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# SURVEY OF REQUIREMENTS FOR AIR-TRANSPORTABLE 30-kw(e) TO 2-Mw(e) ELECTRIC POWER PLANTS AND THE CHARACTERISTICS OF AVAILABLE POWER PLANTS

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## Abstract

The Army, Navy, and Air Force require substantial amounts of electric power at remote sites that are difficult of access and expensive to supply. These include bases in the antarctic, arctic, Dew Line radar stations, and undersea installations. In addition to these military requirements, there are a wide variety of other potential government and commercial applications for compact, transportable nuclear electric power plants. These include requirements of the Coast and Geodetic Survey, Bureau of Fisheries, Weather Bureau, Civil Defense, and a number of possible undersea mining and oil-well drilling operations.

This report summarizes the information available on the size, weight, cost, operating characteristics, operating life, and special environmental requirements for typical applications. The characteristics of available conventional and nuclear electric power sources are then summarized and compared with the power plant requirements of the previous section. The shortcomings of the nuclear reactor power plants that have been built or represent a small extrapolation of the present technology with respect to the basic requirements for the various applications are then reviewed, and an effort is made to point out areas where important improvements in technology can reasonably be expected.

## Applications

Both the Army and the Air Force require substantial amounts of power at remote bases that are difficult of access and expensive to supply. These include bases in the arctic and antarctic, Dew Line radar stations, island outposts, and bases in a war theater. The cost of supplying the latter in time of war is high but particularly difficult to estimate because of the complex logistics problems that prevail under wartime conditions.

The Navy requirements for air-transportable electric power units are essentially similar to those of the Army and the Air Force, that is, for remote bases and dockside service. In addition, the Navy has a need for

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air-transportable power plants for use in connection with undersea exploration and various undersea installations, such as Sealab.

In addition to these military requirements, there is a wide variety of other potential government and commercial applications, including uses by the Coast and Geodetic Survey, Bureau of Fisheries, Weather Bureau, Civil Defense, and other government services. Perhaps the most important potential commercial uses are for oil-drilling rigs in water depths of 300 ft or more and for undersea mining operations.

## Power Plant Requirements of the Major Applications

Power plant requirements vary from one type of application to another in terms of the amount of power; the availability of air, cooling water, crew quarters, and space for the installation; accessibility for maintenance; power plant life; cost of transportation and resupply; and the like. Table 1 summarizes the information that has been obtained on these requirements for the principal applications under consideration. While many of these requirements are not sharply defined and the picture is incomplete, the values given in Table 1 were based on the best information available to Oak Ridge National Laboratory to date. The following sections present some qualifying remarks.

### Power Range

The range of power requirements for each of the different applications involves uncertainties as to what extent the power requirements will increase with time, especially if power sources are available at costs lower than the costs of any of those currently developed. Another important consideration is the extent to which the user would prefer to employ a multiplicity of power units in order to obtain multiengine reliability. The Army and the Air Force, for example, commonly employ multiples of as many as 16 diesel engines in a power plant simply because units can readily be added as the power requirements of the base increase. On the other hand, the unit cost of a power plant — and this is particularly true for nuclear plants — can be reduced as the power output per unit is

increased, if there is an adequate demand for the larger units to yield reasonable production quantities in units per year.

Voltage and Frequency

Virtually all the applications are for ac power, and hence the voltage output of the generator is not an important consideration, since transformers are inexpensive and very reliable. While there are some applications for which dc power is desired, these can be satisfied with motor-generator sets or solid-state conversion devices. Further, brush troubles in dc generators are so common that it is hard to see how a satisfactory degree of reliability could be obtained from a conventional dc generator.

The bulk of the military field equipment is either 60 cycle or 400 cycle, with the latter coming to occupy a progressively larger fraction of the total because of its lighter weight and smaller size. The Air Force has found that with only a small weight penalty most of their electronic equipment can be designed to operate with 50-, 60-, or 400-cps power, and this requirement may be included in future specifications.[1]

The voltage and frequency regulation requirements vary substantially from one application to another. There are two major aspects to the problem: (1) steady-state regulation and (2) permissible fluctuations in the course of load transients. The system dynamics and the design of the control system will depend on whether the load is primarily a resistive load, such as would be the case with tungsten electric lights, a strongly inductive load, such as would be represented by electric motors, or a load with a great deal of capacitance. It is also important to establish the load range over which stable operation with close control of voltage and frequency is required for extended periods. The load factor is a determining consideration in establishing the burnup requirements to be imposed on the fuel. The maximum amplitudes and rates of change in load to be expected either in the form of ramp changes or step changes have important influence on the design, cost, and complexity of the control system. The availability of auxiliary power from batteries or from other sources for emergency conditions and the requirements for such power may have important influences on the design of the plant.

Military specifications on voltage and frequency control were gradually tightened until the requirements became ±1/2% on frequency and ±1 or 2% on voltage. While diesel-generator sets could meet these requirements in acceptance tests, it was found that deterioration in service led to much poorer performance, and specifications are currently being relaxed by the Air Force. (See proposed revision of MIL-E-4158, June 20, 1966.[2])

## Size and Weight Requirements

In many instances there may be a strong incentive to limit the size, weight, or shape of the power plant to make it adaptable to air, motor, or rail transportation. For some oceanographic applications bouyancy may be a consideration.

For land installations the principal advantage of small size is to facilitate shipping. Ordinarily, the size of a package is the more important consideration than its weight, even for air transport. For rail shipment, package sizes must be kept to 10 by 14 by approximately 60 ft in length if special routing is to be avoided. Similar size limitations apply to truck transport. For air transport, the size limitations depend on the aircraft. A typical craft is the C-130A, which will take a package 8 by 10 by 30 ft in length weighing up to 35,000 lb. Table 2 indicates the limitations on size and weight for packages to be carried by military transport aircraft.

A major item in the cost of a power plant installation at a remote base is the cost of transportation, particularly if it is necessary to deliver the equipment by air.

## Economic Considerations

For a nuclear power plant to be attractive for any given application, it must be at least competitive in cost with other sources of power, such as diesel-generator sets or batteries. While it is very difficult to estimate the cost of a nuclear power plant, it is usually not so difficult to estimate the maximum cost of a plant that would be acceptable for a given application. Since costs depend so heavily on the volume of production, it is necessary to associate such an estimated cost with the

number of units that would be required per year for that application. It is hoped that it will be possible to find sufficient similarity in the requirements for the various applications that the total number of units required per year for plants of a typical output will be sufficient to reduce the cost of production to an attractive level. It may be that for a given application only one or two units per year would be used if the initial cost per unit were relatively high, whereas at a substantially lower cost per unit a much larger number would be used.

Items C-2 and C-3 are intended to give an indication as to the amount that could be justified in the way of operating costs for fuel and operating personnel, respectively. The total core life and equivalent full-power hours are an important consideration in the design of the fuel element. Similarly, the total system life in equivalent full-power hours (or, where appropriate, the total lifetime) is also important in the design of such items as the turbine-generator. In some applications there may be no objection to having a small operating crew, whereas in others there may be stringent limitations on the crew size, or completely remote or even automatic control may be required.

The degree of the remoteness of this control is an important factor in the design of the control system. Item C-9 (Table 1) is intended to give an indication of the extent to which the transportability of the power plant can be improved by draining off most or all of a large water shield so that only a relatively small lead gamma shield would be required for protection from fission-product decay gammas. Item C-10 is intended to indicate the extent to which supporting facilities would be available to aid in maintenance or repair.

## General Considerations

For some applications it may be that the power plant will be started up only infrequently and will be run for long periods of time between shutdowns. In addition, a very long shelf life may be required of the power plant, and this will influence the design and choice of materials.

The power plant reliability, item D-3, is closely tied to the size of the available maintenance crew and supporting facilities. The desired reliability is expressed in terms of the probability of operating for

10,000 hr without a forced outage. For an undersea mining application, for example, an extremely high degree of reliability would be required, since maintenance might be quite impracticable.

Item D-4 is intended to indicate the date at which the first power plant is desired. Item D-6 is intended to call attention to the difference between applications from the standpoint of the availability of water for carrying off waste heat or for shielding. A plant designed to operate far out in a desert, for example, might be provided with shielding water with no great difficulty, but there would not be enough water to employ a cooling tower, let alone for the sort of simple cooling system that would be practicable for a power plant used in an undersea mining operation.

For some applications it may be possible to set the power plant up in a very neat fashion, whereas in others it may be desirable simply to drop the power plant to the sea floor and accept a 10-, 20-, or 30-deg list to ease the setup problems. Similarly, in shipment and installation it may be important that the power plant be designed to tolerate substantial lateral and vertical accelerations. If the power plant is to be mounted on a barge or a floating platform at sea, it may be subject to substantial lateral or vertical accelerations during operation.

Item D-9 is intended to give an indication as to whether the user would prefer a system in which individual components would be accessible and replaceable or whether it appears better to replace the complete power package and take it to a shop for overhaul. Items D-10 and D-11 are concerned with the temperature, pressure, and humidity conditions of the environment. For example, air-side corrosion would probably not be a problem in a desert environment, but there would be a serious possibility of dust and sand getting into moving parts. On the other hand, in a deep mine it might be necessary for the power plant to operate under 100% humidity conditions with dirty water splashing or spraying on the various power plant components. Temperature conditions will also vary widely with the application. The temperature of the cooling air or water has an important effect on the condenser temperature in a Rankine cycle plant and hence on its thermal efficiency and the size of the heat exchangers

Table 2. Characteristics of Military Cargo Type Aircraft

| Aircraft Designation | Cargo Compartment Volume ($ft^3$) | Loading Door Height and Width (ft) | Maximum Payload (lb) | Flight Radius at Maximum Load (nautical miles) | Take-Off Distance (ft) | Type of Airfield Required |
|---|---|---|---|---|---|---|
| C-47 | 1,425.5 | 4.6 min × 7.0 | 9,485 | ~600 | 5000 | Semiimproved hard surface |
| C-54 | 3,335.4 | 5.6 × 7.9 | 28,565 | 800 | 5800 | Improved hard surface |
| C-119 | 2,690.9 | 8.0 × 9.2 | ~18,000 | 600 | 5000 | Semiimproved hard surface |
| C-124 | 10,173.2 | 11.6 × 11.3 | ~74,000 | 500 | 7200 | Improved hard surface |
| C-130 | 3,980.4 | 9.2 × 10.0 | 35,000 | 1100 | 3000 | Unimproved level and firm surface |

Table 1. Estimated Requirements for Nuclear Terrestrial Power Plants

| | Army Corps of Engineers | | Navy Bureau of Yards and Docks | | | Civil Defense |
|---|---|---|---|---|---|---|
| | Air Transportable | Mobile | Sealab | Dock Service | Ocean Floor | |
| **A. Power requirements** | | | | | | |
| 1. Maximum load, kw(e) | 2000 | 2000 | 100 | 1500 | 100 | 100 |
| 2. Type of load (ratio of resistive to inductive) | 50/50 | 50/50 | 50/50 | 50/50 | 50/50 | 75/25 |
| 3. Range of load, % | 10 to 100 | 10 to 100 | 10 to 100 | 10 to 100 | 10 to 100 | 20 to 100 |
| 4. Load factor | 0.60 | 0.60 | 0.60 | 0.60 | 0.60 | 0.80 |
| 5. Voltage, v | 230 | 230 | 230 | 230 | 110 | 110 |
| 6. Frequency, cps | 400 | 400 | 400 | 400 | 400 | 400 |
| 7. Rates of change in load, %/sec | 1 | 1 | 1 | 1 | 1 | 1 |
| 8. Maximum step changes in load, % of full load | 20 | 20 | 20 | 20 | 20 | 20 |
| 9. Quality of power | | | | | | |
| a. Allowable variation at steady load | | | | | | |
| Frequency, % | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 5 |
| Voltage, % | 2 | 2 | 2 | 2 | 2 | 5 |
| b. Allowable variation during load changes | | | | | | |
| Frequency, % | 5 | 5 | 5 | 5 | 5 | 10 |
| Voltage, % | 15 | 15 | 15 | 15 | 15 | 15 |
| 10. Auxiliary and/or emergency power requirements, % of rating | 100 | 5 | 5 | 100 | 5 | 10 |
| **B. Size and weight requirements** | | | | | | |
| 1. Overall dimensions, ft | 8 × 8 × 30 | 8 × 8 × 40 | 8 × 8 × 30 | 8 × 8 × 30 | 8 × 8 × 8 | |
| 2. Maximum size of transportable packages, ft | 35,000 | 8 × 8 × 30 | 8 × 8 × 30 | 35,000 | 8 × 8 × 30 | |
| 3. Weight, lb | | 45,000 | 35,000 | | 25,000 | |
| 4. Shape | | | | | Sphere | |
| 5. Bouyancy limitations | Not applicable | Not applicable | Neutrally bouyant | Not applicable | Neutrally bouyant | Not applicable |
| **C. Economic considerations** | | | | | | |
| 1. Initial cost per unit, $/kw(e) | <3,000 | <3,000 | <10,000 | <3,000 | <10,000 | <1,000 |
| a. Number of units per year | 2 | | 1 | 1 | 1 | |
| 2. Fuel cost, mills/kwhr | <30 | | | <30 | | |
| 3. Crew costs, $/man year | 25,000 | 25,000 | | 25,000 | | |
| 4. Cost of power for principal competition, mills/kwhr | 30 to 300 | 30 to 300 | >1000 | 30 to 100 | >1000 | |
| 5. Core life, equivalent full-power hours | 20,000 | 20,000 | 10,000 | 10,000 | 10,000 | 3,000 |
| 6. System life, equivalent full-power hours | 100,000 | 100,000 | 100,000 | 100,000 | 100,000 | 3,000 |
| 7. Operating crew size | | | | | | |
| a. At startup | 10 | 5 | 2 | 10 | 0 | 1 |
| b. During operation | 2 | 2 | 0 | 2 | 0 | 0 |
| c. After shutdown | 10 | 5 | 2 | 10 | | 0 |

Table 1 (continued)

| | Army Corps of Engineers | | Navy Bureau of Yards and Docks | | | Civil Defense |
|---|---|---|---|---|---|---|
| | Air Transportable | Mobile | Sealab | Dock Service | Ocean Floor | |
| C. Economic considerations (continued) | | | | | | |
| 8. Degree of remoteness of control | | | | | | |
| a. Operator at plant | Yes | Yes | No | Yes | No | Yes |
| b. Cable – separation distance, ft | | | 100 | | | |
| c. Largely automatic | Yes | Yes | Yes | Yes | Yes | Yes |
| 9. Cooldown time before moving, days | 10 | 10 | 10 | 10 | 10 | 100 |
| 10. Supporting facilities available | Yes | No | No | Yes | No | No |
| D. General considerations | | | | | | |
| 1. Incidence and duration of shutdowns | 1/year; 1 month each | | 4/year; 2 months each | 1/year; 1 month each | 1/year; 1 month each | |
| 2. Shelf life, years | 5 | 5 | 5 | 5 | 5 | 20 |
| 3. Probability of 10,000 hr of operation without outage | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 |
| 4. Date desired | 1974 | | 1972 | | | |
| 5. Growth capability | To 10 Mw(e) | To 10 Mw(e) | To 300 kw(e) | To 10 Mw(e) | To 1 Mw(e) | |
| 6. Availability of water for cooling | 80% of sites | | Yes | Yes | Yes | 80% of sites |
| 7. Permissible attitude range, deg | ±15 | ±15 | ±15 | ±5 | ±15 | ±5 |
| 8. Permissible lateral and vertical accelerations, g | 8 | 15 | 5 | 5 | 5 | 5 |
| 9. Maintainability in situ | Yes | Yes | No | Yes | No | No |
| 10. Environment (depth of operation), ft | Surface | Surface | 600 | Surface | 24,000 | |
| 11. Environment temperature, °F | -100 to +100 | -100 to +100 | 30 to 90 | -100 to +100 | 30 to 60 | 40 to 70 |
| 12. Location of emergency power source | At plant | | Near plant | At plant | Near plant | |
| 13. Vessel surface temperature, °F | <150 | | <120 | <150 | <120 | |
| E. Hazards | | | | | | |
| 1. Location | Semiremote | Semiremote | Remote | Semiremote | Remote | City |
| 2. Required containment life, years | 20 | 20 | 50 | 10 | 50 | 10 |
| 3. Radiation to environment | | | | | | |
| a. During operation (at 50 ft) | <6 mr/hr | <6 mr/hr | | 6 mr/hr | | 6 mr/hr |
| b. After shutdown (at 6 ft) | <6 mr/hr | <6 mr/hr | | 6 mr/hr | | 6 mr/hr |
| 4. Provisions for positive shutdown | Yes | Yes | Yes | Yes | Yes | Yes |

required to reject the heat from the cycle. These temperatures may vary from −130°F at the South Pole to +150°F in a desert.

Item D-12 is concerned with the degree of remoteness of the emergency power source available, that is, whether it would be located right beside the nuclear plant or whether it would be a long distance off, for example, on a surface vessel with the power plant on the sea floor. Item D-13 is intended to include any limitations that may be imposed on the temperature of the vessel used to contain the power plant, if such a vessel is required.

Hazards

Hazards considerations are very important factors in the design of air-transportable power plants. The locations in which the power plant is to be used relative to inhabited areas (i.e., the degree of remoteness of the installation) may have a vital influence on the design, as may the directions of the prevailing winds or water currents. Item E-2 is concerned with the required life of the containment system. It may be that a power plant to be placed on the sea floor will have to be fitted with a containment vessel that would not rust through in a period of 10, 50, or even more years.

Item E-3 is concerned with radiation to the environment both during operation and after shutdown. This will affect the maintainability of the power plant, radiation damage to various forms of plant or animal life in the vicinity of the power plant, and possible hazards to personnel working in the vicinity of the power plant.

Item E-4 is intended to indicate the possible needs for special assurances that shutdown of the reactor has been achieved. This includes secondary shutdown systems or possibly such a drastic measure as removal of the reactor reflector during shipment to assure that criticality could not occur.

## Conventional Sources of Electric Power

Power costs, reliability, safety, size, and weight are the primary considerations in arriving at a design and operating philosophy for

reactors for Terrestrial Low Power Reactor (TLPR) applications. Relative rather than absolute values for cost, size, and weight data are easier to obtain and are adequate for comparisons of the various systems. The other systems with which the TLPR must compete depend on the application, and include diesel-generator sets, batteries, fuel cells, and radioactive isotopes.

Diesel-Generator Units

The cost of power from a diesel-generator plant depends on plant location and size, with the fuel being the major cost item. Tables 3 and 4 give cost data from an Air Force study[3] of Alaskan Air Command and Air Defense Command Dew Line power plants. The power costs shown in Table 3 are different than those in Ref. 3 in that the annual capital costs given in the table are assumed to be 5% of the investment cost. The data in Ref. 3 for the costs of power and heating were combined for the Dew Line sites, and separate power costs were not given. However, the unit cost of the diesel-generator equipment at the smaller Dew Line stations was about two to four times the total installation cost at the Alaskan Air Command Bases, and the power costs were considerably greater. One item that was not included in the costs of these installations in either Ref. 3 or Table 3 was the diesel fuel inventory.

The operating and maintenance costs for the Alaskan Air Command plants are also given in Table 3. The average for all sites is 11.6 mills/kwhr. However, by omitting the Shemya base, which has a larger capacity than that being considered for the TLPR program, the average cost at the other sites is 15.2 mills/kwhr.

A study by Kaiser Engineers[4] that compares the cost of both several types of reactor system and diesel-generator plants for inland antarctic stations indicated the installed cost of the diesel plants to be from $6000 to $7400 per kilowatt for capacities of 210 to 525 kw. The largest cost item for these plants was the air-freight cost for the fuel-oil reserves; this varied from $1800 to $2400 per kilowatt. The oil inventory for the permanent stations was an 18 months supply based on full-power operation. Full power for these stations varied from one-half to two-thirds of installed capacity. The cost for the plants included the

Table 3. Alaska Air Command Diesel-Generator Power Cost (From Ref. 3)

| Site | Maximum Power Demand (kw) | Annual Load (kwhr) | Installed Capacity (kw) | Cost of Diesel Generators ($) | Cost of Buildings ($) | Cost of Fuel Facilities ($) | Total Installation Cost ($) | Fuel Cost ($/gal) | Annual Fuel Cost ($/yr) |
|---|---|---|---|---|---|---|---|---|---|
| King Salmon | 1,125 | 4,130,500 | 1,950 | 584,000 | 336,000 | 119,880 | 1,039,880 | 0.2225 | 91,905 |
| Galena | 720 | 4,092,000 | 1,200 | 787,000 | 235,800 | 159,132 | 1,181,932 | 0.2036 | 76,550 |
| Shemya | 5,200 | 37,373,600 | 10,300 | 1,127,000 | 1,637,000 | 1,926,810 | 4,690,810 | 0.165 | 616,664 |
| Indian Mountain | 800 | 3,914,000 | 1,800 | 370,000 | 247,000 | 79,904 | 696,904 | 0.335 | 131,119 |
| Fort Yukon | 1,050 | 6,948,000 | 2,000 | 431,300 | 131,600 | 245,525 | 808,425 | 0.2408 | 167,307 |
| Tin City | 600 | 3,155,000 | 1,100 | 315,000 | 300,000 | 198,021 | 813,021 | 0.3137 | 99,000 |
| Cape Lisburne | 620 | 3,736,200 | 1,100 | 315,000 | 300,000 | 392,616 | 1,007,616 | 0.3468 | 129,557 |
| Northeast Cape | 750 | 3,740,000 | 2,000 | 315,000 | 300,000 | 392,940 | 1,007,940 | 0.2799 | 104,682 |
| Tatalina | 725 | 3,865,000 | 1,100 | 315,000 | 300,000 | 221,010 | 836,010 | 0.1828 | 70,652 |
| Unalakleet | 675 | 4,099,600 | 800 | 135,000 | 113,700 | 292,160 | 540,860 | 0.225 | 92,241 |
| Sparrevohn | 975 | 5,893,000 | 1,800 | 212,000 | 299,000 | 107,156 | 618,156 | 0.335 | 197,415 |
| Campion | 600 | 3,519,200 | 1,200 | 274,500 | 300,000 | 146,010 | 720,510 | 0.2036 | 71,651 |
| Cape Newenham | 575 | 2,925,000 | 1,100 | 315,000 | 300,000 | 139,725 | 754,725 | 0.2225 | 65,085 |
| Cape Ronanzof | 550 | 3,192,500 | 1,100 | 315,000 | 300,000 | 277,350 | 892,350 | 0.23 | 72,967 |
| Kotzebue | 750 | 3,987,400 | 1,000 | 228,800 | 121,000 | 296,070 | 645,870 | 0.3356 | 127,106 |
| Total | | | 29,500 | | | | 16,255,009 | | |

Table 3 (continued)

| Site | Total Installation Cost Divided by 20 ($/yr) | Annual Operating (Labor) Cost ($/yr) | Annual Maintenance (Labor) Cost ($/yr) | Total Operating Cost ($/yr) | Unit Cost of Power (mills/kwhr) | Installation Cost Per Unit of Capacity [$/kw(e)] | Load Factor | Fuel Consumption (kwhr/gal) | Operation and Maintenance Cost (mills/kwhr) |
|---|---|---|---|---|---|---|---|---|---|
| King Salmon | 51,994 | 45,359 | 50,250 | 239,508 | 57.985 | 533.272 | 0.24 | 9.9999 | 23.15 |
| Galena | 59,096.6 | 42,094 | 30,100 | 207,840.6 | 50.791 | 984.943 | 0.38 | 10.8835 | 17.64 |
| Shemya | 234,540.5 | 120,417 | 97,900 | 1,069,521.5 | 28.617 | 455.418 | 0.41 | 10.0000 | 5.84 |
| Indian Mountain | 34,845.2 | 39,606 | 24,300 | 229,870.2 | 58.730 | 387.169 | 0.24 | 10.0000 | 16.33 |
| Fort Yukon | 40,421.25 | 29,132 | 24,400 | 261,300.25 | 37.608 | 404.212 | 0.39 | 10.0001 | 7.71 |
| Tin City | 40,651.05 | 21,684 | 27,055 | 188,390.05 | 59.712 | 739.110 | 0.32 | 9.9972 | 15.45 |
| Cape Lisburne | 50,380.8 | 22,584 | 21,325 | 223,846.8 | 59.913 | 916.015 | 0.38 | 10.0011 | 11.75 |
| Northeast Cape | 50,397 | 30,731 | 33,489 | 219,299 | 58.636 | 503.970 | 0.21 | 10.0001 | 17.17 |
| Tatalina | 41,800.5 | 26,914 | 30,545 | 169,911.5 | 43.962 | 760.009 | 0.40 | 10.0000 | 14.87 |
| Unalakleet | 27,043 | 23,477 | 36,728 | 179,489 | 43.782 | 676.075 | 0.58 | 10.0000 | 14.69 |
| Sparrevohn | 30,907.8 | 44,121 | 43,200 | 315,643.8 | 53.562 | 343.420 | 0.37 | 10.0000 | 14.82 |
| Campion | 36,025.5 | 28,707 | 29,000 | 165,383.5 | 46.995 | 600.425 | 0.33 | 10.0000 | 16.40 |
| Cape Newenham | 37,736.25 | 21,684 | 47,500 | 172,005.25 | 58,805 | 686.114 | 0.30 | 9.9994 | 23.65 |
| Cape Ronanzof | 44,617.5 | 21,684 | 25,200 | 164,468.5 | 51.517 | 811.227 | 0.33 | 10.0631 | 14.69 |
| Kotzebue | 32,293.5 | 21,138 | 28,000 | 208,537.5 | 52.299 | 645.870 | 0.45 | 10.5280 | 12.32 |
| Total | | | | | | 550.08 | | | |

Table 4. Air Defense Command Dew Line Site Diesel Data (From Ref. 3)

| Site | Maximum Demand (kw) | Critical Load (kw) | Total Annual Load (kwhr) | Average Load (kw) | Number of Diesels | Ratings of Diesels (kw) | Original Cost of Diesels ($) | Cost of Fuel Delivered ($/gal) | Cost Per Overhaul of Diesels ($) | Frequency of Overhaul of Diesels Per Year | Overhaul Cost Per Year ($/yr) | Overhaul Cost Per Unit of Power (mills/kwhr) | Original Cost of Diesels ($/kw) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| LIZ-2 | 100 | 91 | 762,120 | 87.0 | 4 | 60 | 344,000 | 0.50 | 1,400 | 0.480 | 2,688 | 3.5 | 1430 |
| LIZ-3 | 102 | 86 | 753,360 | 86.0 | 4 | 60 | 344,000 | 0.50 | 1,400 | 0.480 | 2,688 | 3.6 | 1430 |
| POW MAIN | 201 | 183 | 1,603,080 | 183.0 | 7 | 60 | 516,000 | Not available | 1,400 | 0.480 | 4,704 | 2.9 | 1230 |
| POW-1 | 100 | 77 | 657,000 | 75.0 | 4 | 60 | 344,000 | 0.50 | 1,400 | 0.480 | 2,688 | 4.1 | 1430 |
| POW-2 | 107 | 81 | 665,760 | 76.0 | 4 | 60 | 344,000 | 0.50 | 1,400 | 0.480 | 2,688 | 4.0 | 1430 |
| POW-3 | 108 | 89 | 779,640 | 89.0 | 4 | 60 | 258,000 | 0.50 | 1,400 | 0.480 | 2,688 | 3.5 | 1080 |
| BAR MAIN | 881 | 856 | 7,498,560 | 856.0 | 4 | 350 | 1,988,000 | 0.50 | 9,000 | 0.433 | 15,588 | 4.3 | 850 |
| | | | | | 5 | 175 | | | 7,500 | 0.433 | 16,237 | | |
| | | | | | 1 | 60 | | | 1,400 | 0.480 | 672 | | |
| BAR-1 | 151 | 126 | 1,103,760 | 126.0 | 6 | 60 | 578,430 | 0.3349 | 1,400 | 0.480 | 4,032 | 3.7 | 1610 |
| BAR-2 | 163 | 144 | 1,252,680 | 143.0 | 6 | 60 | 428,400 | 0.3349 | 1,400 | 0.480 | 4,032 | 3.2 | 1190 |
| BAR-3 | 171 | 121 | 1,103,760 | 126.0 | 6 | 60 | 429,840 | 0.3349 | 1,400 | 0.480 | 4,032 | 3.7 | 1190 |
| BAR-4 | 149 | 126 | 1,095,000 | 125.0 | 6 | 60 | 514,920 | 0.3349 | 1,400 | 0.480 | 4,032 | 3.7 | 1430 |
| PIN MAIN | 306 | 256 | 2,242,560 | 256.0 | 5 | 150 | 812,160 | 0.3349 | 5,000 | 0.433 | 10,825 | 5.1 | 1000 |
| | | | | | 1 | 60 | | | 1,400 | 0.480 | 627 | | |
| PIN-1 | 153 | 133 | 1,130,040 | 129.0 | 6 | 60 | 510,750 | 0.3349 | 1,400 | 0.480 | 4,032 | 3.6 | 1420 |
| PIN-2 | 197 | 162 | 1,392,840 | 159.0 | 6 | 60 | 514,770 | 0.3349 | 1,400 | 0.480 | 4,032 | 2.9 | 1430 |
| PIN-3 | 187 | 167 | 1,366,560 | 156.0 | 6 | 60 | 514,780 | 0.3349 | 1,400 | 0.480 | 4,032 | 3.0 | 1430 |
| PIN-4 | 164 | 164 | 1,401,600 | 160.0 | 6 | 60 | 428,560 | 0.3349 | 1,400 | 0.480 | 4,032 | 2.9 | 1190 |
| CAM MAIN | 300 | 260 | 2,277,600 | 260.0 | 5 | 150 | 809,860 | 0.3349 | 5,000 | 0.433 | 10,825 | 5.0 | 1000 |
| | | | | | 1 | 60 | | | 1,400 | 0.480 | 672 | | |
| CAM-1 | 173 | 165 | 1,427,880 | 163.0 | 6 | 60 | 508,190 | 0.3349 | 1,400 | 0.480 | 4,032 | 2.8 | 1410 |
| CAM-2 | 145 | 125 | 814,680 | 93.0 | 6 | 60 | 511,580 | 0.3349 | 1,400 | 0.480 | 4,032 | 4.9 | 1420 |
| CAM-3 | 152 | 132 | 1,059,960 | 121.0 | 6 | 60 | 512,970 | 0.3349 | 1,400 | 0.480 | 4,032 | 3.8 | 1430 |
| CAM-4 | 160 | 144 | 1,191,360 | 136.0 | 6 | 60 | 525,590 | 0.2382 | 1,400 | 0.480 | 4,032 | 3.4 | 1460 |
| CAM-5 | 170 | 145 | 1,226,400 | 140.0 | 6 | 60 | 522,540 | 0.2382 | 1,400 | 0.480 | 4,032 | 3.3 | 1450 |
| FOX MAIN | 1445 | 1370 | 12,001,200 | 1370.0 | 6 | 500 | 850,000 | 0.2382 | 10,000 | 0.433 | 25,980 | 2.2 | 280 |
| | | | | | 1 | 60 | | | 1,400 | 0.480 | 672 | | |
| FOX-1 | 160 | 153 | 1,340,280 | 153.0 | 6 | 60 | 510,150 | 0.2382 | 1,400 | 0.480 | 4,032 | 3.0 | 1420 |
| FOX-2 | 172 | 161 | 1,392,840 | 159.0 | 6 | 60 | 510,150 | 0.2382 | 1,400 | 0.480 | 4,032 | 2.9 | 1420 |
| FOX-3 | 194 | 174 | 1,524,240 | 174.0 | 6 | 60 | 627,880 | 0.2382 | 1,400 | 0.480 | 4,032 | 2.6 | 1740 |
| FOX-4 | 196 | 176 | 1,454,160 | 166.0 | 6 | 60 | 513,740 | 0.2382 | 1,400 | 0.480 | 4,032 | 2.8 | 1430 |
| FOX-5 | 214 | | 1,646,880 | | 6 | 60 | 534,020 | 0.2382 | 1,400 | 0.480 | 4,032 | 2.4 | 1480 |
| DYE MAIN | 894 | 804 | 7,043,040 | 804.0 | 5 | 500 | 1,778,990 | 0.2382 | 10,000 | 0.433 | 21,165 | 3.5 | 510 |
| | | | | | 4 | 100 | | | 1,500 | 0.433 | 2,598 | | |
| | | | | | 1 | 60 | | | 1,400 | 0.480 | 672 | | |
| RES-X-1 | 182 | 176 | 1,401,600 | 160.0 | 7 | 60 | 598,000 | 0.2677 | 1,400 | 0.480 | 4,704 | 3.4 | 1420 |
| DYE-1[a] | 395 | 375 | | | 6 | 150 | 240,000 | 0.115 | 7,500 | 0.433 | 19,485 | | 270 |
| DYE-2[a] | 414 | 397 | 3,381,360 | 386.0 | 6 | 150 | 240,000 | 0.115 | 7,500 | 0.433 | 19,485 | 5.8 | 270 |
| DYE-3[a] | 342 | 333 | 2,803,200 | 320.0 | 6 | 150 | 240,000 | 0.115 | 7,500 | 0.433 | 19,485 | 7.0 | 270 |
| DYE-4[a] | 764 | 728 | 6,193,320 | 707.0 | 9 | 150 | 243,000 | 0.115 | 7,500 | 0.433 | 29,227 | 4.7 | 180 |

[a]Diesel equipment at DYE-1, -2, -3, and -4 was foreign made.

heating systems, but for the power generation alone it would be in the range of $5000 to $6000 per kilowatt. The cost of fuel delivered to these stations was about $2.60 per gallon.

The fuel consumption of diesel-generator plants is very nearly constant at 0.1 gal/kwhr, and the fuel cost in mills/kwhr is equal to the fuel cost in cents/gal. Thus, the reported power costs from diesel-generator plants in remote locations can be summarized as follows: for the Alaskan Air Command (excluding the Shemya Base), the cost is from 40 to 60 mills/kwhr; for the small Dew Line stations, the cost is about 100 mills/kwhr; and for the inland antarctic stations, the cost is about 350 mills/kwhr. No rate of return on the capital investment and only 5% per year capital cost are assumed. These costs can be adjusted to any desired rate of return; however, before going into these details, we would also need a better breakdown of the fuel costs used in these studies, especially the costs associated with fuel-storage depots, distribution systems, and fuel inventories.

Isotope Power Units

In studying the cost of power from a radioisotope heat source, it becomes rather apparent that applications of this heat source will be limited in size and that the maximum capacities of such units will probably be well below those of interest in the TLPR program. The reason for this can be seen from the fuel inventory value and decay costs given in Table 5. (Data for Table 5 were taken from Refs. 5 through 9.) For a rather optimistic net plant efficiency of 15% and a plant factor of 0.8%, the data of Table 5 can be converted to costs per unit electrical output, as given in Table 6.

These figures are based on the predicted future costs of the isotopes, and do not include the decay of the isotope during fabrication, between the time of fabrication and its use in generating power, or during reprocessing. The fuel lease charge was based on one year at a rate of 4.75% per year. The fuel inventory was fixed at the amount required at the beginning of power production to give an output of 1 kw at the end on one year. Thus the fuel lease charge and decay cost alone amount to over 1300 mills/kwhr.

Table 5. Radioisotope Properties and Costs (From Refs. 5 through 9)

| | $^{60}Co$ | $^{90}Sr$ | $^{137}Cs$ | $^{144}Ce$ | $^{147}Pm$ | $^{170}Tm$ | $^{210}Po$ | $^{228}Th$ | $^{232}U$ | $^{238}Pu$ | $^{242}Cm$ | $^{244}Cm$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Half-life, y | 5.24 | 28 | 30 | 0.78 | 2.62 | 0.35 | 0.38 | 1.9 | 74 | 87.6 | 0.45 | 18.1 |
| Principal modes of decay | β, γ | β, γ | β, γ | β, γ | β, γ | β, γ | α, γ | α, γ | α, γ | α, γ | α, γ | α, γ |
| Decay energy, Mev | 0.31, 1.17 | 2.24, 1.73 | 0.53, 0.66 | 1.32, 2.18 | 0.22, 0.12 | 0.96, 0.084 | 5.3, 0.8 | 5.42, 0.084 | 5.32, 0.058 | 5.49, 0.044 | 6.11, 0.04 | 5.80, 0.04 |
| Activity, curies/w | 65.1 | 148 | 207 | 126 | 2788 | 385 | 31.2 | 24 | 26 | 29.1 | 27.7 | 33.8 |
| Power density, w/cc | 46.2 | 0.825 | 0.24 | 21.9 | 2.09 | 7.9 | 824 | 1270 | 33 | 3.6 | 397 | 21.6 |
| w/g | 5.31 | 0.223 | 0.077 | 3.47 | 0.286 | 1.03 | 82.4 | 141 | 3.3 | 0.39 | 44.1 | 2.40 |
| Typical fuel composition | Metal | $SrTiO_3$ | Glass | $CeO_2$ | $Pm_2O_3$ | $Tm_2O_3$ | GdPo | $ThO_2$ | $UO_2$ | $PuO_2$ | $Cm_2O_3$ | $Cm_2O_3$ |
| Typical fuel density, g/cc | 8.7 | 3.7 | 3.1 | 6.3 | 7.3 | 7.7 | 10.0 | 9.0 | 10.0 | 10.0 | 9.0 | 9.0 |
| Fuel form melting temperature, °C | 1480 | 1900 | 1275 | 2680 | 2270 | 2300 | 1635 | 3220 | 2880 | 2280 | 1950 | 1950 |
| Isotopic content in fuel, % | 34 | 25 | 14 | 11 | 82 | 6.6 | 87 | 83 | 75 | 70 | 34 | 86 |
| Permissible concentration of isotope in air, μc/cc | $1 \times 10^{-10}$ | $3 \times 10^{-12}$ | $1.5 \times 10^{-10}$ | $7 \times 10^{-11}$ | $7 \times 10^{-10}$ | $3 \times 10^{-10}$ | $2 \times 10^{-12}$ | $7 \times 10^{-14}$ | $3 \times 10^{-13}$ | $2 \times 10^{-14}$ | $1 \times 10^{-12}$ | $9 \times 10^{-14}$ |
| Shielding thickness for a 1000-w(th) source | | | | | | | | | | | | |
| To give a gamma dose of $1.6 \times 10^{-2}$ mrad/hr at 1 meter, cm of uranium | | 14.5 | 8 | | 5.2 | 1 | | 22 | 24 | 3 | | 11.5 |
| To give a neutron dose of $10^{-2}$ mrad/hr at 1 meter | | | | | | | | | | | | |
| $H_2O$, g/cm$^2$ | | | | | | | | 62 | 62 | 55 | | 90 |
| LiH, g/cm$^2$ | | | | | | | | 40 | 40 | 35 | | 58 |
| Initial cost, $/w(th) | | | | | | | | | | | | |
| 1965 | 33 | 112 | 104 | 126 | 4900 | | | | | | | |
| Future | 10 | 19 | 21 | 1 | 93 | 10 | 10 | 40 | 350 | 600 | 100 | 360 |
| Isotope inventory value for 1 w(th) after 1 year, based on future costs, $/w(th) | 11.4 | 19.5 | 21.6 | 2.4 | 121.1 | 72.5 | 61.7 | 57.6 | 353 | 605 | 465 | 374 |
| Burnup (or decay) costs, mills/kwhr(th) | 160 | 56 | 56 | 160 | 3200 | 7100 | 5900 | 2000 | 370 | 550 | 42,000 | 1600 |
| $/10$^6$ Btu | 47 | 16 | 16 | 48 | 940 | 2100 | 1700 | 590 | 110 | 160 | 12,000 | 470 |
| Power availability, kw(th)/year | | | | | | | | | | | | |
| 1965 | 100 | 12 | 5 | 8 | 0.4 | | | | | | | |
| 1970 | 150 | 90 | 48 | 800 | 10 | | | | | | | |
| 1980 | | 650 | 620 | 4200 | 56 | | | | | | | |

Table 6. Inventory and Decay Costs of Radioisotopes

| Isotope | Inventory Value ($/kw) | Fuel Lease Charge (mills/kwhr) | Decay Costs (mills/kwhr) |
|---|---|---|---|
| $^{60}Co$ | 76,000 | 515 | 1340 |
| $^{90}Sr$ | 130,000 | 880 | 460 |
| $^{133}Cs$ | 144,000 | 975 | 460 |
| $^{144}Ce$ | 16,000 | 110 | 1340 |

Electric Batteries

The use of batteries as a primary source is limited to either low-power or short-duration applications. A summary of the properties of several types of battery is given in Table 7, along with cost data for the lead-acid and silver-zinc types. (Data for Table 7 were taken from Refs. 6 and 9 through 15.) Lead-acid batteries are the least expensive, while the silver-zinc units have the highest energy density of the batteries in use today. The economics of using batteries depend on the duration of the mission. The time requirement affects the cost in two ways: it has a direct effect on the capital investment, volume and weight of the batteries, and it may reduce the overall total energy output of the batteries. The life of a battery may be limited by either the number of recharges or by the time in use. If the applications are for extended time periods, the life of a battery may be determined by its time in use rather than by recharges, and the total power output of the battery over its life will be decreased.

Table 8 summarizes the size, weight, and some costs of lead-acid and silver-zinc batteries for an application requiring 30 kw for 30 days. These data do not include the costs for operation and maintenance or the power for recharging the batteries. For some undersea applications these costs may run $10/kwhr or more. It is apparent that the potential of battery systems in this range is severely limited.

Table 7. Battery Properties and Costs (From Refs. 6 and 9 through 15)

| | Lead-Acid | Nickel-Iron | Nickel-Cadmium | Silver-Zinc | Silver-Cadmium | Zinc-Air |
|---|---|---|---|---|---|---|
| Energy density | | | | | | |
| Theoretical, whr/lb | 115 | 215 | 99 | 220 | 134 | 400 |
| Actual, whr/lb | 12 | 12 | 16 | 50 | 30 | 50 |
| whr/in.$^3$ | 0.9 | 0.8 | 1.6 | 3.0 | 2.0 | 2.5 |
| ft$^3$/kwhr | 0.65 | 0.72 | 0.36 | 0.20 | 0.29 | 0.23 |
| lb/kwhr | 83 | 83 | 63 | 20 | 33 | 20 |
| Cycle life, number of cycles | 500–2000 | | 1800 | 100–150 | 1500 | |
| Initial cost, $/kwhr | 65 | | | 240–460 | | |
| Salvage value, % of initial value | 7 | | | 15–33 | | |
| Total life, kwhr/lb | 15 | | 29 | 6 | 45 | |
| Total battery cost,[a] mills/kwhr | 50 | | | 1900[b] | | |

[a]Initial cost less salvage value divided by total life in kwhr.

[b]Silver-zinc battery cost based on $300/kwhr capacity and 25% salvage value.

Table 8. Weight, Size, and Cost for Lead-Acid and Silver-Zinc Batteries

| | Lead-Acid Batteries | Silver-Zinc Batteries |
|---|---|---|
| Weight, lb | 1,800,000 | 430,000 |
| Volume, $ft^3$ | 14,000 | 4,300 |
| Initial cost, $ | 1,400,000 | 7,000,000 |
| Battery depreciation,[a] mills/kwhr | 600 | 2,400 |

[a]Based on 100 recharges.

## Fuel Cells

The cost of power from fuel cells cannot be predicted with any reliability at the present time. The cost of producing the cells in quantity and their expected life and maintenance costs under various operating conditions are not known. The energy density now achievable from hydrogen-oxygen cells is in the range 0.5 to 1.0 kwhr/lb, excluding the weight of the tanks. For an application requiring 30 kw for 30 days, the total energy required is 21,600 kwhr, and the fuel cell and reactant weight would be 21,600 to 43,200 lb (including the weight of the oxygen). The primary problems with the hydrogen-oxygen system lie in the storage and handling facilities. Also there are chemical hazards involved.

One study[12] comparing undersea power sources concludes that hydrazine-hydrogen peroxide fuel cells were less expensive than either hydrogen-oxygen cells or a radioisotope Brayton cycle for applications requiring 60 kw peak power and 30 kw average for 45 days. The cost of reactants was not given in the paper, but Szego[16] gives the present cost of hydrazine as $1.35 per pound, which would make the cost of hydrazine 566 mills/kwhr for a fuel cell with an efficiency of 100%.

For applications in which air is available, the hydrocarbon fuel cells have the potential of becoming a competitive system for low power output plants. This type of fuel cell is still in the laboratory stage of development, and the economics of the system are more speculative than for the hydrogen-oxygen cells.

## Economic Comparison of Nuclear and Conventional Power Sources

Evaluating the relative merits of reactors and conventional power sources for permanent or semipermanent land-based use is more straightforward than evaluating reactors for undersea use. For use on land in remote areas the principal competing power source will be a diesel-generator unit. The design lives of the two systems are about the same. For reactor systems of a few to several hundred kilowatts, the fuel cost will be about 10 to 30 mills/kwhr; this compares favorably with the cost of diesel fuel in many remote locations. The principal difficulty with reactor plants built in the past has been the high capital and operating cost. The capital charges for the reactor plants are likely to be higher than for diesel-generator sets, and hence the operating cost for reactor systems must be less than for diesel-generator sets, which implies that they must be able to operate unattended or with intermittent attendance and with little or no maintenance. This in turn requires a highly reliable, and therefore simple, system that has inherently good characteristics from the safety standpoint. The approach being taken to couple these requirements to a relatively low-cost system is to evolve a simple, compact system with a minimum of auxiliaries.

It is interesting to note that the economic necessities of land-based plants lead to a set of requirements similar to the high-reliability and compactness requirements of undersea plants. The reactor systems confront much less severe competition from the cost standpoint in the undersea applications of long duration where the logistics problems may be even more severe than for remote land bases. The competing systems for such applications are fuel cells and isotope heat sources and either will require development efforts and expenditures roughly equal to those required to develop a reactor system. The power cost for the fuel cell and isotope systems is difficult to estimate but will probably be at least 1000 to 2000 mills/kwhr, depending on the isotope lease charges, plant life, and the method of calculating capital costs. Thus, since reactor fuel costs are relatively low, the capital cost of a reactor system could be as high as 1000 mills/kwhr and still be competitive with the costs of fuel cells or isotopic sources for this application.

The capital cost of a plant that has annual capital charges equivalent to 1000 mills/kwhr will depend on plant life, plant use factor, and the rate of return on capital investment. The effects of these items are shown in Table 9, which lists the amounts that can be invested in a plant for different values for plant life and return on capital. The zero rate of return means that only the amount invested is returned. The amount that can be invested in a plant is directly proportional to the plant factor; that is for a plant factor of 0.5, the cost must be 0.5 of that shown in the table. It should be noted that the low plant factor will also penalize the other systems, especially the isotope systems, whose decay costs are independent of usage.

Based on the economic considerations discussed above, the present design work is being concentrated on water-cooled reactor systems that will be capable of unattended operation. Unattended operation, as used here, means that continuous supervision of the system is not necessary. For many applications periodic checks and minor system adjustments may be feasible, and the system may be restarted, after an unscheduled shutdown, by personnel at the site. However, any major difficulties would require special crews not normally stationed at the reactor site. Depending on the type of application and the operating environment, the special crew would fly to the site, or the unit would be removed to a special repair area.

Table 9. Capital Cost of a Plant to Yield Capital Charge of 1000 mills/kwhr for a Plant Factor of 1.0

| Rate of Return on Capital Investment (%) | Capital Cost [$/kw(e)] | | | |
|---|---|---|---|---|
| | Plant Life (years) | | | |
| | 2 1/2 | 5 | 10 | 20 |
| 0 | 21,000 | 43,800 | 87,000 | 175,000 |
| 4 | 20,450 | 39,000 | 71,050 | 119,050 |
| 8 | 19,150 | 34,970 | 58,790 | 85,970 |
| 12 | 18,000 | 31,580 | 49,490 | 65,420 |
| 16 | 16,960 | 28,680 | 42,340 | 51,930 |

To obtain the degree of reliability required for such systems the controls must be simple and the number of auxiliaries, especially those requiring control action, must be minimized. In order to eliminate the problems of water makeup, air inleakage, and shaft seals, the systems will be hermetically sealed. The bearings will be water lubricated and the generator will operate in a steam atmosphere.

For steam turbines operating in the range 30 to 2000 kw(e) with steam pressures of 400 to 650 psi, the small volumetric steam flow rate leads to partial admission, a low blade height, and relatively large leakage losses. To reduce these losses it is necessary to minimize the rotor diameter which, when coupled with the high rotor-tip speed requirements, leads to high rotational speeds. The speed range that appears attractive is from 12,000 to 24,000 rpm.

To eliminate the gear box, the generator will be directly coupled to the turbine. This requires a relatively high frequency; 400 cps appears to be attractive. The choice of 400 cps narrows the possible turbine speeds to 12,000 to 24,000 rpm, the speeds given by four-pole and two-pole generators, respectively. Selecting 400 cps will reduce the size, cost, and weight of the generator, as well as the size and weight of the motors and transformers in the electrical system. Some notion as to the extent of the size and weight savings is given by Fig. 1, which shows two 1/4-hp motors — one for 60 cps and one for 400 cps. In general, the weight of a motor, generator, or transformer is reduced by a factor of about six in going from 60 cps to 4000 cps. A wide variety of electrical equipment, including motors and transformers, is available for 400-cps operation as a consequence of Air Force development work, and high reliability can be assured by choosing equipment that has seen extensive, successful operating experience.

Table 10 gives some estimated costs for three plant sizes obtainable with simple, compact systems with water available for cooling. It was assumed in developing the data of Table 10 that the system has been developed and tested and that there is sufficient demand so that the production rate is at least ten per year. The capital costs for the 100-, 500-, and 1000-kw(e) plants are assumed to be $400,000, $650,000, and $1,000,000, respectively. The operating crew cost is assumed to be the

23

73%

Table 10. Nuclear Power Cost

| | | | | | |
|---|---|---|---|---|---|
| Power output, kw(e) | 100 | 100 | 100 | 500 | 1500 |
| Plant life, years | 1 | 5 | 20 | 20 | 20 |
| Plant factor | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |
| Plant cost, $ | 400,000 | 400,000 | 400,000 | 650,000 | 1,000,000 |
| Unit costs, mills/kwhr | | | | | |
| Fuel costs | 20 | 20 | 20 | 15 | 10 |
| Capital costs[a] | 570 | 115 | 30 | 10 | 5 |
| Operating crew costs[b] | 70 | 70 | 70 | 15 | 5 |
| Maintenance costs[c] | | 55 | 55 | 20 | 10 |
| Total cost | 660 | 260 | 175 | 60 | 30 |

[a]Capital cost without return on capital.

[b]Based on two man years at $25,000 per man year.

[c]Yearly maintenance cost assumed equal to 10% of initial plant cost.

equivalent of two man years at $25,000 per man year, and the yearly maintenance cost is assumed to be equal to 10% of the initial capital investment.

## Selection of Primary Objectives for the TLPR Program

Tables 1, 3, 6, and 8 provide a basis for appraising the market for TLPR plants and show that costs provide a prime basis for selection of a power source. The Army reactor plants that have been built to date have cost from $3000 to $7000 per kilowatt, that is, from 20 to 50 times the cost of diesel-generator units that would deliver the same output. On the other hand, the cost of lead-acid batteries to supply power for 60-day-duration undersea operations is about $500,000 per year per kilowatt of average power consumption, or about one hundred times the capital cost per kilowatt for an Army reactor plant. The cost of silver-zinc batteries runs about twice as much. Because of the high cost and great weight of batteries, the size of these power sources has been kept small.

An important element in the cost of special equipment, such as that for nuclear plants, is the number of units to be produced per year. All the Army package reactor plants that have been built to date have been one-of-a-kind, with large charges for engineering and tooling. It seems likely that to make a nuclear plant economically attractive, it will be necessary to find a power plant that will have a sufficiently wide range of applications so that at least ten units per year can be built and the engineering and tooling costs per unit thus kept to reasonable values.

Cooling water, if available, makes it possible to employ a much lighter, more compact, and less expensive form of heat dump than would be required if it were necessary to dump the heat to air. If the available water flow is not sufficient to carry off the heat load with an acceptable temperature rise of 10 to 20°F, but sufficient water ia available to supply a cooling tower, a substantial reduction both in the cost of the installation and of the weight and volume of equipment that must be shipped with the power plant can be effected.

The implications of the above seem clear — it appears best to design a power plant to satisfy Navy and oceanographic requirements for which the principal competition is batteries which are so expensive that a high-cost plant can be justified. Further, if such a power plant were once developed to the point that its costs were competitive, it could be used for most Army and Air Force installations because they normally have adequate quantities of cooling water available. The special requirements of desert installations could be met by adding special equipment if the cost could be justified.

A major element in the operating cost of any power plant is the cost of training and maintaining the crew. In the Army package power plant installations, crews of around 25 men in four shifts of 4 to 8 men each have been required 24 hours per day. The cost just for training and maintaining the crews of the Army reactor plants has been greater than the cost of providing fuel for diesel engines. Diesel-generator sets of comparable output have required much smaller crews, of the order of a half-dozen men. In recent years, small gas-turbine-driven electrical generators have been developed to have a high reliability, and these ordinarily require only an occasional check one to three times a day to make sure

that everything is running properly and that an adequate fuel supply is available. They, of course, have a rather high specific fuel consumption, so they can compete with diesel generators only in some applications. However, it has proved possible to operate them without a crew continuously on duty with a mean time to a forced outage of 2000 hr. This is encouraging in that it indicates that it is feasible to achieve a high reliability with a nearly unattended power plant. It also suggests that a prime objective of the TLPR program should be an unattended plant, particularly in view of Navy and oceanographic requirements.

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