Power Source Equipment: Cost and Reliability

4

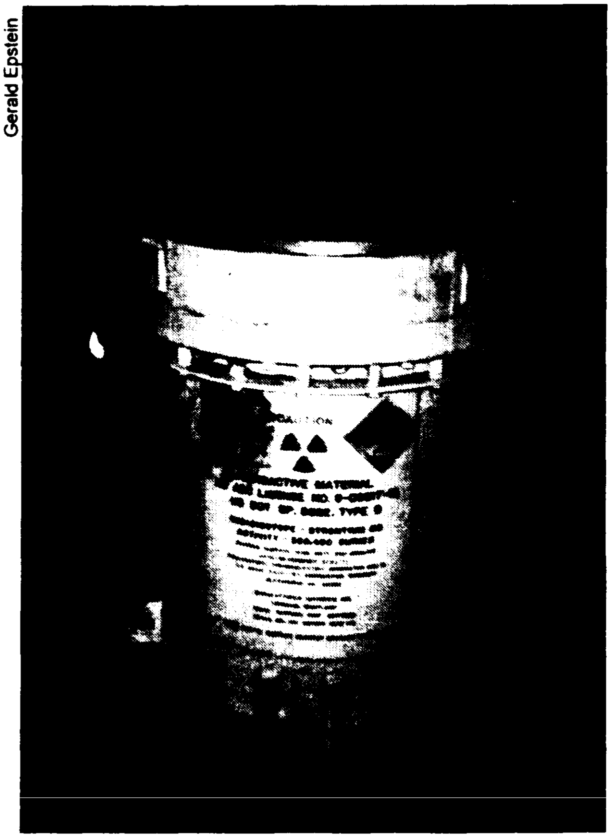
RADIOISOTOPE THERMOELECTRIC GENERATORS

Radioisotope thermoelectric generators (RTGs) are a type of nuclear battery that uses the Seebeck thermoelectric effect to generate electric power from the heat of decay of a radioactive material. The Seebeck effect generates a small electric potential in a thermocouple that spans a temperature gradient. In an RTG, many thermocouples--made of semiconductors--traverse the distance from the hot zone near the nuclear center to the device's cool outer surface. Decay of radioactive material (strontium-90--Sr-9O--in the RTGs at Burnt Mountain) provides the heat. The thermocouples are connected together as a thermopile to boost the electrical output to useful magnitude. Because radioactive decay occurs as an intrinsic property of radioisotopes, the fuel charge in an RTG can be fixed in place and last many years. RTGs are attractive power systems for remote applications because they have no moving parts, the fuel supply is integral to the system, and the units are sealed, operate passively, and require very little maintenance. This is the basis of their high reliability. The level of power generated depends on the amount of radioactive material the device was fueled with, the length of time since the fueling, and how well the heat flow is focused across the thermoelectric conversion module.

RTGs were developed as part of the effort begun in the late 1950s to find peaceful uses for nuclear materials. The first unit was for a weather station. The Sr-90 used in the Sentinel models at Burnt Mountain is a byproduct of weapons manufacture at Hanford, Washington. It was processed into strontium titanate at Oak Ridge, Tennessee. Teledyne Isotopes Inc., Nuclear Systems (now Teledyne Isotopes Inc., Energy Systems Division trading as Teledyne Brown Engineering-Energy Systems) produced the Sentinel series.

The radioisotope fuel in the RTGs at Burnt Mountain is surrounded by shielding and insulating materials, A schematic cross section of a typical RTG is shown in figure 4-1. The Sr-90 fuel is fabricated as strontium titanate: $SrTiO_3$ in the Sentinel 25 models and as Sr_2Ti0_4 in the Sentinel 100F model. The hockey puck-size material is encased in fuel cladding consisting of a stainless steel liner and a superalloy (Hastelloy C) fuel capsule. This fuel capsule is surrounded by a radiation shield fabricated from tungsten. This in turn is enclosed in thermal insulation to direct the heat upward to the thermocouples. Lastly, there is the exterior housing of the unit. Seven of the RTGs at Burnt

Gerald Epstein



One of the RTGs powering the ROF site at Burnt Mountain, where data are collected from remote seismographs and relayed by radio to Ft. Yukon, some 100 km to the south.

Mountain are housed in steel, two in aluminum, and one in cast iron.

The fuel capsules of RTGs have passed stringent heat, thermal shock, impact, and projectile striking tests without developing any detectable leaks of the radioisotope material. The tungsten radiation shield and the housing together are designed to reduce radiation levels to a maximum of 10 millirem per hour at a distance of 1 meter from the RTG surface. As points of reference, a typical chest x-ray is about 45 millirem, and the average annual whole body dose to a person in the United States from natural and manmade sources is about 360 millirems.[1] The RTGs as complete units have not been tested. Instead, engineering analyses were conducted to demonstrate that the RTG designs met the applicable Nuclear Regulatory Commission standards for transportation packaging.

Nine of the RTGs at Burnt Mountain produce continuous power of 9 to 20 watts. The one larger unit produces continuous power of **53 watts. The** smaller units contain approximately 1.2 pounds of Sr-90 and the larger one contains about 3.9 pounds, Each RTG weighs approximately 1 to 2 tons. The units are housed in wooden utility sheds, There are actually four models of RTGs at Burnt Mountain; from smallest to largest (in terms of amount of nuclear material) they are: one Sentinel 25A at 50,000 curies (Ci); seven Sentinel 25Es at 56,000 to 61,000 Ci; one Sentinel 25F at 60,000 Ci; and one Sentinel 100F at 189,000 Ci. These quantities represent the estimated activities in April 1994. Other characteristics of the Sentinel RTGs are shown in table 4-1.

Since RTGs are already in place, the cost of their continued operation is far lower than any possible alternative that would have to be constructed and installed there. However, modifications to the generators and/or the electronics systems would be needed to enable the RTGs to provide enough power over the projected life of Burnt Mountain station.

PROPANE-FUELED THERMO-ELECTRIC GENERATORS

Propane-fueled thermoelectric generators (TEGs) generate electricity on the same principle as RTGs, except that propane or some other hydrocarbon rather than a radioisotope provides the heat. However, unlike RTGs, which can provide

[1] Wright Laboratory, Aeropropulsion and Power Directorate, Aerospace Power Division, "Power System Assessment for the Burnt Mountain Seismic Observatory," report prepared for the Air Force Technical Applications Center, Patrick Air Force Base, FL, May 1994; and National Council on Radiation Protection and Measurements, *Ionizing Radiation Exposures of the Population of the United States,* NCRP report 93 (Bethesda, MD: 1987).

FIGURE 4-1: Schematic of a Typical RTG Used for Terrestrial Applications

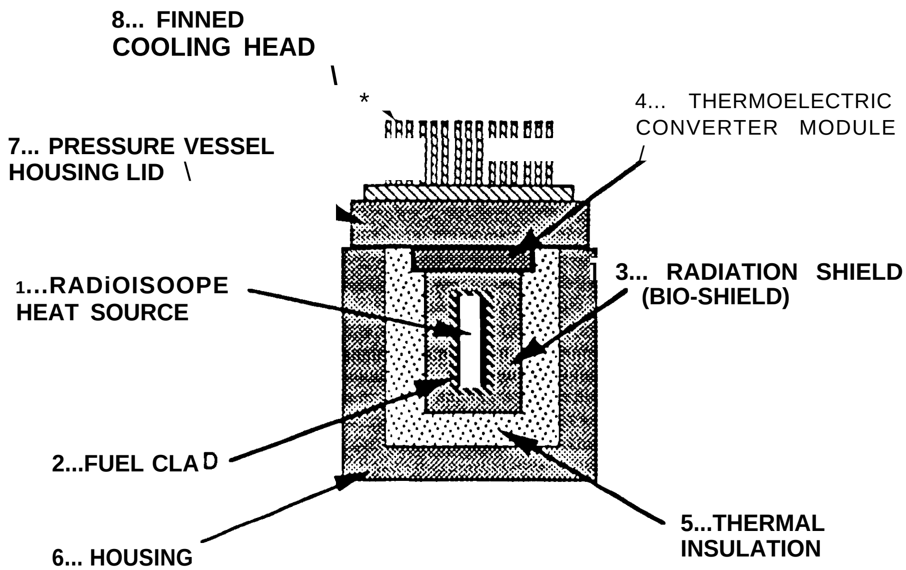


FIGURE 2. Schematic Diagram of a Typical RTG Used for Terrestrial Applications. The diagram illustrates the major features of an RTG.

SOURCE: Wright Laboratory, Aeropropulsion and Power Directorate, Aerospace Power Division, 'Power system Assessment for the Burnt Mountain Seismic Observatory, " draft report prepared for the Air Force Technical Applications Center, Patrick Air Force Base, FL, Oct. 29, 1993.

30 years or more on a single fueling, TEGs require periodic refueling. The Air Force estimates that using TEGs in a centralized configuration at Burnt Mountain would consume 6,300 pounds of propane per year.[2] In a distributed configuration, TEGs would consume 5,000 pounds of propane annually, This fuel would have to stored in large tanks and flown in probably twice a year. The storage tanks would most likely be buried, and the containment would need to be designed to accommodate shifts in the permafrost. In addition, there would need to be some mechanical linkages to control the flow of propane from the tanks to the TEGs and to prevent problems during periods of extreme cold weather.

TEGs are available in essentially the same power and voltage output ranges as the existing RTGs, and therefore could be directly substituted for the RTGs in the existing shelters and distributed configuration. Alternative)) TEGs could be installed in a centralized mode, in order to simplify fuel handling and storage operations.

It is expected that the propane would be transported in bundled 100-pound capacity cylinders via helicopter. Depending on the ac-

[2] Wright Laboratory, op. cit., footnote 1.

TABLE 4-1: Characteristics of the RTGs at Burnt Mountain

	Sentinel 25A	Sentinel 25E	Sentinel 25F	Sentinel 100F
Activity of initial charge (curies)	94,000	105,000-109,000	108,000	329,000
Date of initial charge	1968	1969-71	1970	1972
Activity in April 1994 (curies)	50,000	56,000-61,000	60,000	189,000
Exposure rate at housing surface (millirem/M)	55	65	75	125
Voltage (V)	3.3	3.5	3.5	9
Housing material	Cast iron	Steel	Aluminum	Aluminum
Weight (lbs)	3,000	4,170	1,400	2,720
Dimensions, height x diameter (inches)	35x26	42x26	36x20	46x28
Housing pressure rating (PSI)	500	10,000	500	500
Design applications	Tailored to land and shallow water (300 meter depth) applications	Tailored to deep sea (6,700 meter depth) applications, or land applications with cooling head	Tailored to land and shallow water (300 meter depth) applications	Tailored to land and shallow water (300 meter depth) applications

SOURCE: Product brochures from Teledyne Energy Systems (now Teledyne Brown Engineering-Energy Systems), 1986 tual power configuration and the lift capacity of the helicopters used, four to five helicopter trips would be needed per year. The handling and transport of this much propane raises safety questions that are discussed in the following chapter.

TEGs are inherently less reliable than the existing RTGs because of the need for a more elaborate fuel delivery system, whereas the heat source for RTGs is dependent on radioactive decay and is therefore completely passive and immobile. Nevertheless, TEGs are designed for remote operation, including in severe climates, and their performance and reliability have been demonstrated.[3]

The Air Force report recommends deploying TEGs in a distributed configuration in order to enhance overall system reliability, take maximum advantage of existing equipment and facilities, minimize fuel use, and avoid the expense and environmental disruption of installing transmission cables that would be required for a centralized configuration.[4] However, the study does not appear to give adequate consideration to the increased risks and environmental impacts of the extra fuel distribution operations that will be required to service the TEGs in a distributed configuration. The distributed configuration also would have greater environmental impact due to the need for fuel tank installation at five different sites, instead of just one.

The Air Force report also fails to give adequate consideration to the issue of power supply reliability regarding TEGs. The report cites data on the catastrophic failure rate for the machines, but does not develop any data to indicate their reliability with regard to the far more probable noncatastrophic failure modes, which include problems of flame stability, fuel delivery, and ignition.

PHOTOVOLTAICS

Solar photovoltaic (PV) panels could be used to power the Burnt Mountain equipment. PV generators share some of the most desirable characteristics of the existing RTGs: no moving parts, no need for fuel deliveries, passive operation, and minimal maintenance that can be performed in conjunction with regular service visits to the site for general maintenance procedures. PV systems present minimal health and environmental risks under normal operating conditions. There are, however, risks associated with PV systems in fires or transportation accidents. Possible releases of corrosive or toxic fumes and/or toxic metals in such events could create health and environmental problems. Annual maintenance visits are recommended for PV power and battery systems, but no annual fuel deliveries are necessary.

PV generators also produce a form of power that is very similar to that produced by RTGs with respect to alternating/direct current (AC/DC) characteristics, voltage, and wattage, and PV systems are ideally suited for distributed operating configurations. Indeed, the majority of PV installations in current operation are remote power applications, many in severe environments.[5] PV systems have been proven as reliable power sources for remote, unattended, low-power applications in sites all over the world, including many sites in polar regions (table 4-2).

The most difficult aspect of designing a PV system for use at the Burnt Mountain Seismic

[3] J.H. Doolittle, *Development of an Automatic Geophysical Observatory for Use in Antarctica* (Palo Alto, CA: Lockheed Missiles and Space Co., Inc., Research and Development Division, May 1986).

[4] Wright Laboratory, op. cit., footnote 1.

[5] The Navy has an installation using RTGs at Fairway Reek, west of Wales, Alaska. Stan Read, Environmental Engineering Assistant for Rural Health, Alaska Department of Environmental Conservation, Fairbanks, personal communication, Apr. 18, 1994.

TABLE 4-2: Examples of Photovoltaic Power Systems Used in Cold Regions

Site	Description
Antarctica	Black Island uplink satellite power system, a hybrid that consists of three HR3 wind turbines, 8 kW photovoltaic array, three on-demand 1.2 kW closed cycle vapor turbines.
Antarctica	Energy system for the National Science Foundation portable Sea Ice Laboratory, consisting of a photovoltaic array and heated with passive solar collectors.
Alaska: 8 sites	Hybrid power systems that consist of 720 peak watt photovoltaic arrays, TEGs, and batteries for an Air Force installation.
Canada: Labrador, Newfoundland 2 sites	Solar-powered Obstruction Lighting Systems (SOLS™) to illuminate power transmission lines.

SOURCE: Compiled by Future Resources Associates, Inc. from information provided by Northern Power Systems.

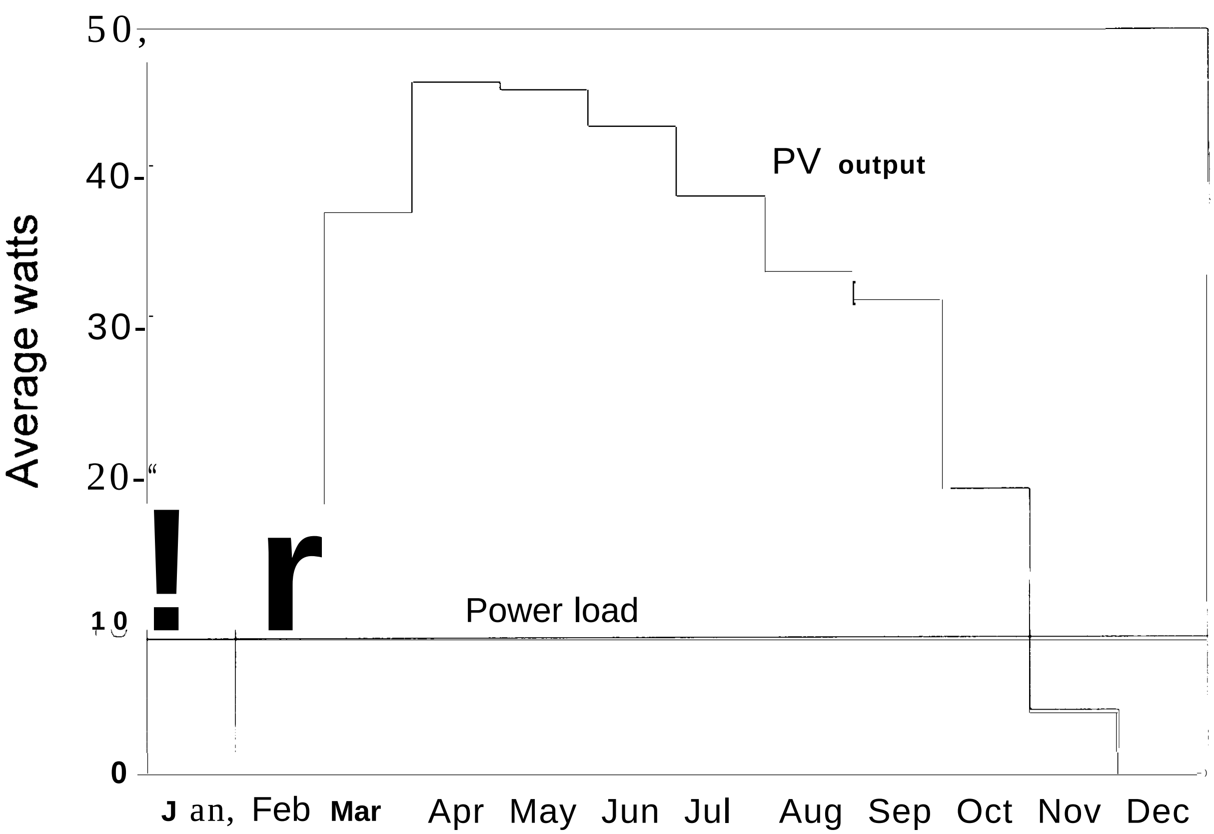
Observatory is the extreme northerly location of the site. For approximately a three-month period, November through January, the site receives very little solar resource (insolation). Figure 4-2 shows the solar resource deficit during the winter months for a possible PV array at Burnt Mountain. The observatory must function during this prolonged dark period, when the PV system provides almost no electrical power.

Two approaches are available for powering the observatory during the three-month dark period using a PV power system: 1) a PV stand-alone system using a battery storage system large enough to allow operations throughout the dark period and a PV array large enough to perform long-term charging of the batteries during the summer, and 2) a hybrid system combining PV power in the summer with an alternative, supplemental source of power during the dark period.

A PV power system for the Burnt Mountain Seismic Observatory could be built in either a central or a distributed configuration. In the central configuration the PV panels and batteries would all be installed at a single site, and a power distribution system would have to be installed at the site to provide power to each of the five remote terminal (RT) sites, and to the remote operating facility (ROF). In the distributed cofiguration, five different PV generation installations would be developed near each of the five RT sites, and no electricity distribution system would be required. The distributed configuration is equivalent to the one used with the existing RTG power system.

The Air Force assessment of alternative power technologies for Burnt Mountain suggested that, if a PV system were deployed at the observatory, it should be designed using a centralized configuration, sited near the ROF site. The report recommends a centralized configuration over a distributed configuration because of possible solar access problems at some of the RT sites. In fact, however, PV systems are ideally suited for distributed configurations, and could easily be integrated into the existing system. The centralized configuration greatly in-

FIGURE 4-2: Solar Balance for a Hypothetical PV Array in an Arctic Location



Based on insolation data **for Beffles, AK (66°55'N, 151°31'VV). The stepped line is the power output averaged over the given month for a PV array consisting of two serial and two parallel PC-4 modules. The straight horizontal line is the power demand of one of the remote terminal sites at Burnt Mountain. The figure shows that there is power surplus in** nine months and a deficit **in three months** (November, December, and January).

SOURCE **Siemens Solar**

creases the total system cost because of the need for more PV panels and battery capacity, as well as for the installation of a power distribution system.

OTA's contractor, Future Resources Associates, Inc. contacted the three major PV system packagers in the United States: Integrated Power Corporation, Photocomm, Inc., and Northern Power Systems. All three recommended that a distributed configuration be used for a PV power system installation at Burnt Mountain if it is at all feasible to do so. PV arrays for several of the RT sites may need to be located a short distance away from the actual monitoring and communications equipment in order to avoid excessive terrestrial shading. Only a proper site survey can determine whether adequate sites are available near each of the RT sites. Optimal layout of a distributed PV system should lead to substantial cost savings in comparison with the centralized system considered in the report. The cost savings include:

fewer total solar panels needed, smaller power inverters and power conditioning equipment needed, and much less transmission cable needed. For the purposes of this background paper, it is assumed that a distributed configuration could be used for a PV energy system installation at Burnt Mountain.

Stand-Alone PV Power System (PV/Battery)

A stand-alone PV power system would require large battery banks for storage through the dark months of November through February, and PV arrays large enough to both run the equipment and recharge the batteries during the period when maximum solar resources are available. These facts make battery design a critical component of a successful stand-alone PV system, but there are no technical barriers to the design of such a system. Due to the northern location of the installation, batteries become a much more dominant component of the overall system than in most remote PV applications.

A battery backup system would entail delivery of a large volume of batteries to the site. The actual amount would depend on the type of battery used. In addition, the PV panels would need to be sized large enough to recharge the batteries in the summer in addition to providing the power needed directly to seismic equipment. The Air Force estimates that 95,000 pounds of batteries would be needed for this service. The estimate is based on the use of lead-acid batteries. In addition, it assumes that these batteries cannot be discharged any more than 20 percent without the risk of freezing. This means that the battery storage must be five times the amount of energy to be used from the batteries. Under these assumptions, approximately 40 helicopter trips would be needed to transport the fully charged batteries to the site for the initial installation.

It is recommended by Northern Power Systems--one of the leading companies involved in the design and implementation of PV energy systems for cold-weather applications--that nickel-cadmium (NiCd) batteries be given serious consideration for use at Burnt Mountain. NiCd batteries cost more than conventional lead-acid batteries, but they have a longer lifetime, and deliver much higher performance under cold-weather conditions with less maintenance requirements. They have a higher power density (power per pound of battery) and they can be discharged more deeply (up to 80 percent). This would yield substantial savings in the transport of the batteries to the site. Another advantage of NiCd batteries is that they require much less maintenance than conventional lead-acid batteries, Over the 30-year expected operating life of the Burnt Mountain Observatory, the batteries will probably have to be replaced one time, instead of twice for the conventional lead-acid batteries.[6]

NiCd batteries are not without disadvantages, though. An accidental release of cadmium would present potential environmental problems. Cadmium is classified by the Environmental Protection Agency as one of the 17 most dangerous substances if released into the environment.

The batteries probably could be housed in the existing shelters, and with adequate insulation it should be possible to maintain the batteries without a requirement for external heating. It is possible that the battery cost could represent as much as 50 percent of the total installed cost of a PV energy system for Burnt Mountain.

Overall system reliability could be enhanced by making, when necessary, a service call to the site in late October to booster charge the batteries with portable generators for the winter haul. This could be performed in years for which

[6] Sealed lead-acid batteries with 20-year lifetimes are now available. Like NiCds, these would only have to be replaced once.

cloudier than normal conditions persist during the summer months. Remote monitoring of battery charge levels should be easy to accomplish.

A stand-alone PV power system for the Burnt Mountain Seismic Observatory would consist of five separate, isolated installations. Each of the installations would include two to three PV panels, support structures, power conditioning equipment, and NiCd storage batteries designed for seasonal power storage. Each PV panel, rated at 50 to 60 watts peak, would measure less than 1 square meter in surface area. Four of the installations would be designed to serve continuous loads of 10 watts and peak loads of 150 watts each. The fifth installation would be designed to serve a continuous load of about 30 watts and a peak load of 150 watts.

Actual PV system costs for such an installation can only be determined by performing a site survey, resource assessment, and preliminary engineering. The regular rule of thumb used in the industry for estimating PV system installed costs for complete systems including batteries is $10 to $15 per installed peak watt of capacity. This rule of thumb covers systems designed for conventional applications, and for sites that do not experience prolonged dark periods. The much larger and more sophisticated batteries needed for an application like Burnt Mountain mean that actual system costs would be much higher than conventional PV systems.

Hybrid Power System (PV/TEG)

The alternative to designing a system with adequate battery storage to allow for 100 percent solar energy production is to utilize a hybrid system, in which power during the dark period and other prolonged periods of unavailability of solar insolation is provided by an alternative power source. Propane-fueled TEG power systems are the primary candidate to act as the supplemental power source. The use of a hybrid system, in comparison with a PV/battery system, allows substantial savings in terms of reduced battery and PV panel size requirements, as seasonal storage is no longer necessary, However, a more complicated control system is required.

However, it also means transporting propane, though a smaller amount than in the TEG alone option. In addition, there would need to be an automatic control system to start the TEG when PV power output was too low. The reliability of such a control system is a concern, especially its cold starting performance.

In a hybrid PV/TEG system for Burnt Mountain, the TEG component of the system would be sized large enough to carry the load fully during the dark period. Each of the remote RT sites (Ul, U2, U4, and U5) would require about a 15 watt TEG, while the U3 site, which would carry the ROF load as well as the RT load, would require about a 40 watt unit. The five TEG units would be expected to operate for approximately 2,200 hours per year (one-quater of the year), using approximately 1,250 pounds of fuel per year, which is about 250 gallons per year. This is one-quarter as much fuel as would be used by a stand-alone TEG power system.

The use of a PV/TEG hybrid power system in a distributed configuration would require the installation of storage tanks for propane fuel and compressed nitrogen at each of the five RT sites at Burnt Mountain. Nitrogen would be required for forcing fuel to the TEG units under the very cold weather conditions that are known to occur regularly during the dark period at the Burnt Mountain site. Electric ignition and flame stabilization would also be required for the TEGs, which would be depended on for operation of the observatory during the most severe weather conditions of the year, when site maintenance is almost impossible.

I Reliability

PVS are able to provide the required level of electric service reliability because they are entirely passive in their operation and have no moving parts. In addition, with a PV system, the observatory's equipment would be powered directly by the battery system, not the PV module itself. The battery system is passive in operation as well, and does not employ any moving parts, It should be easy to install a remote monitoring capability for the battery charge levels as part of a PV power system, in order to allow monitoring of battery performance by the Air Force Technical Applications Center.

Of the three PV system packagers contacted for this background paper, two favor the use of a stand-alone PV system for Burnt Mountain, and the other favors the use of a hybrid PV/TEG system. OTA's analysis indicates that a stand-alone PV/battery system has lower cost, greater operational simplicity, and lower environmental impact. For these reasons, this background paper concludes that a stand-alone system should be given priority in testing and installation.

After the initial period of insolation and weather data collection, several PVS should be operated side-by-side with the RTGs in order to establish their operating reliability and their resistance to windloading and snow and ice buildup. Also, the annual service calls to the Burnt Mountain Observatory site should include full service for the PV energy system. PV service should include annual maintenance on the battery system, as well as cleaning of the PV module and checking of the module's support structure, wiring, and control systems.

In cases where a module has not received sufficient insolation during a given summer period to store up enough charge for the winter run, a portable generator could be brought in to booster charge the battery for continued reliable operation of the system. However, since transporting materials and equipment to Burnt Mountain is costly and logistically challenging, the " PV system should be designed (sized) so that booster charging is required only in extremely rare instances. Under these conditions, a PV power system should be able to deliver the desired level of reliability.

SUMMARY OF COSTS AND RELIABILITY

RTGs have proven very reliable power sources for the Burnt Mountain Observatory. The costs of keeping them operating include annual leak testing trips (which are accomplished in conjunction with electronics maintenance trips) and the $1,500 annual license fees. There will be substantial costs to moving the RTGs from Burnt Mountain whenever they reach the end of their lifetime.

TEGs are also reliable. There is some concern about their cold starting capabilities, but insulation and line burial should minimize problems in this area. The Air Force estimates that the installation costs would be between $430,000 to $880,000 depending on the configuration (table 4-3).

PV power systems are commercially proven technologies for supplying the type of power needed at Burnt Mountain. PV systems currently provide power for remote, unattended applications in polar Alaska and Antarctica. The Air Force estimates that the installation costs would be about $1 million, owing to the cost of laying the power distribution system and the large volume of batteries required. These costs could be considerably lower if a distributed configuration and NiCd batteries were used. Moreover, there are no refueling requirements. Annual maintenance requirements would be low, but periodic replacement of batteries and possibly PV panels would be necessary.

It should be relatively easy to integrate a PV power system into the existing equipment and electrical configuration at Burnt Mountain, as PV modules and battery systems produce electricity in similar form--DC--and voltage to the existing RTG power system. It may be desirable to electrify one RT site with a PV system and operate it for a year or so while the existing RTG system is in place. This approach would help to demonstrate the reliability of the technology prior to removal of the RTGs from Burnt Mountain.

TABLE 4-3: Summary of Costs of TEG and PV Power Sources as Estimated by the Air Force (thousands of dollars, 1994)

	TEG [central)	TEG (distributed)	PV (central)
Installation			
Equipment	$49	$69	$203
Airlift of equipment and fuel	90	104	177
Installation of equipment	192	181	66
Installation of power lines	393		393
Mangement and engineering	156	76	180
Subtotal	$880	$429	$1.020
Replacement (once)			
Equipment (TEGs PV arrays)	49	69	7
Airlift of equipment			26
Management and engineering			7
Subtotal	49	69	41
Replacement (twice)			
Equipment (batteries)			$114
Airlift of equipment			98
Management and engineering			46
Subtotal	0	0	$257
Annual			
Fuel	$10	$8	
Airlift of fuel	23	21	
Miscellaneous supplies (29 years)			15
Management and engineering	7	6	3
Subtotal	$39	$3-I	$18
Total present value[a]	$1,110	$632	$1,207

KEY: TEG = thermoelectric generator, PV = photovoltaic.

@ Calculated at a discount rate of 15 percent

NOTE: Cost estimates based on 30-year lifetime of service

SOURCE: Wright laboratory, Aeropropulsion and Power Directorate, Aerospace Power Division, 'Power System Assessment for the Burnt Mountain Seismic Observatory, " report prepared for the Air Force Technical Applications Center, May 1994. Data is from Tables 2.1.7-1, 2.2.7-1, and 227-2