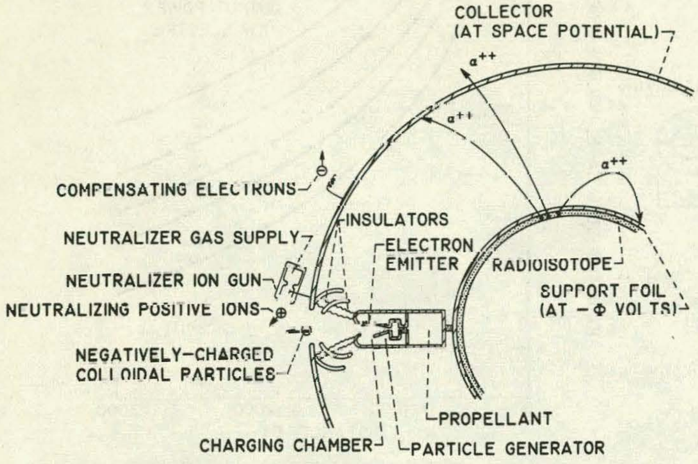

Fig. 2. - Electrostatic propulsion system with electrogenerator using alpha-emitting radioisotope fuel.

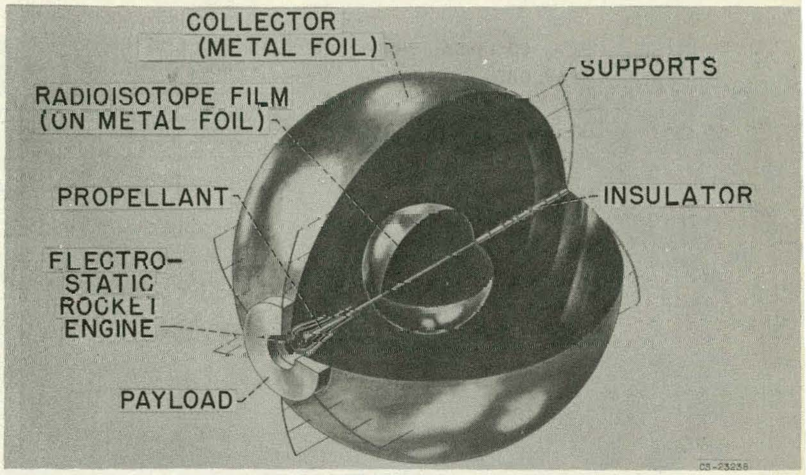

Fig. 3. - Electrostatic propulsion system with direct nuclear electrogenerator.

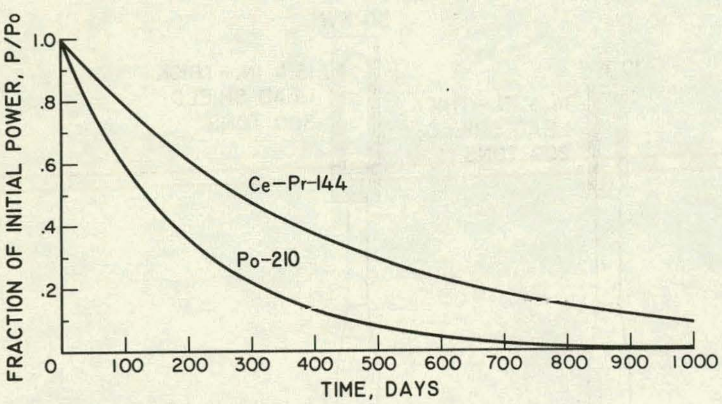

Fig. 4. - Power decay of cerium-144 and polonium-210 radioisotopes.

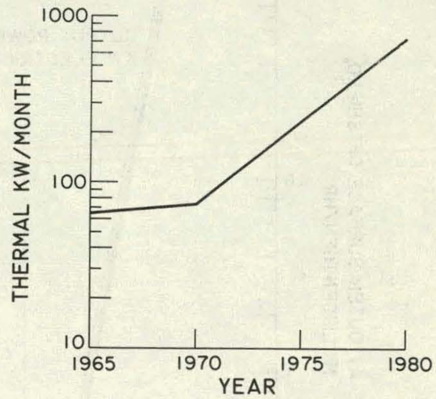

Fig. 5. - Anticipated production of cerium-144 radioisotope from power reactor by-products.

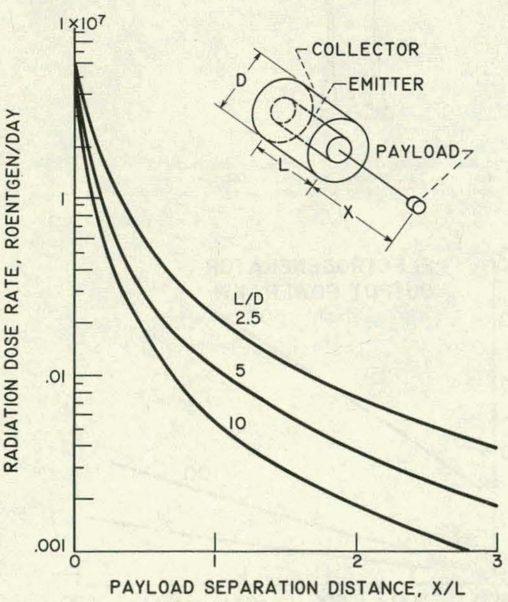

Fig. 6. - Radiation dose rate at payload separated from cerium-144 electrogenerator. Fuel layer thickness, 35 mg/cm^2 (121 curie/cm^2); collector-emitter radius ratio, 2. (Dose rate is independent of power level when plotted against X/L.)

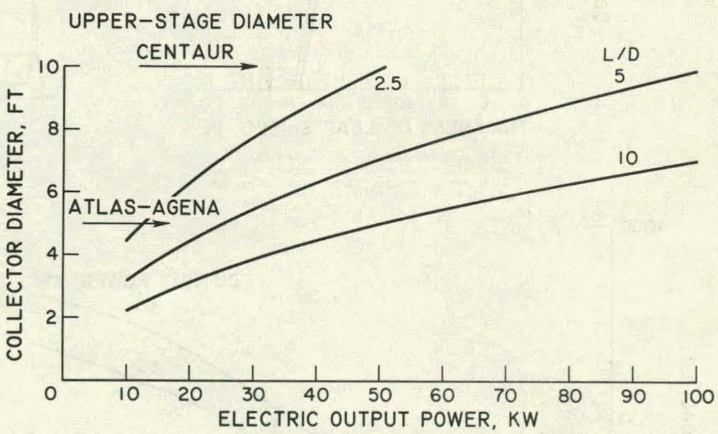

Fig. 7. - Radioisotope electrogenerator cell diameter. Collector-emitter radius ratio, 2; Ce-144-Pr-144 fuel thickness, 35 mg/cm^2 (output power, 0.14 watt/cm^2; η, 0.162; activity, 121 curies/cm^2).

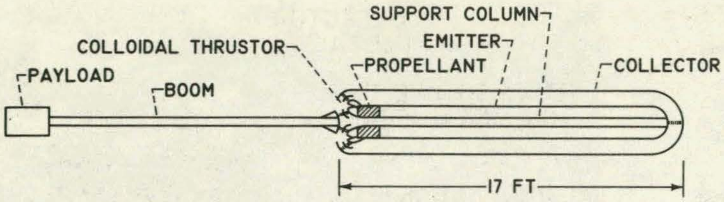

Fig. 8. - Hypothetical radioisotope electrostatic spacecraft design. Propulsion power, 10 kw; radioisotope, 35 mg/cm^2 of Ce-144-Pr-144, (8.5 megacuries); collector-emitter radius ratio, 2; emitter support foil, 1 mil molybdenum; collector foil, 1 mil aluminum; emitter temperature, 410° C (770° F); collector temperature, 240° C (463° F).

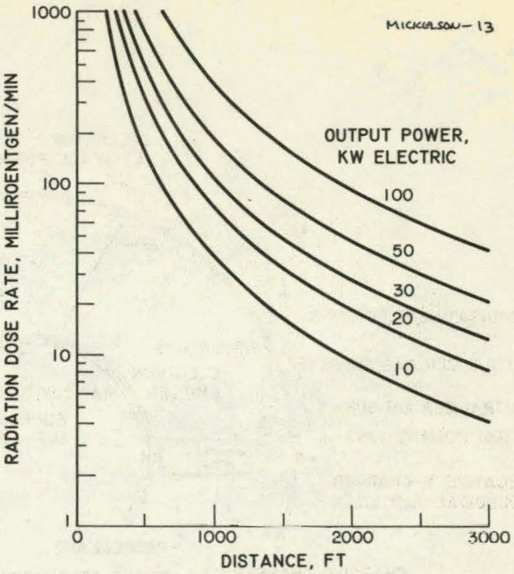

Fig. 9. - Unshielded dose rates around cylindrical cerium-144 electrogenerator. Fuel layer thickness, 35 mg/cm^2; support-foil thickness, 25.9 mg/cm^2; collector-emitter radius ratio, 2.

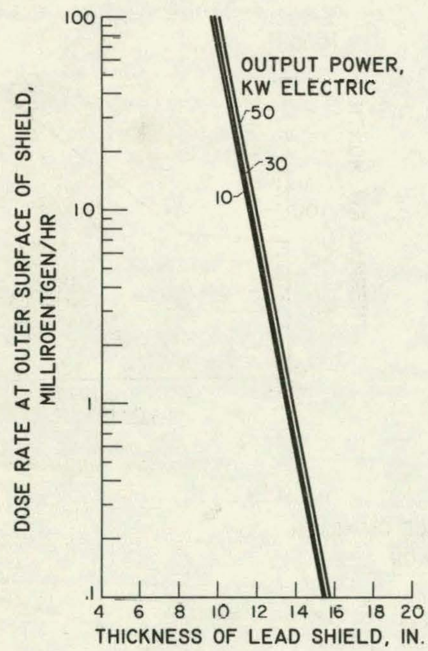

Fig. 10. - Gamma radiation dose rate from shielded cerium-144 electrogenerator. Inside diameters of shields: 10 kw, 5 ft; 30 kw, 7.5 ft; 50 kw, 9.0 ft.

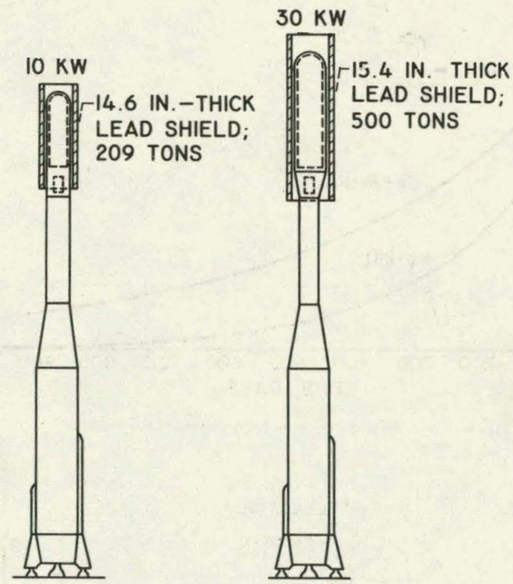

Fig. 11. - Launch pad shielding for 2.5 milliroentgen/hr dose rate at outer surface of shield. Atlas-Agena booster; cylindrical cerium-144 electrogenerator; fuel-layer thickness, 35 mg/sq cm.

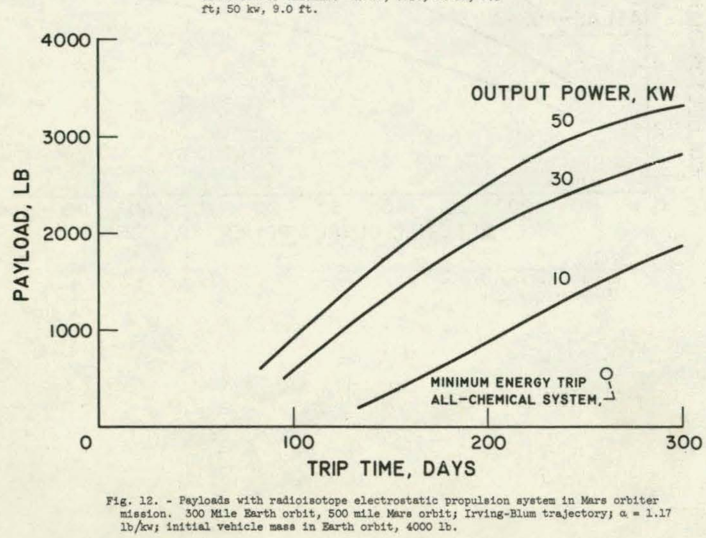

Fig. 12. - Payloads with radioisotope electrostatic propulsion system in Mars orbiter mission. 300 Mile Earth orbit, 500 mile Mars orbit; Irving-Blum trajectory; $\alpha = 1.17$ lb/kw; initial vehicle mass in Earth orbit, 4000 lb.

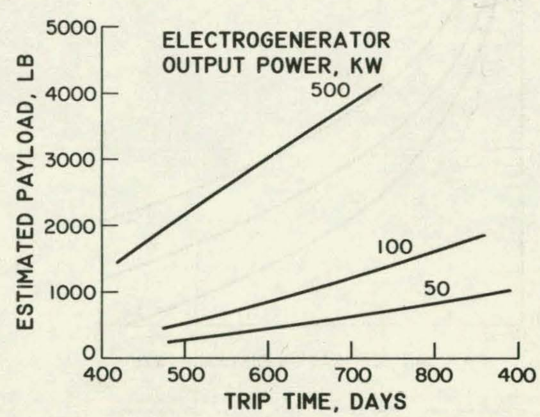

Fig. 13. - Payloads with radioisotope electrostatic propulsion system in Saturn orbiter mission. 300 Mile Earth orbit, 2000 mile Saturn orbit; Irving-Blum trajectory; $\alpha = 1.17$ lb/kw; initial vehicle mass in Earth orbit, 8000 lb.