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Energy for Remote Areas

Generators fueled with radionuclides are supplying power in small terrestrial and space systems.

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A novel, small power plant orbits the earth, supplying power to the Transit 4-A navigation satellite. About 700 miles from the North Pole a similar power plant drives an unattended automatic weather station. Both are without precedent: they derive their power from the heat produced by a decaying radioactive material (*1*). These units, which have been in continuous operation for more than 18 months, prove the value of reliable, long-life energy sources in remote places.

Radioactive isotopes continue to be used widely in tracing, gaging, and radiographing; in teletherapy; and in many related applications. Their use to provide electricity is less common, but it satisfies a need for simple, compact, and reliable power sources in remote areas.

Power is obtained from radioisotopes in the following manner. Absorption of the emitted particulate or electromagnetic radiations in the radioisotope itself and in its container converts the energy of decay into heat. Conveying this energy through a heat engine, such as a thermoelectric or thermionic converter, produces electricity. Unconverted heat must be rejected from the generator system.

The design concept for the generator is as follows. A suitable radionuclide fuel is encased in a heat-conducting capsule in juxtaposition to a static heat-to-electricity conversion system. Efficient thermal insulation minimizes thermal leakage. Through its heat-conducting outer shell, the generator rejects waste heat to the environment. Figure 1 is a cutaway sketch of a thermoelectric conversion unit.

Heat Source

A prime factor in the design of these units is the fuel. There are two major sources of radionuclide fuels. They are obtained from recovered wastes from the controlled fission of uranium, and they are artificially produced through neutron irradiation of target materials. Strontium-90 is an example of a fuel obtained from wastes, curium-242, an example of a fuel that is artificially produced (in this case, through irradiation of americium-241). The task that the power unit is to perform governs the choice of fuel and dictates the criteria for evaluating fuel characteristics such as power per unit volume (or "power density"), half-life, and type of radioactive decay (alpha, beta, and so on). Only isotopes with half-lives longer than 100 days make suitable fuels for most applications. Furthermore, a thermal output of more than 0.01 watt per gram of fuel is necessary. These criteria limit the number of useful fuel materials and preclude the use of currently available fused fission wastes as heat sources. Some characteristics of the more important fuels are listed in Table 1.

Fission wastes in amounts measurable in megacuries are now available from the Atomic Energy Commission's production reactors. The growing nuclear-reactor industry currently regards fission wastes as a major potential disposal problem, but fission wastes may also be viewed as a prime source of low-cost radioisotope fuel. Predictions indicate that 800 million curies of strontium-90 produced through the civilian reactor program will have accumulated by 1980, and that the figure will have increased to 7 billion by the year 2000 (*2*). In terms of power production, calculated on the basis of strontium-90 activity alone, by 1980 reactor wastes will contain about 5 megawatts of usable thermal power. The anticipated problem of waste storage may be alleviated if this source of useful energy can be exploited and some of these wastes can be converted into fuels.

Target irradiation, the second means of obtaining fuel materials, provides alpha-emitting radioisotopes which are particularly useful for space missions. They are identified in Table 1. Because of the ease with which alpha particles are absorbed in the emitting source and in its container and because of the high energy per nucleon, this heat source is of extremely high power density and needs little or no shielding. Power units fueled with alpha emitters are light and easy to handle at the launch pad. Beta emitters are also quite useful. They are less costly and easier to produce than alpha emitters, but they are more difficult to handle. The personnel who handle them require shielding prior to launch, but only a small shadow-shield is carried into orbit, to protect the electronic instruments of the spacecraft.

Energy Conversion

Heat from radioisotope decay may be converted into electricity by various means; these include turboelectric, thermoelectric, and thermionic devices. At present, only thermoelectric conversion provides the efficiency and reliability required at power levels up to 1

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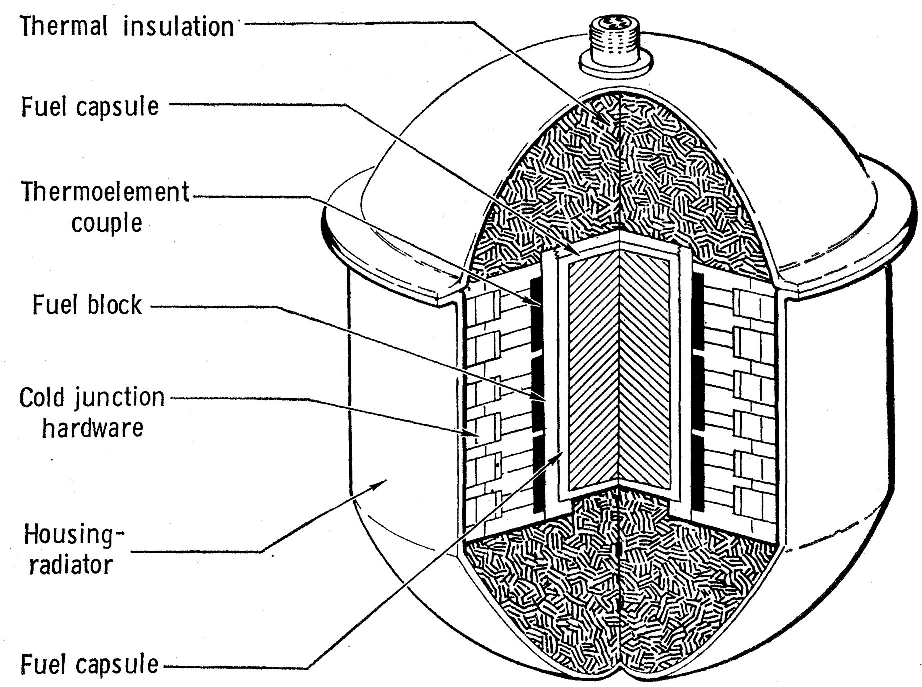
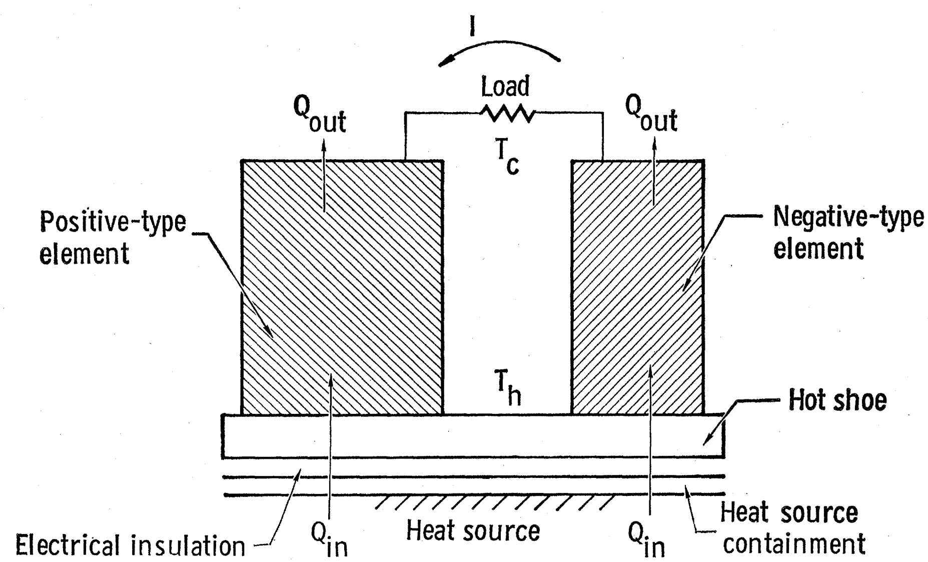
Fig. 1 (top). General configuration of radioisotope-fueled thermoelectric generator. Fig. 2 (middle). Thermoelectric energy conversion by means of thermoelectric couple. Fig. 3 (bottom). Generator configuration, showing mechanism for heat rejection.

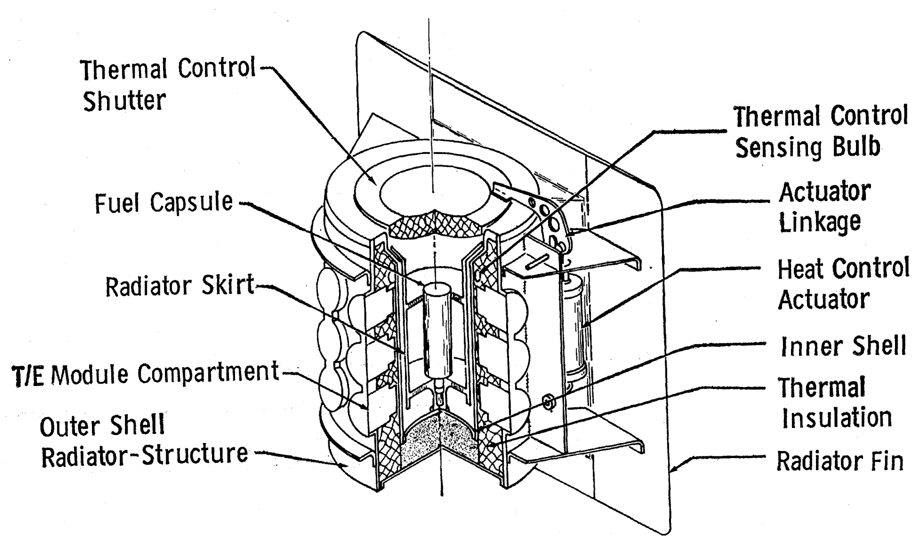
kilowatt. Radioisotope-fueled generators for forthcoming space missions such as Transit and Surveyor and for communications satellites will use thermoelectric converters. When the efficiency and reliability of thermionic conversion have been established, this conversion method will be preferred for space missions.

Thermoelectric conversion is a practical application of the Seebeck effect, in which current flows in a closed circuit of two dissimilar metals, joined at two points, when the junctions are held at different temperatures. The principle is the same as that on which thermocouples operate. The semiconductors, such as lead telluride, now being used as thermoelectric materials offer a significant improvement in efficiency over the simple thermocouple. Figure 2, a schematic diagram of a thermoelectric couple, illustrates how positive-type and negative-type semiconductor materials are connected electrically and thermally to produce a current I through an external load. The quantity Q_{in} represents the heat flow entering the thermoelectric device from the heat source at a hot-junction temperature T_h. The waste heat Q_{out} must be rejected, leaving the cold-junction temperature of the couple at T_c. These couples are thermally connected in parallel, and electrically connected in series, to provide a conversion device with the voltage and power output required.

Thermionic conversion is an application of the phenomenon of emission of electrons from the surface of a conductor at high temperature. At this surface, heat energy appears as additional electron kinetic energy; increasing the heat intensity raises the level of kinetic energy of the electrons. Those electrons that acquire sufficient kinetic energy to overcome the forces binding them to the material escape from the surface. The amount of work required to overcome these forces is called the "work function" of the conductor. If the conductor is heated when in proximity to another, cooler conductor, electrons emitted from the heated surface (the emitter) flow to the cooler surface (the collector). Some of the energy of the electrons is imparted to the collector as heat; the remainder provides electron







flow (electricity) to an external load circuit.

The salient feature of thermionic conversion in connection with the use of radioisotope fuels is the possibility of highly efficient operation (up to 15 to 20 percent) at relatively high heat-source and radiator temperatures. In space, the excess heat generated by the encapsulated radioisotope must be radiated away from the vehicle. The amount of heat radiated increases as the fourth power of the radiator temperature. A conversion system which can function at high temperatures, therefore, is of very great potential usefulness for space applications.

Constraints on Generator Design

Only a relatively small percentage of the heat generated by the radioisotope becomes electricity. The remaining thermal energy must be dissipated in the environment by a method suited to that environment. In space-oriented power units where heat is released through radiation, radiator design is paramount. In terrestrially applied systems, where the heat may be lost through radiation, conduction, or convection, the application dictates the choice of heat sink and the means of energy release.

The need for a constant input to the electrical load for the duration of the mission demands a constant output from the power system. When the temperature at the hot side of the energy-conversion device is constant, the required level of power output prevails. However, the quantity of heat produced by the radioisotope decreases exponentially with time, with a corresponding decrease in "hot-side" temperature. The requirement for constant power is satisfied by fueling the generator with a quantity of radioisotope that, at the end of the mission, will have decayed to a level still sufficient to supply operational thermal energy. The excess heat produced early in the mission may be dissipated as heat. As the amount to be dissipated decreases (that is, as the amount of active radioisotope decreases), the size of the radiating surface may be reduced through the use of shutters, operated by a thermal sensing mechanism, which change the number of conduction paths to the radiating surface. Figure 3 is a schematic drawing of a generator equipped with a thermal shutter. The choice of fuel determines the need for thermal regulation. With strontium-90, for example, there is a 20-percent decrease in power at the end of a 10-year period, making thermal shutters unnecessary.

Table 1. Properties of radioisotopes.

Isotope	Type of decay	Half-life	Chemical form	Specific activity (thermal)		Curie/watt		Mission for lifetime (yr)
				Watt/g	Watt/cm³	Thermal	Electric	
Sr^{90}	Beta	28 yr	Titanate	0.2	0.7	154	4000	10
Cs^{137}	Beta, gamma	27 yr	Glass	0.072	0.215	210	5500	10
Ce^{144}	Beta, gamma	285 days	Oxide	2.3	13.8	128	7000	1
Pu^{238}	Alpha	90 yr		0.56	9.3	29.0	625	10
Cm^{242}	Alpha	162 days	Oxide	120	1170	27.6	1190	1/2
Po^{210}	Alpha	138 days	Metal	140	1320	31.6	1550	1/2
Cm^{244}	Alpha	19 yr	Oxide	2.40	25.4	29.2	840	10

Static energy conversion devices are particularly well suited to operation in the zero-gravity field of space. But before they can be launched into orbit they must pass a number of environmental tests in which conditions of launch and operation are simulated. They must withstand thermal and mechanical shock, vibration, and acceleration commensurate with the mission specifications for the launch vehicle system used. Since the energy-conversion devices are basically high-current, low-voltage systems, appropriate solid-state dc-to-dc converters have been built to bring the voltage to that required by the payload. These converters must also satisfy the environmental test specifications (*3*).

Radioisotope fuel in the quantities required for power generation would create a hazard of some significance if improperly released to the biosphere. A most important factor, therefore, in establishing the practicability of this technology is the assurance that protection from irradiation can be provided.

Terrestrial systems fueled by strontium-90 rely first on the fuel form strontium titanate ($SrTiO_3$), which has been found to be virtually insoluble in fresh water and sea water, to provide good thermal conductivity, to have a melting point at least twice the centerline temperature of the fuel capsule, and not to decompose on melting. The fired ceramic $SrTiO_3$ pellets are sealed in a capsule of Hastelloy C (*4*), which corrodes at the rate of 0.0001 inch per year in sea water. Thus it is assured that the virtually insoluble fuel will be sealed within the capsule for more than 20 half-lives.

For space systems, Atomic Energy

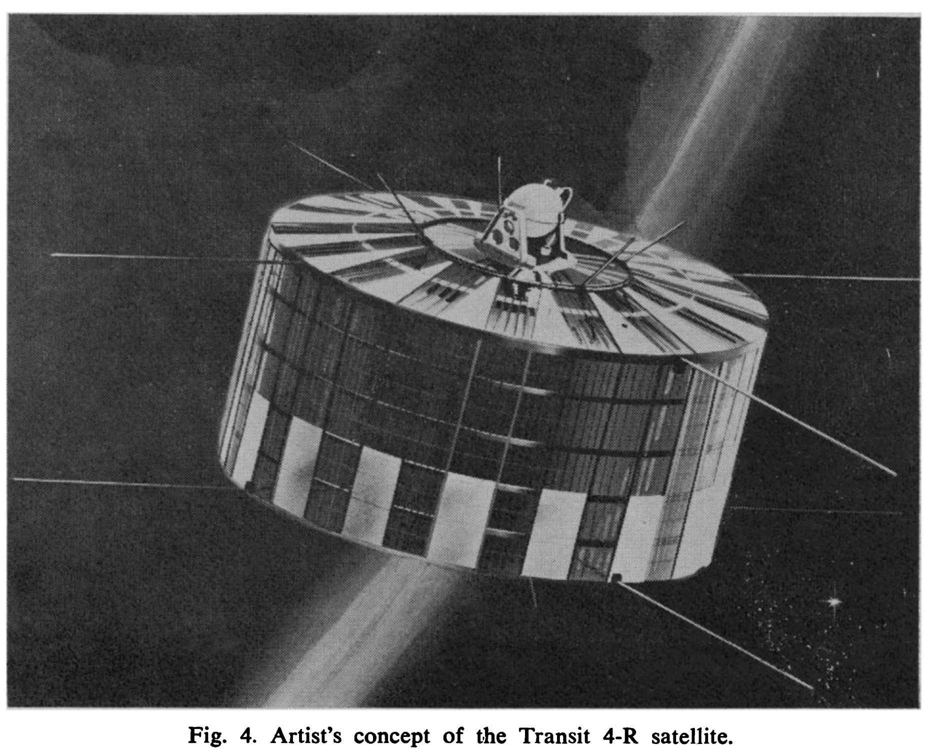


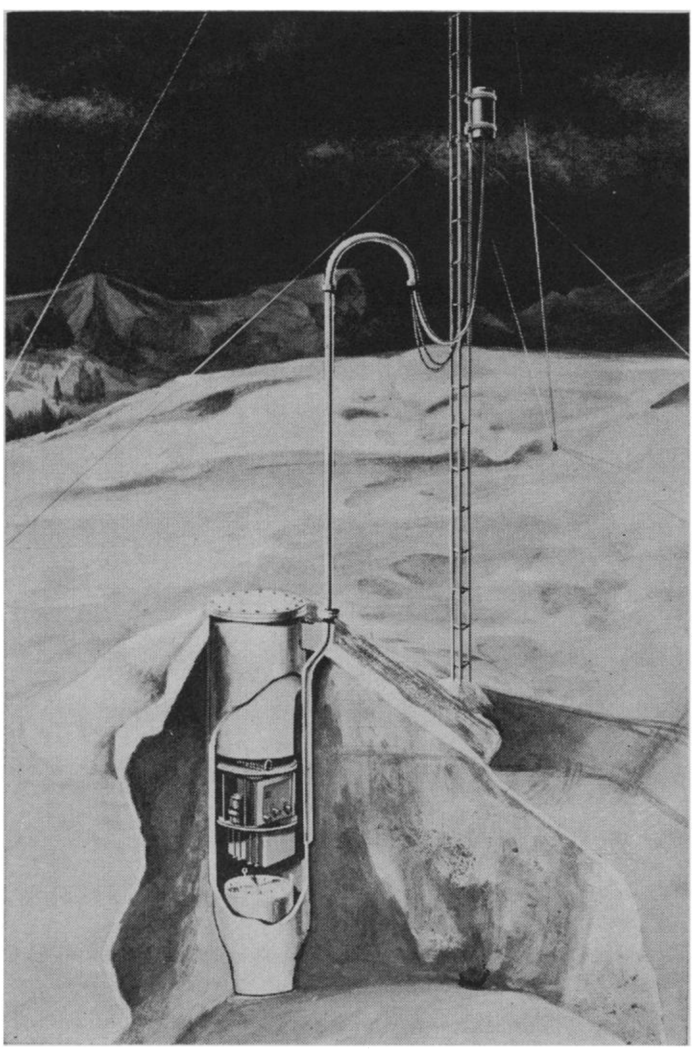
Fig. 4. Artist's concept of the Transit 4-R satellite.

Commission safety regulations require the complete containment of radioisotope fuel within its capsule under conditions of an aborted launch. These include fire and explosion on the launch pad and failure to achieve orbital velocities. In the event of such failure, orbital injection is not accomplished, and the device returns to earth, following a ballistic trajectory that terminates in impact with land or sea. The fuel is encapsulated in high-temperature, high-strength alloys. In rigorous tests, capsules carrying simulated fuel withstood fire and explosion of a simulated vehicle on the launch pad, and high-velocity impact on granite targets at operating temperatures. Extensive testing under conditions of uncontrolled re-entry from orbit has clearly shown that the cores and fuel of systems launched will burn to micron-sized particles that will be dispersed at altitudes above 100,000 feet as a result of aerodynamic heating upon re-entry. The latter condition is a second safety requirement (*5*).

Operational Systems

There are various power systems now in operation or under development (*6*). The Transit satellite system, developed for the U.S. Navy by the Applied Physics Laboratory of the Johns Hopkins University, is designed to provide constant-frequency transmission to ships at sea for a minimum of 5 years. With Doppler-shift techniques, these satellites make accurate navigation data available. Transit 4-A, carrying a Pu^{238}-fueled thermoelectric generator—our first nuclear power supply in space—was launched on 28 June 1961 (Fig. 4 is an artist's concept of the satellite in space). The generator is still operating at design power, although the performance of its companion photovoltaic power supply has deteriorated as a result of effects encountered in the radiation belt. Table 2 lists the characteristics of the thermoelectric generator. The Transit program and the Systems for Nuclear Auxiliary Power (SNAP) program merged after several unsuccessful attempts to supply power to similar satellites through solar cells and batteries. The generator launched in Transit 4-A was a modified SNAP 3 (a proof-of-principle prototype). Transit 4-B, launched on 15 November 1961, carried power sources identical to those of Transit 4-A. After 6 months of operation at design power, the nuclear system suddenly failed. Telemetry data showed that the failure was not in the generator. No additional information could be obtained, however, because of the gradual fading of solar-cell performance and the consequent silencing of the satellite. An operational navigation satellite, Transit 5, will carry a generator fueled with plutonium-238, designated SNAP 9A, which will supply all the power required for satellite functions.

Other power sources under study and development include SNAP 11, a thermoelectric generator fueled with curium-242, for Project Surveyor (the un-



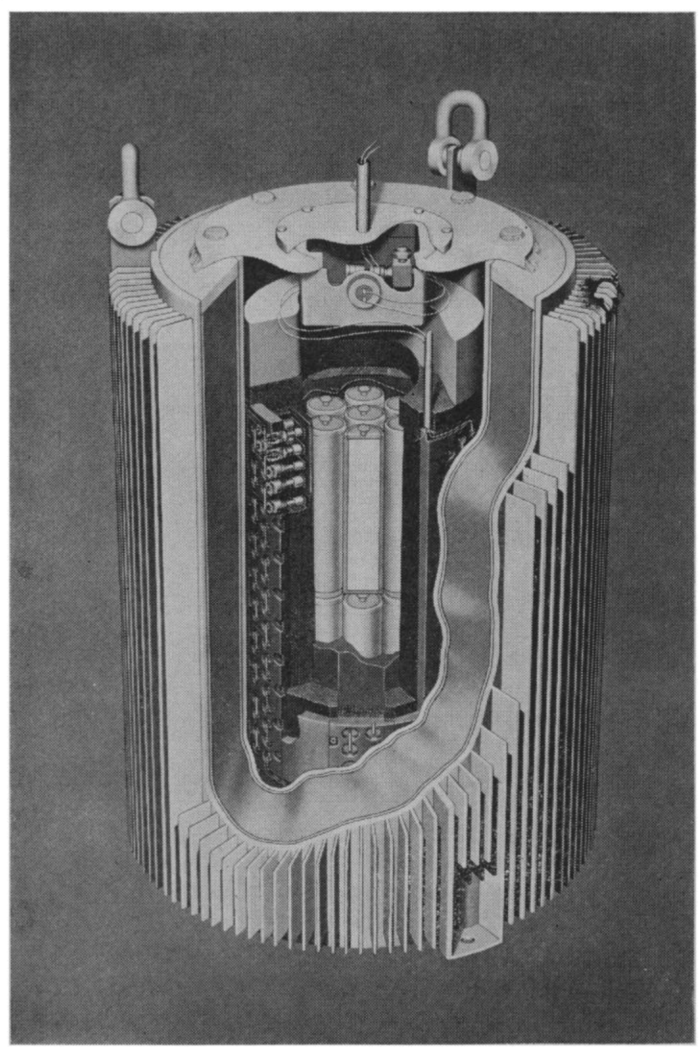


Fig. 5 (left). Weather station at Axel Heiberg Island in the Arctic Ocean. Fig. 6 (right). The SNAP 7B-D generator.

manned lunar laboratory); generators fueled with strontium-90 for synchronous, half-synchronous, and random-orbit communications satellites; and SNAP 13, a system in which thermionic conversion of the heat from curium-242 is employed.

The first isotope-powered, unattended, automatic weather station was installed near the North Pole on 17 August 1961 and has transmitted weather information every 3 hours since that time (*7*). It represents the successful cooperation of the U.S. Atomic Energy Commission, the U.S. Weather Bureau, and the Canadian Weather Bureau (Fig. 5).

The thermoelectric generator (fueled with strontium-90), the telemetry package, and the weather-sensing instruments were designed to operate for 2 years without maintenance; to measure ambient temperature, barometric pressure, 8-minute-average and 1-minute-average wind speeds, and wind direction; to record data in binary digital form; and to provide simultaneous two-frequency transmission of the station call letters and the measured data, in a 10-second period, to a receiving station 200 miles away.

Between periods of operation of the telemetry package, the system is dormant, requiring no power input. During the transmission period, power consumption exceeds 1 kilowatt. The telemetry package consumes 165 watt-minutes of electric energy for each operating cycle. The nominal 5-watt output of the generator is used to recharge a nickel-cadmium battery during the "station-off" periods, and the static converter is used to raise the output of the generator to the battery-charging voltage.

To avoid exposing the system to the extreme arctic temperatures, its designers chose to install it underground in a cylindrical steel housing 8 feet tall. The ground temperature 8 feet below the surface in the permafrost regions of the Arctic remains between −10° and +30°F throughout the year; the waste heat from the generator maintains the interior of the housing at a temperature between 40° and 80°F. The buried housing also provides protection from animals and reduces the level of radiation from the generator to "near-ambient." The wind vane, anemometer, and thermometer are mounted on a 38-foot mast furnished by the Weather Bureau. The altimeter-setting indicator is located within the station housing (which is kept at atmospheric pressure). Two half-wave dipole antennas furnished by the Weather Bureau complete the installation.

The SNAP 7 series represents an increase in power and an improvement in design over the generator used in the weather station. The design improvements include the use of integral thermoelectric modules, each consisting of several prewired thermoelectric couples; the use of depleted uranium (the material remaining after fissionable uranium-235 atoms have been removed from natural uranium) as the radiation shield; and control of the conversion efficiency by alteration of the thermal conductivity of the insulation. SNAP 7A, designed to power a Coast Guard light buoy, eliminates the need for changes of batteries at 6-month intervals. This generator was designed to operate for 10 years or longer without refueling. Excess heat is conducted through the buoy to the surrounding water. SNAP 7B will be used in a fixed Coast Guard light station to operate the beacon and foghorn. This generator (like SNAP 7D) has a multicapsule fuel block that accommodates 14 fuel capsules of $SrTiO_3$ clad in Hastelloy C. Figure 6 shows the capsules and the fuel block inside the assembled generator. SNAP 7C, similar to 7A, is powering a weather station in Antarctica. A barge-mounted weather station to be deployed in the Gulf of Mexico will be powered by SNAP 7D. SNAP 7E, also similar to 7A, is to supply power to a deep-moored navigation beacon in the Atlantic Ocean. SNAP 7C, 7D, and 7E all serve in missions of the U.S. Navy. For this family of power units there is a single design concept; the units differ primarily in size, power output, and application. Their characteristics are indicated in Table 2.

Summary

Radioisotope-fueled generators are classed by (i) application (space or terrestrial), (ii) fuel (alpha-emitter or fission product, short or long half-life), and (iii) converter type (thermoelectric or thermionic). The environment determines the design of the heat sink mechanism. The type of fuel is chosen according to the application and the availability and cost of the fuel. The space systems are suitable for low-powered (less than 1 kw), long-lived, earth-orbit missions, making storage batteries unnecessary. They are independent of radiation belts and solar transients and are suitable for lunar missions, where power is needed during the long lunar night; for probes into the dense atmosphere of Venus; and in general, for missions away from the sun.

The terrestrial systems fill a need for dependable power at remote, hard-to-reach locations on land and at sea. There are hundreds of serious gaps in the worldwide network of weather-observing stations; many of these gaps are in polar regions which are accessible for only a brief period each year. Yet weather data from the polar regions are needed for long-range weather prediction. The unattended arctic and antarctic stations powered by strontium-90 are helping to fill these gaps. Eventually, networks of automatic stations may transmit their data to computation centers, which in turn may issue area weather maps.

The cost of radioisotopes and generators is still high (about $3000 per electrical watt for 10 years, at present prices of strontium-90), but the cost is decreasing as more generators are built and more fuel is used. Weather sta-

Table 2. Generator specifications.

Generator*	Design power (watt)	Design life (yr)	Weight (lb)	Length (in.)	Diameter (in.)	Nuclide fuel		Operation date	Mission
						Kind	Quantity		
Transit 4-A, B	2.7	5	4.6	5.5	4.8	Pu^{238}	95 g	1961	Navigation (prototypes)
SNAP 9A	25	6	27	9.5	20†	Pu^{238}			Operational transit
SNAP 11	25	¼	30	9	6	Cm^{242}			Surveyor
SNAP 13	12	¼	4	4	2.5	Cm^{242}			Proof of principle
Arctic weather station	4.5	2‡	1680	20	18	Sr^{90}	17.5 kc	1961	Axel: Heiberg
SNAP 7A, C	10	10	1870§	21	20	Sr^{90}	40 kc	1962	Buoy; weather station
SNAP 7E	6.5	10	8000‖	56	30	Sr^{90}	31 kc	1963	Undersea beacon
SNAP 7B, D	60	10	4600	34.5	22	Sr^{90}	225 kc	1963	Fixed light; barge weather station

* SNAP 13 is a thermionic device; all the others are thermoelectric. † Includes fins on generator. ‡ Minimum. § Includes weight of shield, 1726 lb. ‖ Special pressure vessel for deep mooring.

tions, buoys, and navigation aids will continue to use radioisotope power. Through this technology many as yet undetermined missions will be carried out—missions which, without this power, would have been impossible.

References and Notes

1. The work described in this article was performed by the Martin Company for the U.S. Atomic Energy Commission under contracts AT(30-3)-217, AT(30-1)-2519, -2871, -2952, -2958, -3021, -3060, and -3062.
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Hazards of New Drugs

The scientific approach is necessary for the safest and most effective use of new drugs.

Walter Modell

No drug, no matter how thoroughly tested by time or trial, is absolutely safe. The size of the problem is indicated by a report in the *Journal of the American Medical Association* (*1*) that one of every 20 patients admitted to a large hospital in New York City was there because of adverse reaction to treatment. Serious reactions occur with all therapies—the safe as well as the hazardous, the useful as well as the useless, the old as well as the new, the folk remedy as well as the modern miracle drug. What seems an innocent therapeutic procedure may have serious unanticipated effects. For example, the age-old program of bed rest for the sick seemed so reasonable, was so well grounded in tradition, so plainly harmless, and, one would think, so well tested by usage that, until about 20 years ago, no one challenged it. Yet William Dock (*2*) called it the most dangerous of all therapeutic procedures, supported his revolutionary view with evidence that it caused venous thrombosis and other complications, and ushered in the present era in which the bed is eschewed if the patient can manage to be up and around. In many cases, as well as being happier, patients are clearly safer out of bed than in it. Nothing must be accepted at face value in modern medicine; modern proof by modern standards is essential. The thoroughgoing scientific experiment and the scientific attitude are the only safeguards against the specter of drug disaster.

The aim with all new therapies is to establish a more favorable ratio between probable adverse effect of treatment and probable adverse effect of untreated disease. Testing new drugs involves developing and pursuing the most effective methods for determining therapeutic effectiveness and reaction hazard. Only with tested drugs is there an index of danger of adverse reaction and of potential for therapeutic usefulness. If the information is substantial, one can elect to use the drug on the basis of a calculable risk; without such information one has no way of knowing whether the clinical use of the new drug is defensible.

Preclinical Testing

If medicine is to progress, the determination of calculable risk and expectation for benefit from new drugs is of the first importance. Why, then, are these factors not always precisely determined before new drugs are used in clinical medicine? The reaction of an animal to drugs may differ qualitatively as well as quantitatively from that of man. Therefore, although essential, animal experiments provide a limited view of the potential danger and usefulness of drugs in man. Much more can be learned from preclinical trials in man, and the more extensive these trials, the more informative they are. This is the information that is largely depended on in introducing new drugs, but unfortunately it does not tell the whole story; at best it provides only the basis for a well-informed estimate of immediate effects. It tells little about what will happen after several years of use. It does not tell much about what has not been looked for, and since what we look for is determined by past experience, it is quite possible that entirely new reactions to drugs will go undetected. It does not tell precisely what will happen when the drug is used by the general practitioner, as compared with its effects in the much more careful studies of preclinical testing. Information from preclinical testing is not often extensive enough to cover the rare occurrence. The full extent of both the risk and the ultimate benefit of the drug is therefore learned only after extensive use in actual practice, usually for 2 or 3 years.

Obviously, testing should be conducted with minimum risk to the subject, but since there is no drug without hazard, there can be no testing of new drugs without risk. The justification for taking this risk is that without it there can be no reasonable basis for introducing and using new drugs, and that the danger involved in using them clinically without such testing would be greater than the danger involved in preclinical testing. Therefore, society must recognize that in its demand for new drugs there is clearly implicit a license for qualified individuals to take certain risks in testing drugs as well as to take calculable risks in using them clinically. Medical science is obligated to keep these risks within reasonable limits. But both the medical profession and society in general must be fully aware of the potentiality of drugs to produce disaster.

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