Costs of Designs Chosen for Analysis

LOW-TEMPERATURE DESIGNS

The design chosen for hot water storage is a tank which is buried in the ground, surrounded by a layer of polyurethane insulation (where necessary) and a vapor barrier which protects the insulation from ground moisture. (See figure xi-2). If the collector uses a fluid other than water, a heat exchanger is also required. Heat exchangers would also be required if the storage were pressurized while the other parts of the system were not under pressure. The primary costs are divided into three categories: the tank itself, the excavation and backfill, and the insulation. Costs presented here exclude the contractor's overhead and profit (25 percent), which is added later.

Excavation, Backfill, and Soil Compaction.

Figure XI-5 shows as a solid line the excavation, backfill, and compaction cost per cubic meter of tank volume as a function of tank volume. Costs were derived from Means[8] using the following assumptions:

Excavated volume is 1.3 times the tank volume to allow for clearance, insulation, etc. Backfill volume is 0.3 times tank volume. Because there is a mobilization and demobilization charge for heavy equipment, small jobs can be done less expensively by hand labor. For tanks greater than 3.35 m^3 excavation is done with a track-mounted, 3½-cubic-yard, front-end loader. Backfill is done by bulldozer for tanks greater than 28 m^3, Soil compaction in all cases is done in 12-inch layers with vibratory plate compactors.

Hot Water or Oil Tanks

Figure XI-5 also plots installed tank costs, excluding excavation and insulation, for a variety of types of tanks suitable for storing heated or chilled water or other fluids. These prices exclude pumps and piping, It can be seen that for the range O to 1,000 m^3 it is possible to have a tank installed, including excavation and backfill, for $80/$m^3$ or less. The baseline design assumes $80/$m^3$ for this size range. The assumed cost is plotted as the dashed line in the figure.

Insulation

Insulation costs depend strongly on the temperature of the storage and the length of time needed for storage, The insulation chosen for analysis is polyurethane. This material can be foamed on in place for approximately $0,24/board foot ($101.71/m^3).[9] (A thin polyethylene vapor barrier adds negligible cost.) This cost might be reduced if a plant dedicated to producing storage equipment manufactured preinsulated tanks. The conductivity of urethane protected by a good vapor barrier is approximately 0.13 Btu inch/hr ft^2 °F.

Analysis

Two cases are considered: 1) a case which applies to storage for use with systems designed to supply domestic heating and hot water (thermal energy supplied between 2000 and 1200 F and returned at 900 F); and 2) systems designed to supply absorption air-conditioners and other industrial process-heat loads (thermal energy supplied between 2700 and 2200 F and returned at 2000 F). Case I requires a storage volume of 0.02013 m^3/kWh_t if mixing is assumed, or 0.0146 m^3/kWh_t if there is no mixing in a single tank. The cost of insulation in these

[8] *Building Construction Cost Data 1976,* Robert Snow Means Company, Inc , R S Godfrey, ed , pp *18, 22, 258*

[9] John L Renshaw of John L Renshaw, Inc (an insulating firm in the metropolitan Washington, D C area), private communication, August 1976.

cases is \$101.71 V_i, where V_i is the volume of insulation in m^3.

$$\text{Case I: } C_i = (1.35\Theta E^{1/3} - 3.917E)\$$$

$$\text{Case II: } C_i = (5.29\Theta E^{1/3} - 6.268E)\$$$

where E is the storage capacity in kWh_{th} and Θ is the desired storage time in hours. Note that if the above equations yield a negative result, the earth alone provides sufficient insulation and $C_i = 0$.

The installed cost of buried tanks is assumed to be $\$80V_s$ for tanks less than 1,000m3. For tanks with volumes greater than 1,000m 3 an appropriate cost per cubic meter was taken from figure XI-22.

$$\text{Case 1: } C_t = \$80 \times 0.02013E$$

$$\text{Case II: } C_t = \$80 \times 0.03221E$$

(Systems larger than 1,000m3 would substitute an appropriate tank cost for \$80 in the last equation.)

HIGH-TEMPERATURE DESIGNS

Since very few of the concepts which have been suggested for high-temperature thermal storage have ever been fabricated as complete systems, it is difficult to estimate what they would cost if they were produced commercially. An attempt has been made to select for the analysis systems which are as simple as possible, both because such systems show the greatest promise of reaching the market in the next decade and it is much easier to estimate the potential cost of these systems. The analysis is fairly conservative, and may be used to provide an upper limit for future high-temperature thermal storage costs.

in cases where the materials require factory work done off site, the bare materials cost is multiplied by 1.6 to account for overhead, wages, and profit in the factory. This number is obtained from the Department of Commerce input-output tables for "Sector 40: Heating, Plumbing, and Structural Metal Products."[10] Cost of onsite assembly and installation (excluding the contractor's overhead and profit, which is added later) is assumed to be 32 percent of the cost of the components from the factory. This comes from the Department of Commerce tables for "Sectors 11, 12: All New Construction.'" Thus, in cases where better estimates of assembly and installation were not available, bare materials costs have been increased by 211 percent for materials which require additional factory work, or 32 percent for systems which do not.

Oil Storage for Residential Organic Rankine Devices

The highest temperatures used in the baseline-design organic Rankine engines for the single family house are 4200 F (216 °C). For storage at this temperature, a sensible-heat storage system using fuel oil has been chosen. The oil is liquid at all temperatures of interest and thus can be used as a heat-transport system for conveying heat from the collector to the tank as well as serving as the storage medium. Heat exchangers are only needed to transfer heat to the heat engines used to generate electricity, The storage system operates at atmospheric pressure. Since heat engines operating at the small temperature differences available for the single family system are already operating at relatively low efficiencies, the system is not able to tolerate a large drop of temperature at the input of the heat engine, For this reason, separate tanks are used for hot fluids emerging from collectors and cold liquids returned from the thermal loads to ensure a constant high temperature to the inlet. The assumptions and resulting costs are summarized in table XI-9 Costs are computed as shown in table XI-C-1.

---

[10] "Input-Output Structure of the U S Economy 1963, " Survey *of Current Business.* U S Department of Commerce, National Economics Division, November 1967, pp 16-47

[11] Ibid

Table XI-C-1 .—Assumptions for Hot Fuel Oil Thermal Storage, Single Family House [420" F organic engine]

Two-tank system
No heat exchanger to collectors
Heat engine temperatures (organic Rankine) = 420° to 90" F (216° to 32°C)
[a]Heat exchanger temperature drop to heat engine: 10°c (18" F)
Storage temperature swing: 439° to 108° F (226° to 42 "C)
Heat capacity of storage medium (refined fuel oil) = 0.795 $kWh_{th}/m^{3\circ}C$
[b]Thermal conductivity of insulation (foam glass): k = 0.5 Btu in/ ft2hr° F
Ground temperature = 55° F (13" C)
Credit for earth's insulation: equivalent to insulation thickness of (0.0833)R
[a]Heat exchanger constant = 4.5 $kW/m^{2\circ}C$
Temperature efficiency: $\eta_T = 1.0$
clns.tailed cost of insulation" (foam glass) = $1 14/m3 Of insulation = $3.24/ft³
Installed cost of buried tanks and excavation = $160/ m^3 of oil
Installed cost of storage medium (refined fuel oil) = $146/m³
[a]Installed cost of heat exchanger to heat engine = $80/ m^2 of heat exchanger
Insulation cost = $(6.428\ \theta E^{1/3} - 0.32595\ E)\$$ or zero
Tanks, excavation, oil = 2.092E$
Heat exchangers = 1.78P$

NOTE Costs exclude contractor's overhead and profit (25%), which is added later. "E" is storage capacity in kWh_{th}. "θ" is storage Interval in hours. "R" is storage tank radius "P" is discharge rate in kW_{th}

[a]R W Hallet and R L Gervais, *Central Receiver Solar Thermal Power System, Phase 1, Final Report*, MDC G6040, McDonnell. Douglas Astronautics Company, January 1976
[b]See figure XI-B-1
[c]*Means Building Cons truction Cost Data, 1976*, P. 111

Table XI-C-2.—Assumptions for Therminol-55/ Rock Thermal Storage [600 "F heat engine]

Two-tank system: no heat exchanger to collectors; 70% rocks by Volume
Heat engine temperatures: 600° to 100" F (316° to 38° C)
[a]Heat exchanger temperature drop to heat engine: 10" C (18° F)
Storage temperature swing: 618° to 118°F (326° to 48°C)
Heat capacity of Therminol-55: 31 Btu/ft3° F (0.577 kWh/m3° C)
Heat capacity of rocks: 27.3 Btu/ft3° F (0.509 kWh/m3° C)
System heat capacity: 28.4 Btu/ft3° F (0.529 kWh/m3 "c)
[b]Thermal conductivity of insulation (foam glass): k = 0.6 Btu in/hr $ft^{2\circ}$ F
[a]Heat exchanger constant = 4.5 $kW/m^{2\circ}$ C
Temperature efficiency: $\eta_T = 1$
Ground temperature: 55° F (13° C)
Credit for earth insulation: equivalent to insulation thickness of (0.1)R
[c]Installed cost of insulation (foam glass) = $114/m³ of insulation = $3.24/ft³
[a]Installed cost of heat exchangers to heat engine = $80/m² of heat exch.
Installed cost of rocks = $0.01/lb x 140 lb/ft³ x 70% = $0.98/ft3 storage = $34.61/m3
Installed cost of Therminol-55 = ($.38matl + $.05 shipping)/lb x 43 lb/ft3 x 30% = $5.55/ft3 = $195.89/m³ storage
Installed cost of buried tanks and excavation = $160/ m3 of storage:
Insulation cost = $(9.84\ \theta E^{1/3} - 0.389E)\$$ or zero
Tanks, excavation, Therminol, rock = 2,655E$
Heat exchangers = 1.78P$

NOTE: Costs exclude contractor's overhead and profit (250/.), which is added later. "E" is storage capacity in kWh_{th}. "8" is storage interval in hours "R" is storage tank radius. "P" is discharge rate in kW_{th}

[a]Hallet and Gervais, MDC G6040.
[b]See figure XI- B-1
[c]*Means. 1976*, p. 111

Therminol-55/Rock Storage

The Therminol-55/rock-storage system is similar to the hot fuel oil system just examined. Two tanks are used to maintain a high discharge temperature and thus a high "temperature efficiency" (for heat engines). The rocks are assumed to occupy 70 percent of the storage volume. The assumptions and resulting costs are summarized in table XI-C-2.

Storage in Steel Ingots

The steel-ingot system can eliminate the need for heat exchangers, but this requires the use of 150 psia steam in the collector system. This is assumed to be acceptable since the heat engine will operate at this pressure, and thus an operator familiar with the engine should be able to supervise the steam transport system. The ingots could be integrated into the structure of the building or buried in the earth. Earth burial is assumed for the following calculations, although individual installations may present other opportunities. Excavation and backfill costs are taken from figure XI-5. The Jet Propulsion Laboratory (JPL) has calculated that a system operating between 9500 and 1000 F (510 °and 38 "C) can be discharged by about 68 percent of its total sensible-thermal capacity before the output steam starts to fall below 950° F.[12] The analysis therefore reduces the thermal capacity of the steel accordingly and assumes that al I of the discharge steam is at 9500 F. The following cost assumptions were also taken from the JPL study: steel ingots at $.15/lb; welded headers at $50/hole ($25 each end); rail transportation of materials at $.01/lb; miscellaneous (flow valves, controls, sensors, weatherproofing, etc.) at $.0067/lb of ingots. It also is assumed that the ingots are piled in a stack whose shape is close enough to a cylinder (with length = 4R) that the insulation calculations can be done using equations already developed for cylindrical tanks. The assumptions used are shown in table XI-C-2.

High-Temperature Phase Change Storage

Several designs for storing thermal energy in the heat of fusion of sodium hydroxide have been examined, and operating units of at least two different approaches have been constructed.[3] These units use electricity to charge the storage to about 9000 F. Total system cost for these devices is estimated to be between $1 .35/MBtu and $1.50/MBtu ($4.61-512/kWh th). Examining figure *XI-19,* it can be seen that the available energy for use at 9000 F is approximately twice the available energy for the temperature swing between 6200 and 4200 F which is required for the heat engine. The price appropriate for the on site application would thus be approximately $3/MBtu ($10.24/kWht) JPL has designed a sodium hydroxide storage system for use with a solar system which operates between 6500 and 4000 F for a cost of approximately $3.7/MBtu ($12.63/kWhJ.

The system which will operate with the Stirling cycle will have a very similar design. The costs of the two systems are estimated in parallel in the following discussion.

The heat of fusion storage system is assumed to be produced in factory-assembled modules. Each modular tank contains within it a bundle of sealed, long, narrow, cylinders full of the storage material. The cylinders occupy three-fourths of the tank volume, and heat-pipe fluid circulates in the space around the cylinders, as shown in figure IV-20. During charging, the heat-pipe fluid is heated directly in the solar collector, and during discharging, the heat-pipe fluid condenses at the heat engine, eliminating the expense of separate heat exchangers. Each cylinder is assumed to be 4 feet long and 3 inches in diameter. There are 60 cylinders per tank, and the tanks are 59 inches long and 27 inches in diameter. The cylinder walls are 0.040 inches thick. This is thick enough to contain the weight of the storage material if adequate room is provided for expansion during phase changes. The volume of containment material per cylinder is thus 302 cm^3, and each cylinder can contain 5,260 cm^3 of storage material. The characteristics of potential container materials are shown in table XI-C-3.

The cylinders are assumed to be made of stainless steel. Although stainless steel is not completely resistant to corrosion by pure fluorides, N. V. Philips reports that by adding a small amount of aluminum to the melt, all corrosion is eliminated. Corrosion testing was done for more than 14,000 hours at 850 "C with ordinary 18/8 stainless steel.[5]

Each tank is a double-wall pressure vessel, insulated by a vacuum and multifoil super-

[12] R H Turner (J PL), "Thermal Energy Storage Using Large Hollow Steel Ingots, " *Sharing the Sun: Solar Technology in the Seventies.* J oint Conference, American Section, International Solar Energy Society and Solar Energy Society of Canada, Inc , Winnipeg, Canada, Aug 15-20, 1976, Vol 8, pp 155-162

[1] 'R E Rice, *Thermal Storage for Application to Energy Conservation,* Comstock and Wescott, Inc , April 1975, Cited in Bramlette, et al , (Sandia Laboratories, Livermore) SAN D75-8063

[14] J Schroder (N V Philips Aachen Lab), "Thermal Energy Storage and Control, " *Journal of Engineering for Industry,* August 1975, pp 893-896

[15] J Schroder (N V Philips Aachen Lab), private communication, Jan 13, 1977

Table XI-C-3.—Assumptions for Steel-Ingot Thermal Energy Storage

Steam Rankine engine: no heat exchangers
Heat engine temperatures: 950° to 10O"F (510° to 38°C)
Storage temperature swing: 950° to 100" F (510° to 38°C)
Storage temperature swing: 950" F to 100" F (510°C to 38" C)
Storage medium: cast steel ingots, 60 ft long, 1 ft wide, 1 ft high; 9 axial holes, 2 in diameter per ingot
Headers: 2 in diameter, low-alloy, seamless pipe Schedule 50, formed into thermal stress expansion loop and welded to ingot holes
Steel heat capacity = 58 Btu/ft3° F
System heat capacity (20% holes; 32% unrecoverable) = 0.608 kWhth/m3° C
[a]Thermal conductivity of insulation (foam glass): k = 0.8 Btu in/hr ft2°F
Ground temperature = 55°F (13°C)
Credit for earth insulation: equivalent to insulation thickness of (0.13)R
Discharge temperature: constant 950°F during entire discharge (68% of thermal capacity used)
Temperature efficiency: η_T = 1 (68% of thermal capacity used)
[b]Installed cost of insulation (foam glass) = $114/m3 of insulation = $3.24/ft3
Header cost: $50 per hold, including welding = $265/m3 of ingots
Installed cost of ingots ($.15/lb + $.01 shipping) = $62/ft3 = $2,188/m3
Cost of excavation and backfill = $120 + $1.24/m3 of ingots
Miscellaneous (see text) = $115/m3 = $3.24/ft3:
Insulation cost = (4.03 θE$^{1/3}$-0.130E)$ or zero
Ingots, excavation, and miscellaneous = 8.95 E$ + 120$

[a]See figure XI- B-1
[b]*Means, 1976,* p 111.

NOTE Costs exclude contractor's overhead and profit (25%), which is added later. "E" is storage capacity in kWh th. "θ" is storage interval in hours. "R" is radius of the pile If it is possible to use concrete or some other inexpensive material instead of steel, the cost could be reduced by a factor of three or more

insulation. This type of insulation has a thermal conductivity of 0.0049 Btu in/hr ft^2°F.[16] The cost of the metallic foil insulation is estimated at $2.00/ft^2 of surface area, and the resultant thermal conductivity is so low that even seasonal storage results in "very small heat losses.'"[7] The tank walls are assumed to be ¼-inch stainless steel, fabricated at $2.00/lb.[8] The two heat pipes are assumed to add $200 each to the cost of each tank.[9]

The installed cost of the cylinders is estimated using the materials costs in tables XI-4 and XI-C-4, adding $().1()/kg for shipping, and multiplying by the factor of 2.11 to account for factory and onsite fabrication and installation. The cost assumptions are summarized in tables XI-C-5 through XI-C-7.

BATTERY STORAGE COSTS

The costs of battery storage used in the analysis conducted in this study are summarized in figure *XI-28* and table XI-11. There appears to be a reasonable concensus that costs as low as $55/kWh are feasible in the "intermediate term, " but a considerable amount of disagreement about how far prices will fall in the long term. The Bechtel summary of battery costs estimated that advanced batteries could be produced for *$10* to $25/kWh[20] while other sources have estimated that prices below !$25/kWh are unlikely .21 22 The "long-term" cost $11/kWh shown in the table reflects an assumption that a low-cost iron-REDOX system has been developed.

Neither estimate of O&M cost given in table XI-8 would add appreciably to the overall costs of battery storage. Even if O&M costs for advanced batteries are a factor of 2 higher, the O&M costs would still be minor. Consequently, 0.0284/kWh has been used for all three cases in table XI-11.

"N. E. Polster and W R. Martini (University of Washington), *Self-Starting, Intrinsically Control/cd Stirling Engine, 11th* I EC EC.

"R L. Pens and R. J. Fox (Aeronautronic Ford Corp. and Walt Disney Productions), *A Solar/Stirling Total Energy System,* unpublished, 1976.

[18]Ibid,

"Ibid

[20]*An* Engineering *Study of a 20 M W, .200 MWh Lead-Acid Battery Energy Storage Demonstration P/ant,* Bechtel Corporation, ANL Contract No. 31-109-38-2692, October 1975.

*'James Birk (E PRI), private communication, Jan. *20,1977.*

[22]*An Assessment of Energy Storage Systems Suitable for Use by* Electric Utilities, *Final Report* by PSEG on ERDA Contract No. E (11-1 }2501, Vol. II, July 1976, pp. 4-60.

Table XI-C-4.—Containment Materials

Material	Density (kg/m 3)	Yield strength • (N/m2)	cost ($/kg)
8515-70 carbon steel. . . .	7.8 x 10^3	3.1 x 10^8	.22
304 stainless steel[ab] . . .	7.9 x 103	2.4 x 10^8	1.76
Steelite-21 [abcde]	8.3 x 103	5.7 x 108	40.00
Inconel [ce].	7.8 x 103	2.7 x 108	**11.00**
Hastelloys[abcde]	9.0 x 103	3.8 X 108	26.00

• Room temperature values
[a]Oxidation resistant
[b]High-temperature al loy
[c]Resistant to chemical attack
dReslstant to most fluorides
[e]Resistant to fluorides if Al ıs added to the fluoride

SOURCES T T Bramlette (Sandia Laboratories, Livermore), compiled for OTA, 1976. Note e added by J Schroder (N. V. Philips Aachen Lab), private communı - cation, Jan 13, 1977

The salvage value (or reduced replacement cost) for near-term batteries is principally the value of the lead in the battery. The replacement price for intermediate-term batteries is based on a crude average of the fractional replacement prices projected in table XI-8. Most of the advanced batteries use inexpensive materials which would have negligible salvage value. Consequently, no salvage value is assumed. If one of the batteries containing lithium were used, the replacement price would clearly be less than the inital price, since lithium can be effectively recycled.

Battery storage systems for utility applications are expected to use a large number of cells which have individual storage capacities of 5 to 40 kWh. [23] These are the systems for which virtually all of the available cost projections apply. It is expected that smaller systems will require somewhat smaller cells to obtain reasonable system voltages Detailed studies of the relative cost of such systems have not been completed. However, the direct product cost ($/kWh) for a 7 kWh mass-produced cell would probably be about 14 percent higher than a 50 kWh cell, and batteries in the 20 kWh size range may cost 20 to 25 percent more than batteries for large storage facilities. Detailed design studies now underway may change this estimate. 24

Table XI-C-5 .—Latent-Heat Storage Tank Assumptions

Volume of stainless steel in tank wall = 0.04477m3
Surface area of tank = 38.48ft2
Tank wall cost = (0.0447 m3)(7,900kg/m3)(2.2lb/kg) ($2/lb) = $1,560
Insulation cost = (38.48ft2)($2.00/ft2) = $77
Heat pipe cost = $400
60 cylinders per tank
Cylinder cost = (302cm3)(.0079kg/cm3)($1.86/kg) (2.1 1) = $9.36/cylinder
NaOH cost + (0.00526 m3)(1,784kg/m3)($0.65/kg) (2.11 = $12.87/cylinder
NaF/MgF2 at $0.50/lb = (0.00526m3)(2190kg/m3) ($1.20/kg)(2.11) = $29.17/ cylinder
NaF/MgF2 at $0.25/lb = (0.00526m3)(2190kg/m3) ($0.65/kg)(2.11) = $15.80/ cylinder
Volume of storage material per tank = 0.3156m3
Overall volume of tank = 0.60m3
Total installed tank, NaOH: $3,371 plus excavation and backfill
Total installed tank, $0.50 NaF/Mg F2: $4,349 plus excavation and backfill
Total installed tank, $0.25 NaF/Mg F2: $3,547 plus excavation and backfill

[23] James R Birk, *The Lead-A c/d Battery for Electric Utilities A Review and Analysis,* presented at the ERDA EPRI Lead-Acid Battery Workshop 11, Dec 9,1976

[24] Nick Maska lick (Westinghouse Corporation), private communication, Jan. 31, 1977

Table XI-C-6.—Assumptions for NaOH Latent-Heat Storage [600° F heat engine]

Heat pipe to collectors and to engine heat exchanger
Heat engine temperatures: 600°-400° F (316°- 204–C)
[a]Heat exchanger temperature drop, heat pipe to engine: 10°C (18°F)
Storage temperature swing: 618°-418° F (326°-214°C)
[b]Melting temperature: 320°C (608° F)
[b]Heat of fusion: 0.0442 kWh/kg
[b]Solid/solid phase change at 295°C (563° F)
[b]Heat of solid/solid phase change: 0.0442 kWh/kg
[b]Specific heat, liquid: 5.75×10^{-4} kWh/kg°C
[b]Specific heat, solid (295°-320°C): 5.97×10^{-4} kWh/kg °C
[b]Specific heat, solid (below 295°C(: 5.89×10^{-4} kWh/kg°C
"Temperature efficiency": $\eta_T = 0.92$
Credit for earth insulation: none
Heat capacity per tank: (0.3156m³) (1784kg/m³) (0.154kWh/kg) = 86.7kWh
Cost of excavation and backfill: (see figure IV-22)
E ≤ 484 kWh; cost = \$0.165/kWh
484 < E < 4,046 kWh; cost \$70 + \$0.0208/kWh
E ≥ 4,046 kWh; cost = \$120 + \$0.00858/kWh
[c]Cost of instruments & controls: \$1,000
Total storage cost:
E ≤ 484 kWh; cost = (1,000 + 39.05E)\$
484 < E 4,046 kWh; cost = (1,070 + 38.90E)\$
E ≥ 4,046 kWh; cost = (1,120 + 38.89E)\$

NOTE Costs exclude contractor's overhead and profit (250/.), which is added later. "E" is storage capacity in kWh_t Insulation is adequate for seasonal storage

[a]Hallet and Gervais, MDC G6040
[b]See table XI-7
[c]R L. Pens and R J Fox.

Table XI-C-7.–Assumptions for NaF/MgF2 Latent-Heat Storage [1 ,400°F heat engine]

Heat pipe to collectors and to engine heat exchanger
Heat engine gas temperature: 1,400°F (760°C)
[a]Heat exchanger temperature drop, heat pipe to engine: 18°F (10°C)
Storage temperature swing: 1,550°-1,418°F (843°-770°C)
[b]Melting temperature: 1,530°F (832°C)
[b]Heat of fusion: 0.174 kWh/kg
[b]Specific heat, liquid: 4.07×10^{-4} kWh/kg°C
[b]Specific heat, solid: 4.1×10^{-4} kWh/kg°C
"Temperature efficiency": $\eta_T = 1.0$
Credit for earth insulation: None
Heat capacity per tank: (0.3156m³)(2,190kg/m³) (0.2040kWh/kg) = 140.1 kWh
Cost of excavation and backfill: (see figure XI-5)
E ≤ 782 kWh; cost = \$0.102/kWh
782 < E < 6,538; cost = \$70 + \$0.0129/kWh
E ≥ 6,538; cost = \$120 + \$0.00531/kWh
Cost of instruments & controls: \$1,000
Total storage cost: (.50 NaF/mg F2 \$/kg)
E ≥ 782 kWh; cost = (1,000 + 31.14E)\$
782 < E < 6,538; cost = (1,070 + 31.05E)\$
E ≥ 6,538; cost = (1,120 + 31.05E)\$
Total storage cost: (.25NaF/F2 \$/kg)
E ≥ 782 kWh; cost = (1,000 + 25.42E)\$
782 < E < 6,538; cost = (1,070 + 25.33E)\$
E ≥ 6,538; cost = (1,120 + 25.32E)\$

[a]Hallet and Gervais, NDC G6040
[b]See table XI-7

For purposes of this study, we increase the large system prices by 10 percent for the commercial and multifamily residential systems, and 20 percent for home systems.

POWER-CONDITIONING COSTS

As noted earlier, the bulk of the cost of power-conditioning apparatus results from the cost of the inverter system. Estimates of the cost of voltage regulators vary from 1 to 6 percent of the cost of the inverter. The cost of the interface varies from about 10 to 20 percent of the inverter cost for systems in the kilowatt range to about 2 percent of inverter cost for systems in the megawatt range. Estimates of current and potential power-conditioning costs are shown in figure XI-28.

The prices chosen to represent "near-term," "intermediate," and "speculative" technologies are chosen somewhat arbitrarily to represent the spectrum of estimates shown. The "near-term" prices selected are somewhat lower than the average prices of contemporary power-conditioner devices since many of the units now available are overdesigned for solar application, and many of the small systems shown operate at voltages much lower than would be required for solar applications (low-voltage systems are usually more expensive than higher voltage devices with similar power capabilities).

In the intermediate term, it can be assumed that at the lower power levels, increased production volume will lower prices, although in many of today's systems, standard components such as inductors and capacitors represent a significant fraction of the cost, and this will limit the production economies possible. At higher power levels, systems will probably continue to be essentially custom-designed, but increased engineering experience should lower costs somewhat, as assumed for the intermediate case of figure XI-28.

in the longer term, it can be assumed that power-conditioner units in the smaller sizes can be made for substantially lower prices by mass-producing units designed with power transistors so that the use of components such as inductors is minimized. Westinghouse has estimated that such units could be produced for $50 to $70/kW.[25] At intermediate and higher power levels, market size and component size will probably prevent automated production, and the price may go up for some sizes as suggested by the curve sketched for the "long-term" case in figure XI-28

It should be noted that the prices discussed so far have been in terms of rated *capacities* which are related to the normal load of the system. Most systems can actually supply 1.5 to 3 times the rated capacity, depending on the specific characteristics of the power conditioner and the load.[26] In the integrated system cost runs, it has been assumed that power conditioners have a peak capacity 1.5 times their rated capacity.

BUILDING AND OTHER COSTS

In addition to the battery and power conditioner costs, there is a significant cost associated with installation, electrical wiring, and instrumentation, and the room in which the battery system will be housed. No detailed estimates of these costs were available for systems of the size considered in this study, It was assumed that the batteries would be located in the basement of homes or in the equipment rooms of apartments and shopping centers. Unfinished basement space in such buildings costs about $5.00 to $7.50 per square foot. "Building and Other Costs" were assumed to be twice the cost of the space and it was assumed that the batteries we arranged so there were 2 to 3 kWh per square foot of floor space for present lead-acid battery systems. It is assumed that "advanced battery systems" will have higher energy densities, and require less space. REDOX batteries do not have a high energy density but it should be easier to integrate the liquid storage tanks which make the system bulky into building space than it would be to find space for more complex systems requiring high temperatures or potentially hazardous materials It was therefore assumed that the building and other costs associated with the REDOX systems would be no greater than those of other batteries. It was assumed that the "building and other costs" and power conditioner costs scale with battery capacity in the same way (see table XI 1-11)

[25] F Pittman, Program Manager for Westinghouse Electric Corporation Research Laboratories, *Final Report on Conceptual Design and Systems Analysis of Photovoltaic Power Systems*, ERDA Contract No E (1 1-.2744), December 1976

[26] Peter Wood, Westinghouse, private communication, Jan. 18, 1977