Volcanism and Geothermal Resources

Alaska has more than 80 late Cenozoic volcanoes. Most of these have been active within the last million years (Miller and Barnes, in press) and more than 40 have erupted during historic time (Figure 8). Geothermal resources are closely associated with geologically-young volcanoes and volcanic fields, with particular emphasis on silicic volcanism (i.e., rhyolitic-dacitic domes and ejecta) and collapsed calderas.

Silicic Volcanism: The most promising Alaskan volcanic targets are located in the Aleutian-Alaska Peninsula segment of the circum-Pacific volcanic belt and in the Wrangell Mountains. Following the views of Smith and Shaw (1975) and others, silicic magmas are more likely to be stored and/or erupted from shallow (<10 km) chambers than basaltic (basic) melts, in the circum-Pacific volcanic belt. Conversely, however, basaltic melts are stored and erupted from shallow magma reservoirs under Kilauea Volcano, Hawaii, in the oceanic setting.

Following Smith and Shaw's rationale, geothermal targets are more likely to be associated with young silicic volcanic centers, where silicic magmas may still remain in the subsurface conduit and reservoir system. Such targets may range from hot dry rock to convective systems in suitable reservoir rocks. Possible subsurface targets would be signalled by very young (<10 million years) silicic domes and collapsed calderas with peripheral blankets of silicic pyroclastic rocks. The silicic ejecta domes and/or caldera association is known to occur at Katmai, Peulik, Aniakchak, Black Peak, Veniaminof, Emmons and Dana

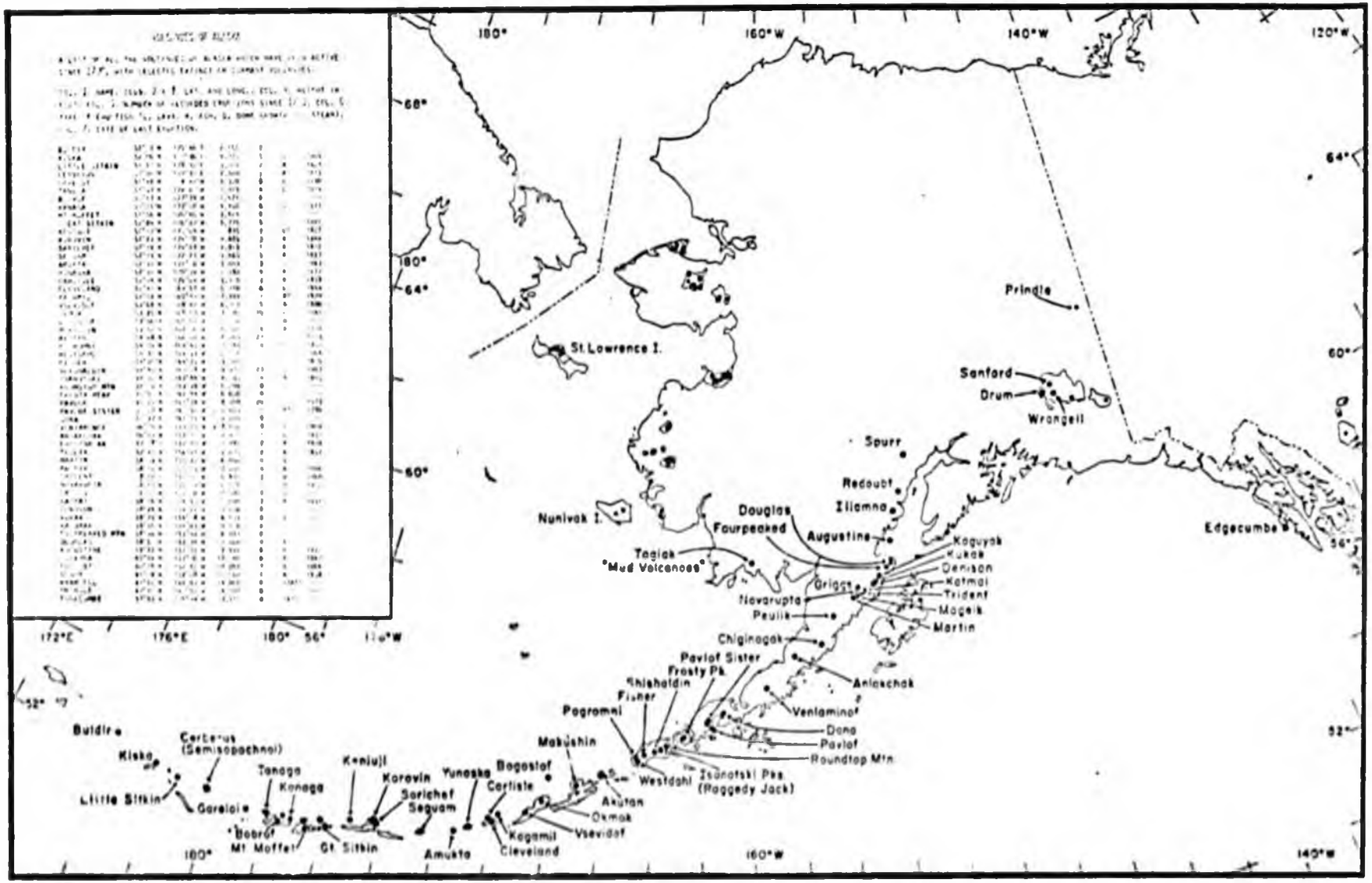

Figure 8: Location of the main volcanic centers in Alaska showing volcanoes active in the last 200 years and other important recent volcanoes of the Aleutians, recent volcanoes of southern and southeastern Alaska, and alkalic Tertiary and Quaternary volcanic centers of western and eastern Alaska. (Taken from Kienle, 1974)

Volcanoes on the Alaska Peninsula, Fisher Volcano on Unimak Island, and Mt. Drum in the Wrangell Mountains (recent reconnaissance work by Miller, Barnes and Smith [Miller and Barnes, in press]).

All the known late Cenozoic volcanoes of the Aleutian volcanic arc could be considered as potential geothermal target areas because they indicate anomalously high heat flow in geologically recent time. The maximum depth at which geothermal systems might be exploited is thought to be less than 10 km (Muffler and White, 1972; White, 1973). Geothermal target areas can therefore be reduced, as a first approximation, to those volcanoes that hav , or had, large magma chambers relatively close to the surface. A possible criterion for selection of such sites is the presence of a collapsed caldera, which in itself implies a magma chamber at relatively shallow depths for collapse to have occurred following magma withdrawal. Furthermore, Smith and Shaw (1973) have postulated that most large (10^2 - 10^5 km^3) magma chambers that have formed in the upper 10 km of the crust are either silicic or have silicic differentiates.

Powers (1958) listed 20 known calderas in the Aleutian volcanic ar . One of these, the Buldir depression in the western Aleutian Islands, has since been referred to as a volcanic-tectonic depression rather than a true caldera (Marlow and others, 1970). Recent work has shown that at least three more calderas on the Alaska Peninsula, including Black Peak, Peulik, and Emmons can now be added to the list of known calderas (Miller and Barnes, in press).

Because of the length and subsequent remoteness of the Aleutian Islands, the calderas on the aska Peninsula such as Peulik,

Aniakchak, Black Peak, Dana and Fisher and those on the easternmost islands, perhaps as far west as Okmok Caldera on Umnak Island, may be considered as having more immediate potential for commercial development. Calderas farther out on the Islands such as Great Sitkin or Kanaga may have some potential for use by military bases. Some of these calderas could be eliminated from consideration because of inaccessibility. The conjectured caldera at Davidof, for instance, is under water and the Veniaminof caldera is completely filled with ice and snow.

Basaltic Volcanic Fields: Late Cenozoic volcanic rocks underlie a total area of about 25,000 km^2 (9,600 mi^2) in interior Alaska, mostly in the western part of the region. These volcanic rocks are chiefly olivine tholeiite and alkalic basalt; no intermediate or silicic rocks of Pliocene or younger age have been reported in this part of Alaska. Potassium argon (K/Ar) age dates obtained on basalt from the western part of this province range from 6.12 $\pm$ 0.18 million years (m.y.) to 30,000 $\pm$ 20,000 years Before Present (B.P.) on Nunivak Island (Hoare and others, 1968) and from 2.19 $\pm$ 0.1 m.y. to 65,000 $\pm$ 100,000 years B.P. on the Pribilof Islands (Cox and others, 1966). Stratigraphic and morphological evidence, moreover, suggests that volcanic activity has continued almost to the present time; Hopkins (1963) states that the Lost Jim Lava Flow on the Seward Peninsula may be as young as a few hundred years.

The volcanic province, ranging in age from 6 m.y. to 30,000 years or younger, may still be volcanically active. No hot springs, fumaroles or other manifestations of current volcanic activity, however, occur within areas underlain by these basalts and the known thermal springs in interior Alaska show no spatial association with them.

Volcanism in Southeastern Alaska: Late Cenozoic volcanic rocks occur in a few scattered localities in southeastern Alaska. The most important occurrence is Mount Edgecumbe, an inactive composite volcano about 980 m in elevation located about 26 km west of Sitka. The volcano (Figure 8) is part of a volcanic field of Quaternary age that covers about 260 km^2 on the southern end of Kruzof Island and ranges in composition from olivine-augite basalt to rhyolite. Radiocarbon dates indicate that eruptions that deposited ash and lapilli as far away as 225 km occurred as recently as 9,000 to 11,000 years B.P. (Brew and others, 1969; McKenzie, 1970). Volcanic rocks of probable late Cenozoic age also crop out in several other small areas in southeast Alaska. As is the case with Quaternary volcanic rocks of interior Alaska, little or no spatial relation is shown between the thermal springs of southeastern Alaska and the young volcanic rocks.

The geothermal energy potential of areas underlain by late Cenozoic volcanic rocks in interior parts of southeastern Alaska appears to be low. Most geothermal areas now exploited in other parts of the world are associated with calc-alkaline volcanism whereas the Quaternary volcanic rocks of interior Alaska are primarily basalt and basaltic andesite and probably originated from considerable depth without large magma chambers relatively close to the surface. These volcanic areas display no signs of current activity such as fumaroles, geysers or thermal springs. The Mount Edgecumbe volcano area, however, with its relatively recent calc-alkaline volcanism, has higher geothermal potential.

Estimated Magnitudes and Heat Contents of Alaskan Volcanic Systems: Smith and Shaw (1975) have calculated estimated magnitudes and heat contents of Alaskan volcanic systems. These data are shown in Table 5.

Direct Extraction of Energy From Volcanoes

In the last few decades, the production of geothermal power has experienced a very slow growth, based on the discovery and development of vapor phase reservoirs. New concepts, such as artificially-induced reservoirs in hot-dry rock and the direct magma tap, offer new avenues for the exploitation of geothermal energy. Two approaches seem to offer the most promise for the direct extraction of volcanic energy:

1) Production and packaging of hydrogen, produced from the disassociation of water by volcanic heat

2) Generation of electricity by heat transfer from a magma to a conventional power plant on the surface via a heat exchanger immersed in the magma (an approach under investigation by Sandia Laboratories)

The problem, however, is to locate a suitable shallow magma reservoir, which is amenable to such an experiment. Very little is known about the physical characteristics of magma reservoirs and the internal plumbing of volcanoes. It is not certain that molten lava pools exist at depth. The geophysical evidence for magma at depth is highly speculative and inferential.

The depths of the magma chambers discussed in the literature range from about 4 km to greater than 60 km. Unfortunately, we do not yet know of one proven shallow magma reservoir in Alaska, although recent seismic studies (Eaton, et al., 1975) indicate such a reservoir under Yellowstone Park.

Magnitudes and Heat Contents of Identified Volcanic Systems
(As taken from Smith and Shaw, 1975)

ALASKA

S-S No.	NAME OF AREA	LAT	LONG	CONFIGURATION LAST ERUPTION	AGE DATA	CHAMBER AREA	CHAMBER [illegible] RANGE	[illegible] VOLUME	SEISMIC ACTIVITY STATE	ΔQ TOTAL CALORIES	ΔQ NOW CALORIES	ΔQ OUT CALORIES	REMARKS	
A-1	[illegible]	52°03 N	[illegible]	BASIC	[illegible]								>10 KM DEPTH	
A-2	NISHA	52°08 N	177°36 E	BASIC	ACTIVE								>10 KM DEPTH	
A-3	SEGULA	52°00 N	178°03E	BASIC SILICIC?	<10°								NEED MORE DATA ON COMPOSITION AND AGE	
A-4	DAVIDOF	51°58 N	178°23E	NO DATA	<10°	5 A_c	175 V_c	125	>650°	7	7			
A-5	LITTLE SITKIN	51°57 N	178°32E	BASIC	ACTIVE	75 A_c	45 V_c	75	>550°	45	45			
A-6	SEMISOPOCHNOI (CERBERUS)	51°56 N	179°35E	BASIC	ACTIVE	42.9 A_c	[illegible]	150	>550°	86	86			
A-7	SUGARLOAF	51°54 N	177°36E	BASIC	<10°								>10 KM DEPTH	
A-8	GAREL OI	51°48 I	178°53W	BASIC	ACTIVE								>10 KM DEPTH	
A-9	TAHAGA	51°53 N	178°00W	BASIC ?	ACTIVE	659 A_c	313 [illegible]	420	>850°	230	230			
A-10	TANADAKHA	51°52 N	178°33W	BASIC ?	<10°	69 A_c	22.5 [illegible]	>225	>850°	13	13			
A-11	BOBROF	51°55 N	177°27 W	BASIC ?	<10° ?								>10 KM DEPTH ?	
A-12	MANUA	51°53 N	177°03W	BASIC ?	ACTIVE	850 A_c	575 [illegible]	75	>550°	45	45			
A-13	MOFFET	51°55 N	176°13 W	BASIC	<10° ?								>10 KM DEPTH	
A-14	AGASHAN	51°55 N	176°36 W	BASIC	<10° ?								>10 KM DEPTH	
A-15	GREAT SITKIN	52°04 N	176°07 W	BASIC	ACTIVE	18 A_c	11 [illegible]	<1	>550°	3	3			
A-16	KASATOCHI	52°11 N	175°30 W	BASIC ?	ACTIVE ?								>10 KM DEPTH ?	
A-17	AGATUJI	52°13 N	175°02 W	BASIC ?	ACTIVE ?								>10 KM DEPTH ?	
A-18	SEGULI	52°10 N	174°25 W	NO DATA	NO DATA								NEED CONDITION AND AGE DATA	
A-19	KOROVIN	52°23 N	174°10 W	BASIC	ACTIVE								>10 KM DEPTH	
A-20	KLIUCHEF	52°19 N	174°03 W	NO DATA	NO DATA	286 A_c	73 [illegible]	>100		58			NEED COMPOSITION AND AGE DATA	
A-21	SARICHEF	52°19 N	174°09 W	BASIC ?	ACTIVE ?								>10 KM DEPTH	
A-22	SEGUAM	52°19 N	172°23 W	NO DATA	ACTIVE	2281 A_c	60 [illegible]	200	>850	115	115		[illegible]	
A-23	AMUTA	52°30 N	171°16 W	BASIC ?	ACTIVE								>10 KM DEPTH ?	
A-24	CHAGULAN	52°38 N	171°01 W	BASIC ?	<10° ?								>10 KM DEPTH ?	
A-25	BUNIDA	52°30 N	170°39 W	NO DATA BASIC ?	ACTIVE	121 A_c	33 [illegible]	40	>550	23	23			
A-26	HERBERT	52°45 N	170°07 W	BASIC ?	<10° ?								>10 KM DEPTH ?	
A-27	CARLISLE	52°54 N	170°04 W	BASIC ?	ACTIVE								>10 KM DEPTH ?	
A-28	CLEVELAND	52°49 N	169°56 W	BASIC ?	ACTIVE								>10 KM DEPTH ?	
A-29	ULAGA	52°50 N	169°51 W	BASIC ?	<10° ?								>10 KM DEPTH ?	
A-30	TANA	52°50 N	169°46 W	BASIC ?	NO DATA								>10 KM DEPTH ?	
A-31	HAGAMIL	52°58 N	169°49 W	BASIC ?	ACTIVE								>10 KM DEPTH ?	
A-32	VSEVIDOF	53°03 N	168°41 W	SILICIC	ACTIVE								NEED MORE DATA	
A-33	RECHESCHNOI	53°00 N	168°10 W	BASIC ?	<10°								NEED MORE DATA	
A-34	OKMOK	53°26 N	168°10 W	BASIC	ACTIVE 8000 T_c	627 A_c	35 [illegible]	250	>850	100	100			
A-35	TUMA	53°28 N	168°01 W	BASIC	NO DATA								>10 KM DEPTH	
A-36	[illegible]	53°30 N	167°55 W	BASIC	ACTIVE								>10 KM DEPTH	

Magnitudes and Heat Contents of Identified Volcanic Systems
(As taken from Smith and Shaw, 1975)

ALASKA

S-S No.	NAME OF AREA	LAT	LONG	COMPOSITION LAST ERUPTION	AGE DATA	CALDERA AREA km²	CALDERA VOLUME RANGE km³	CALDERA VOLUME V_c km³	SOLIDIFICATION STATE °C	ΔQ TOTAL CALORIES ×10²⁸	ΔQ NOW CALORIES ×10²⁸	ΔQ LAST CALORIES ×10²⁸	REMARKS
A-34	MAKUSHIN	53°31'N	166°56'W	SILICIC ?	ACTIVE	36 A_c	9-36 V_c	>10	>850	6	6		
A-35	TABLE TOP	53°38'N	166°10'W	BASIC	NO DATA								>10 KM DEPTH
A-39	AKUTAN	54°08'N	166°00'W	BASIC ?	ACTIVE	35 A_c	9-36 V_c	>10	>850	6	6		
A-40	MT. GILBERT (AKUN)	54°16'N	165°35'W	BASIC ?	NO DATA								>10 KM DEPTH ?
A-41	POGROMNI	54°34'N	166°42'W	BASIC	ACTIVE								>10 KM DEPTH
A-42	WESTDAHL	54°21'N	166°39'W	NO DATA	ACTIVE								NEED MORE DATA
A-43	FISHER	54°30'N	166°23'W	BASIC	ACTIVE ? <2×10⁸ T_g	122 A_c	9-36 V_c	600	>850	345	345		
A-44	SHISHALDIN	54°45'N	163°58'W	BASIC	ACTIVE								>10 KM DEPTH
A-45	ISANOTSKI	54°45'N	163°44'W	BASIC ?	ACTIVE								>10 KM DEPTH ?
A-46	ROUNDTOP	54°48'N	163°36'W	NO DATA	ACTIVE ? <2×10⁸ ?								
A-47	AMAK	55°25'N	163°09'W	BASIC ?	NO DATA								>10 KM DEPTH ?
A-48	FROSTY	55°04'N	162°51'W	SILICIC ? BASIC ?	NO DATA								
A-49	WALRUS (MOREHEAD)	55°03'N	162°30'W	BASIC	NO DATA <10⁸ ?								>10 KM DEPTH
A-50	DUTTON	55°11'N	162°16'W	[illegible]	NO DATA								>10 KM DEPTH
A-51	EMMONS	55°20'N	162°01'W	BASIC	ACTIVE	1173 A_c	[illegible]	600	>850	345	345		
A-52	ISANGO	55°21'N	161°53'W	BASIC	ACTIVE								
A-53	DOUBLE CRATER	55°43'N	161°37'W	BASIC	ACTIVE ?								
A-54	PAVLOF	55°23'N	161°51'W	BASIC	ACTIVE								>10 KM DEPTH
A-55	PAVLOF SISTER	55°27'N	161°51'W	BASIC	ACTIVE								>10 KM DEPTH
A-56	DANA	55°37'N	161°12'W	SILICIC	NO DATA <10⁸ ?	16 A_c	9-36 V_c	>3		>3			NEED MORE DATA
A-57	KUPREANOF	56°01'N	159°48'W	NO DATA BASIC ?	ACTIVE								NEED MORE DATA
A-58	VENIAMINOF	56°10'N	159°23'W	BASIC	ACTIVE 37×10⁸ T_g	324 A_c	[illegible]	200	>850	115	115		
A-59	BLACK (PURPLE)	56°32'N	158°27'W	SILICIC	<10⁸ ?	69 A_c	[illegible]	>20	>850	12	12	6	NEED MORE DATA
A-60	AMAKNAK	56°33'N	158°10'W	SILICIC	ACTIVE 58×10⁸ T_g	358 A_c	[illegible]	225	>850	129	129		
A-61	CHIGINIGAK	57°08'N	157°00'W	BASIC ? SILICIC ?	ACTIVE								NEED MORE DATA
A-62	KUKLASHIN	57°02'N	156°42'W	NO DATA	[illegible]								NO DATA
A-63	PEULIK	57°45'N	156°21'W	BASIC ? BASIC	ACTIVE ?	10.5 A_c	[illegible]	>20	>850	12	12		[illegible]
A-64	MARTIN	58°09'N	155°29'W	BASIC ?	ACTIVE								>10 KM DEPTH ?
A-65	MAGEIK	57°52'N	155°15'W	?	ACTIVE								SILICIC DOMES ? NEED MORE DATA
A-66	KATMAI	58°17'N	155°08'W	SILICIC	ACTIVE	31 A_c	[illegible]	>20	>850	29	29		
A-67	MT. GRIGGS (MAGE PEAK)	58°22'N	155°30'W	BASIC ?	ACTIVE								>10 KM DEPTH ?
A-68	TRIDENT	58°14'N	154°07'W	BASIC	ACTIVE								>10 KM DEPTH ?
A-69	MARMAL	58°19'N	154°58'W	BASIC	ACTIVE	31 A_c	23-83 V_c	>20	>850	12	12		
A-70	SNOWY	58°20'N	154°11'W	NO DATA	NO DATA								NO DATA
A-71	DENISON	58°25'N	154°21'W	NO DATA	NO DATA								NO DATA
A-72	STELLER	58°26'N	154°24'W	NO DATA	NO DATA								NO DATA

Magnitudes and Heat Contents of Identified Volcanic Systems (As taken from Smith and Shaw, 1975)

ALASKA

S-S No.	NAME OF AREA	LAT	LONG	COMPOSITION LAST ERUPTION	AGE DATA	CHAMBER AREA Km²	CHAMBER VOLUME RANGE Km³	CHAMBER DEPTH Km	SOLIDIFICATION STATE	ΔQ TOTAL CALORIES x10²⁹	ΔQ NOW CALORIES x10²⁹	ΔQ OUT CALORIES x10²⁹	REMARKS
A-13	KUKAK	58°27.5'N	154°21'W	No Data	Active?								No data
A-14	DEVILS DESK	58°26 N	154°17 W	No Data	No Data								No data
A-15	KAGUYAK	58°37'N	154°25'W	Silicic	<10⁶ ?	41 A_c	40 V_c	~15	>250	5	3	3	Need age data
A-16	FOURPEAKED	59°6'N	153°42'W	No Data	<10⁶ ?								No data
A-17	DOUGLAS	59°52 N	155°29 W	No Data	Active?								No data
A-18	AUGUSTINE	59°22 N	153°21 W	Silicic	Active								Need geophysical data?
A-19	ILIAMNA	60°02 N	153°06 W	Basic	Active								>10 Km depth
A-20	REDOUBT	60°28 N	152°45 W	Basic	Active								>10 Km depth
A-21	DOUBLE	60°46 N	152°35 W	No Data	No Data								No data
A-22	BLACK	60°51 N	152°25 W	No Data	No Data								No data
A-23	SOUTH	61°18 N	150°13 W	Basic	Active								Caldera? Need more data
A-24	DRUM	62°01 N	144°38 W	Silicic	[illegible]	100 A_c	[illegible]	4-6	~850?	250	~200	>100	
A-25	SANFORD	62°13 N	144°07 W	No Data	[illegible]								Need data on possible recent age on flanks of dissected [illegible]
A-26	WRANGELL	62°00 N	144°0 W	Basic?	Active on flanks?	15 A_c	[illegible]	5+	~250	20	20		
A-27	WHITE RIVERS	61°27 N	140°48 W	Silicic	[illegible]		80 V_E	80	~210	60	15		
A-28	WRANGELL	61°01 N	139°26 W	Basic & Silicic	Active? & 90,000 [illegible]	10 A_c	[illegible]	~250	~850	100	100	80	Silicic on rims Basic on flanks

A direct magma tap to extract thermal energy from subsurface magma reservoirs is a new concept in the geothermal energy field. The Sandia Laboratories, Albuquerque, New Mexico, which is presently pioneering magma tap research, estimates that one cubic mile (4 km^3) of 1000°C magma contains enough energy to drive several 100 MW electrical plants for a hundred years. Vast quantities of thermal energy are dissipated by passive and active volcanoes throughout the world. Table 6 is a compilation of energy released in historic volcanic eruptions. The energy yields are impressive. The Krakatoa eruption of 1883 released about 10^{25} ergs of energy, which compares to the total power consumption in the U.S. in 1970. The 1952 eruption of Kilauea represents a value of $350 million if converted to commercial electrical power today! Volcanoes represent a very high-grade energy source if we could somehow tap them.

va lakes also dissipate large amounts of energy (Table ', which represents but a fraction of the energy stored in the depths of the volcanoes.

Thermal Springs as Geothermal Resources

Origin of Thermal Spring Water: Just a few years ago, most of the steam and/or water that was erupted by thermal springs and/or fumaroles was thought to be primary or magmatic water. More recently, however, based on oxygen and hydrogen isotope studies and other evidence, we have learned that less than 5% of this water is of magmatic origin and about 95% is recirculated ground water (Figure 9).

Vapor-Dominated Versus Hot Water Systems: Geothermal systems, as discussed by White, Muffler and Truesdell (1971), have been subdivided into two types:

(1) Hot water systems

(2) Vapor-dominated (dry steam) systems

TABLE 6

Total Energy Released in Volcanic Eruptions

Volcano	Year	Energy Released	Volcano	Year	Energy Released
Tambora[1]	1815	8.4×10^{26}	Una-Una[1]	1898	1.8×10^{22}
Sukurajima[1]	1914	4.6×10^{25}	Mihara[1]	1954	$1.[illegible] \times 10^{22}$
Bezymianny[1]	1955-1966	2.2×10^{25}	Adatarasan[1]	1900	6.4×10^{21}
Krakatoa[1]	1883	ca. 1.0×10^{25}	Asama[1]	1938	4.0×10^{21}
Asama[1]	1783	8.8×10^{24}	Mihara[1]	1912	6.3×10^{20}
Fuji[1]	1707	7.1×10^{24}	Tokachidake[1]	1926	2.8×10^{20}
Sakurajima[1]	19[illegible]	2.1×10^{24}	Kusatsu-Shirane[1]	1932	1.6×10^{13}
Torishima[1]	1939	9.7×10^{23}	Showa Sin-San[1]	1944	1.4×10^{20}
Komagatake[1]	1929	5.6×10^{23}	Capelinhos[1]	1957	4.0×10^{24}
Miyakeshima[1]	1940	4.8×10^{23}	Arenal[1]	1968	1.0×10^{2}[illegible]
Bandaisan[1]	1888	ca. 1.0×10^{23}	Kilauea[2]	1952	1.8×10^{24}
Pematang Bata[1]	1933	4.5×10^{22}	Nyamlagira[3]	1938-1940	8.4×10^{25}

[1] After Yokayama (1957) with additions.
[2] After MacDonald (1972).
[3] After Verhoogen (1948).
After Verhoogen (1948).

(As prepared by Kienle, 1974)

TABLE 7

Heat Energy Released from Lava Lakes

Volcano	Year	Energy Released (ergs/sec)	Remarks
Halemaumau (Kilauea)	during 1909	9.6×10^{15}	As heat energy (R.A. Daly, 1911).
Nyiragongo	during 1959	9.3×10^{15}	As heat energy in the form of radiation and conduction away from the surface by convecting air (Bonnet, 1960).
Nyiragongo	during August 1959	3.6×10^{19}	Total heat output by radiation, transport outward by gases and conduction into surrounding rocks (Delsemme, 1960).

(As prepared by Kienle, 1974)

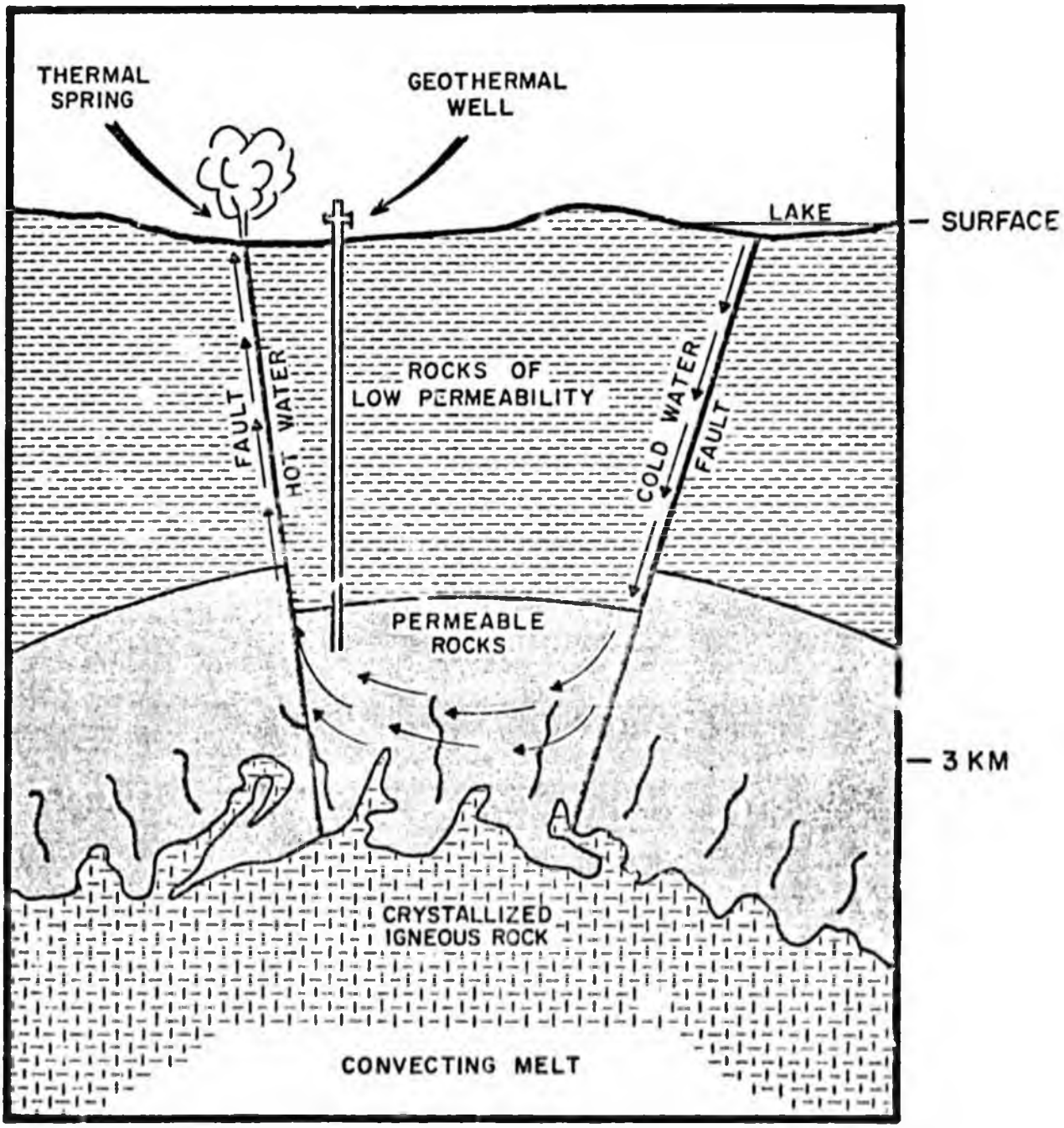

Figure 9: Diagram showing a hypothetical vapor-dominated, two-phase geothermal system as driven by convecting melt at depth. Meteoric (cold) water descends along fault line to hot permeable reservoir rock where it is heated by the cooling melt. Due to lowered density, the hot water ascends along another fault system to emerge at the surface as a thermal spring. A geothermal well has been driven into the reservoir rocks. In vapor-dominated systems, boiling will begin before the water reaches the surface.

Hot water systems appear to be about 20 times as common as the vapor dominated type (White, 1970).

In hot water systems, only a small part of the volume is steam, and the water and steam are separated mechanically before the steam is routed to the turbine system. If heat exchange systems utilizing low boiling point fluids such as freon or isobutane are proved feasible, this will increase the number of hot water systems which can be used for the generation of electricity. Producing geothermal fields of this type include the New Zealand fields and more recent discoveries in Mexico and the Salton Sea in California.

The vapor-dominated systems produce superheated steam with subordinate amounts of carbon dioxide (CO_2) and hydrogen sulfide (H_2S). Only three commercial vapor-dominated systems are in production today, including those at Lardello, Italy, (since 1904); the Geysers, California; and a field at Matsukawa, Japan.

Geothermometry: Subsurface reservoir temperatures of thermal systems can be estimated through the use of geochemical techniques. Various geothermometers have been developed based on analyzed concentrations and ratios of the dissolved mineral constituents. The more commonly used indicators are the silica (SiO_2) content (Figure 10), the Na-K ratios* (Figure 11), the Mg content and Mg-Ca ratio, and the Na-Ca and Cl-F ratios.

The assumptions involved in the use of geothermometers have been outlined by White (1970). These include (1) the availability of constituents from the reservoir rocks; (2) the equilibration of water-rock reactions at the reservoir temperature; (3) the rapid flow of water from the reservoir to the surface to eliminate reactions in transit at lower temperatures and to retain the composition of reservoir temperatures; and (4) a lack of mixing with other waters at intermediate levels.

---

*Na=sodium; Mg=magnesium; K=potassium; Ca=calcium; F=flourine; Cl=chlorine.

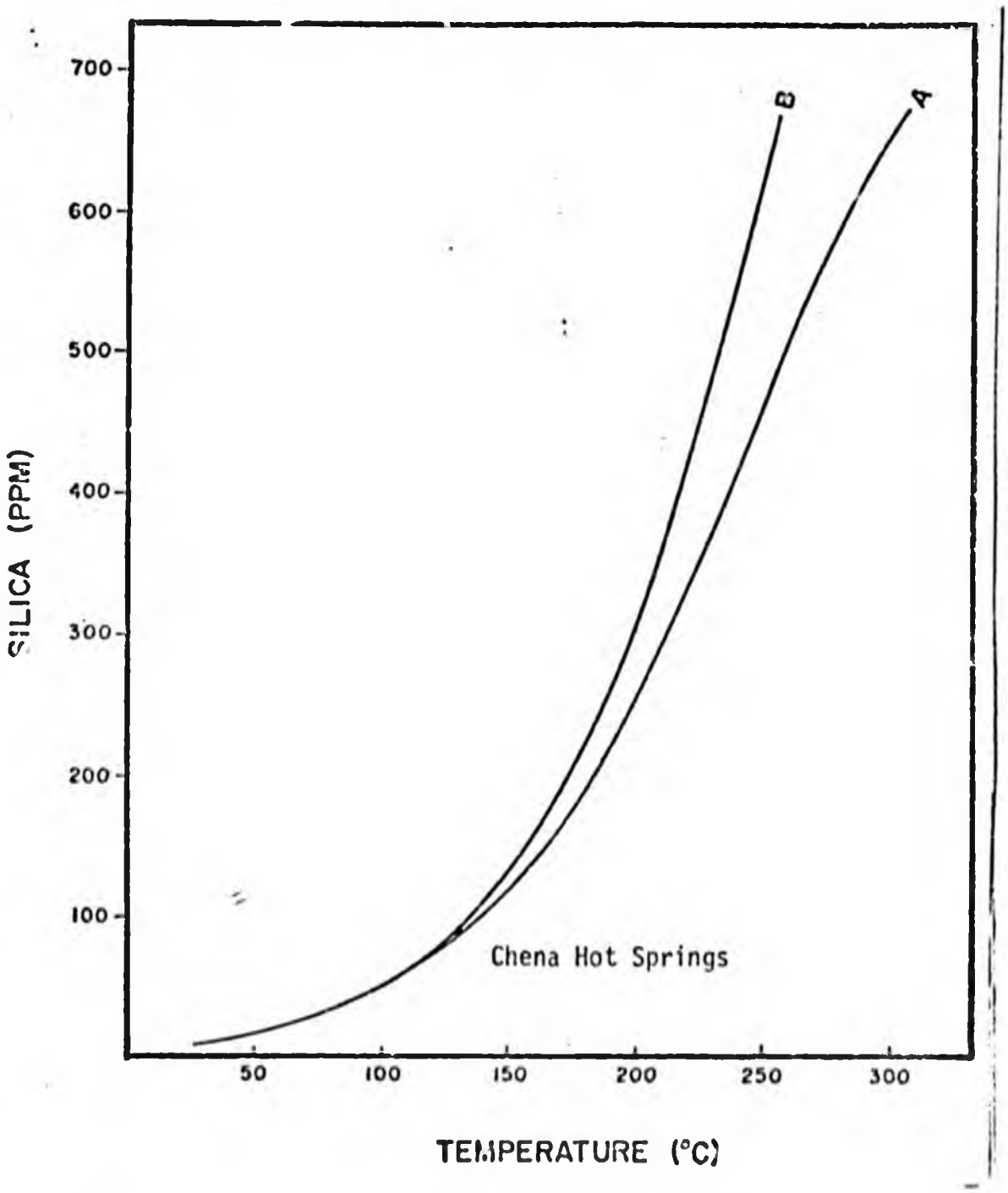

Figure 10: Silica concentration in geothermal water versus estimated temperature of last equilibration. Curve A applies to waters cooled entirely by heat conduction. Curve B applies to waters cooled entirely by adiabatic expansion at constant enthalpy. (From Fournier and Truesdell, 1970)

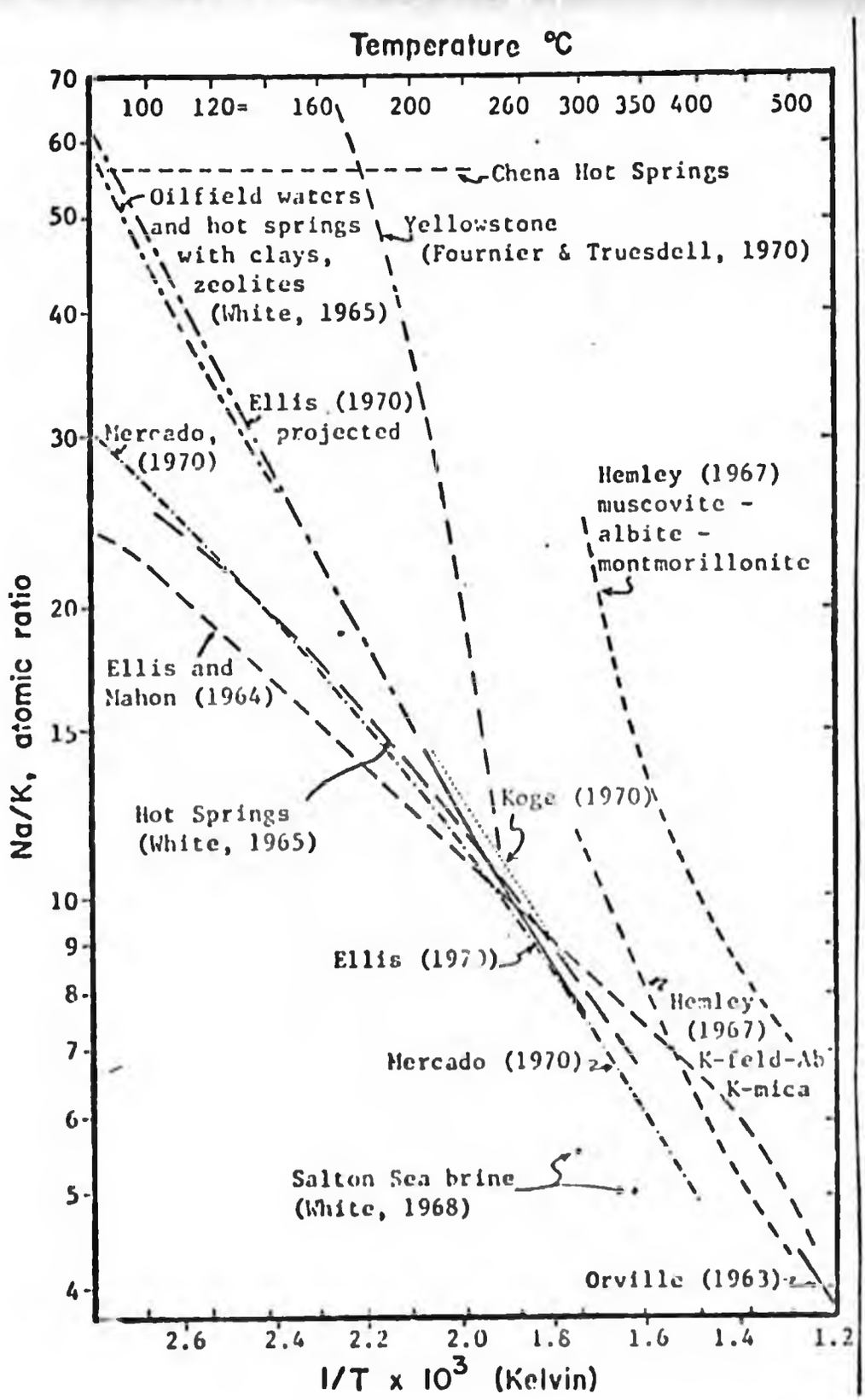

Figure 11: Atomic Na/K ratios versus temperature, showing experimental and empirical curves. (White, 1970)

If equilibrium has been obtained in the subsurface waters, the Na-Ca-K geothermometer should be in general agreement with estimated reservoir temperatures determined from dissolved SiO_2.

Thermal springs which have a high dissolved SiO_2 content, and/or those which deposit silicious sinter at the surface, are probably related to high temperature subsurface reservoirs. Geysers are also a favorable indication of high temperatures at depth.

The Na-Ca-K geothermometer is based on the temperature-dependent base exchange or partitioning of alkalies between solution and solid phases. Discussion of the sodium-potassium equilibria generally applied to systems with temperatures above 175°-200°C, as the alumino-silicate equilibria at lower temperatures, are uncertain (Ellis, 1970).

Factors limiting the possible use of this method are the dilution effects of the deeper water as it rises to the surface, the effect of different mineral suites as source rocks, the effect of continual base exchanges as the waters move toward the surface, and the formation of complex ions. These factors are discussed in greater detail by Fournier and Truesdell (1970).

Geologic Setting of Alaskan Thermal Springs: According to the compilation by Biggar (1973) and the later work of Miller, et al. (1973), there are about 95 recognized Alaskan thermal springs. The geographical distribution patterns indicate that the thermal springs occur in three tectonic settings or geologic associations:

(1) Adjacent to Quarternary volcanoes (i.e. Aleutian Archipelago, Alaska Peninsula, Wrangell Mountains);

(2) In a broad east-west trending zone in northcentral Alaska associated with late Cretaceous or Tertiary granitic plutons; and

(3) In southeastern Alaska, south of the Chatham Strait Fault, in a zone which may be involved in a transform fault system.

Quaternary Volcanic Belts

Some thermal springs in the Aleutian Islands exhibit relatively high surface temperatures (over 100°C), such as Geyser Bight (Table 8). The Aleutian arc also shows evidence of extensive mid-Tertiary intrusive activity (Cameron and Stone, 1970), and is believed to be a consuming plate margin between the Pacific and North American plates.

Many of the Aleutian Islands have not been mapped in detail, and it is probable that there are more thermal springs in the Aleutian Archipelago than those recognized to date.

Southeastern Alaska

Thermal springs on the south side of the Chatham Strait Fault appear to be located along a trend which can be projected underneath the continental block from the North Pacific Rise, where it appears to plunge under the Southeastern Alaskan Archipelago. Quaternary volcanic eruptive centers are also located along this same trend in the Canadian Coast Ranges.

In plate tectonic terms, this area appears to be essentially a transform fault system that connects the actively spreading Explorer and Juan de Fuca Ridges, and the Gorda Rise with the Aleutian Arc system.

Central Alaska

This belt of thermal springs forms a broad zone which extends from the Yukon-Tanana Uplands to the Seward Peninsula. These springs are located on or near the contacts between late Cretaceous or early Tertiary granitic plutons. Portions of this belt may also be underlain by zones of high heat flow.

TABLE 8

Identified hot-water convection systems with indicated subsurface temperatures above 150°C

(As taken from Renner, White and Williams, 1975)

Name	Location Latitude ° ' N	Location Longitude ° ' W	Temperatures °C Surface 1/	Geochemical SiO_2 2/	Geochemical Na-K-Ca 2/	Subsurface 3/	Reservoir Assumptions Subsurface area km^2 4/	Thickness km 5/	Volume km^3 6/	Heat content 10^{18} cal 7/	Comments
ALASKA											
Geyser Bight	53 13	168 28	100	210	236	210	4	2	8	.9	22 springs and geysers in 3 thermal areas i 2 km long zone, near Okmok Caldera; siliceo sinter deposit.
Hot Springs Cove	53 14	168 21	89	131	154	155	2	2	4	.3	Hot springs and geysers in area about 1 km^2 near Okmok caldera.
Shakes Springs	56 43	132 02	52	142	175	155	1.5	1.5	2.25	.2	Several springs discharging ~380 l/m; chemi data not reliable.
Hot Springs Bay	54 10	165 50	83	152	179	180	1.5	1.5	2.25	.2	Hot springs and fumaroles on active Mutan volcano.

1/ Maximum surface temperature reported from a spring or fumarole.
2/ Predicted using chemical geothermometers, assuming fast equilibration in the reservoir; assumes saturation of SiO2 with respect to quartz, and no loss of Ca from calcite deposition.
3/ Assumed average reservoir temperature based on data presently available.
4/ From surface manifestations, geophysical data, well records and geologic inference. Assumes 1.5 km^2 if no data presented to size is available.
5/ Top assumed at depth of 1.5 km if no data available. Bottom assumed at 3 km depth for all convection systems.
6/ Calculated from assumed area and thickness.
7/ Calculated as product of assumed volume, volumetric specific heat of 0.6 cal/cm³ °C, and temperature in degrees C above 15°C.

Maximum Surface Water Temperatures: The hottest water temperatures discovered in Alaska have been measured in thermal springs or hot lakes or pools associated with volcanoes on the Alaska Peninsula or in the Aleutian Islands (e.g., 102°C, Hot Springs Cove, Umnak Island). Water temperatures up to 88°C have been measured in the waters of Bailey Bay Hot Springs, southeastern Alaska.

Estimated Reservoir Temperatures: To date, geochemical studies (Miller and Barnes, in press) indicate that there are only two springs (Geyser Springs Basin, Umnak Island; Chiginigiak Hot Springs, Alaska Peninsula) which are likely to have reservoir temperatures which are over the practical minimum of 180°C, which is needed to drive steam turbine generators, utilizing today's technology. Based on geochemical data reported by Waring (1917), Byers and Brannock (1949), Miller (1973a), the reservoir temperature estimates given by Miller, et al. (1975), and Renner, White and Williams (1975), thermal springs in western and central Alaska are associated with subsurface systems of the hot water types. Maximum estimated reservoir temperatures for 10 springs, as determined by the quartz and Na-Ca-K geothermometers, were 137°C and 167°C respectively.

Reservoir and Conduit Systems

Over 90% of the thermal springs in central Alaska are located near the contact of late Cretaceous and early Tertiary granitic plutons with surrounding country rock. In many cases, the country rocks are crystalline schists with relatively no interstitial porosity and very poor permeability other than that associated with fractures and faults (Figure 12a). In such settings, the probability of large reservoirs at depth is very low.

Considering the low estimated reservoir temperatures there, the prognosis is poor for the discovery of large vapor-dominated geothermal systems in such settings (Miller, et al., 1975). A few springs occur in west-central Alaska near the margins of plutons which have been emplaced in Jr-k sediments (Figure 12b). The probabilities of finding large hot-water reservoirs are higher in such terranes.

Flow Rates

Flow rates of Alaskan thermal springs have been observed which range from slow seepage to rates as high as an estimated 400 gpm at Clear Creek Hot Springs. In some cases, such as that at Pilgrim Springs, spring water flow rates are difficult to determine due to lateral flow, convective circulation and mixing with ground water. Potential electric and nonelectric applications of hot water systems are constrained by flow rates and whether or not such rates can be improved by subsurface drilling.

The potential application of drilling techniques to these systems is an unknown area, as the geometry and reservoir mechanics of the conduits and reservoirs are not understood.

Saline Springs: Four saline springs are known in central and western Alaska including Pilgrim, Serpentine, Kwiniuk and Tolovana (Miller, et al., 1975). These springs are characterized by high concentrations of Cl, Na, Ca, and K. Pilgrim and Serpentine Springs are the most saline (Pilgrim: Na=1450 ppm/Cl=3346 ppm. Serpentine: Na=800 ppm/ Cl=1450 ppm).

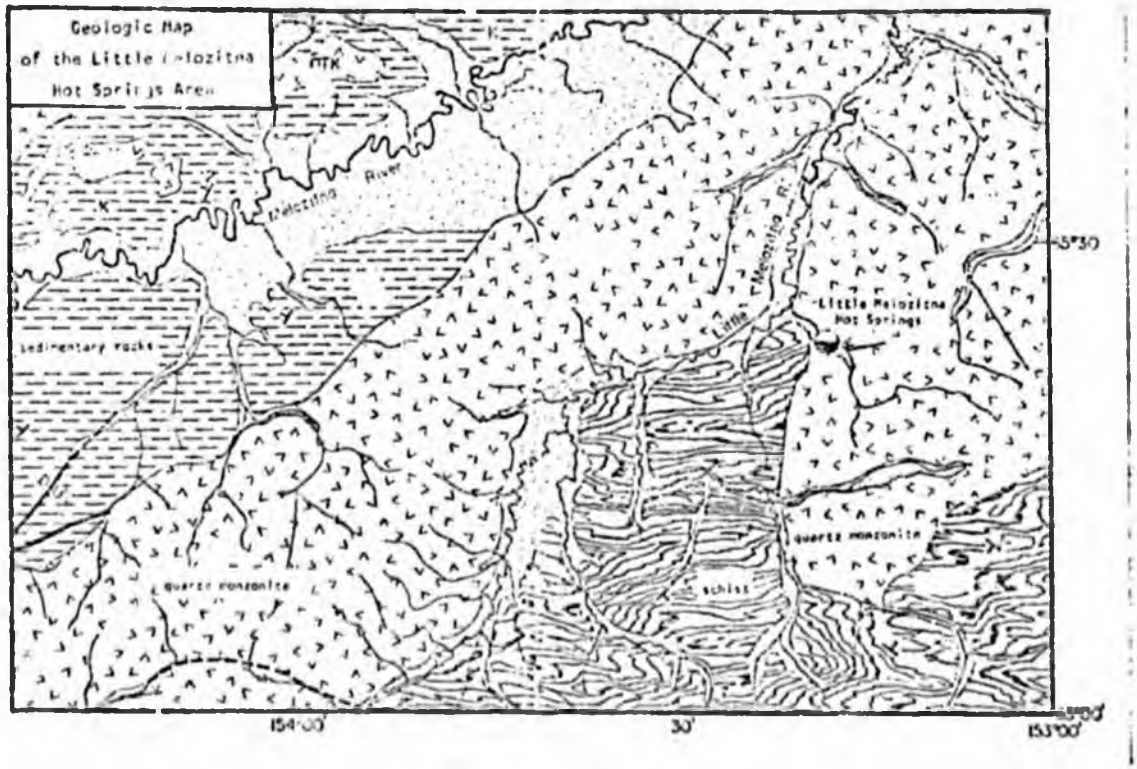

Figure 12a: Geologic map of the Little Melozitna Hot Springs area.

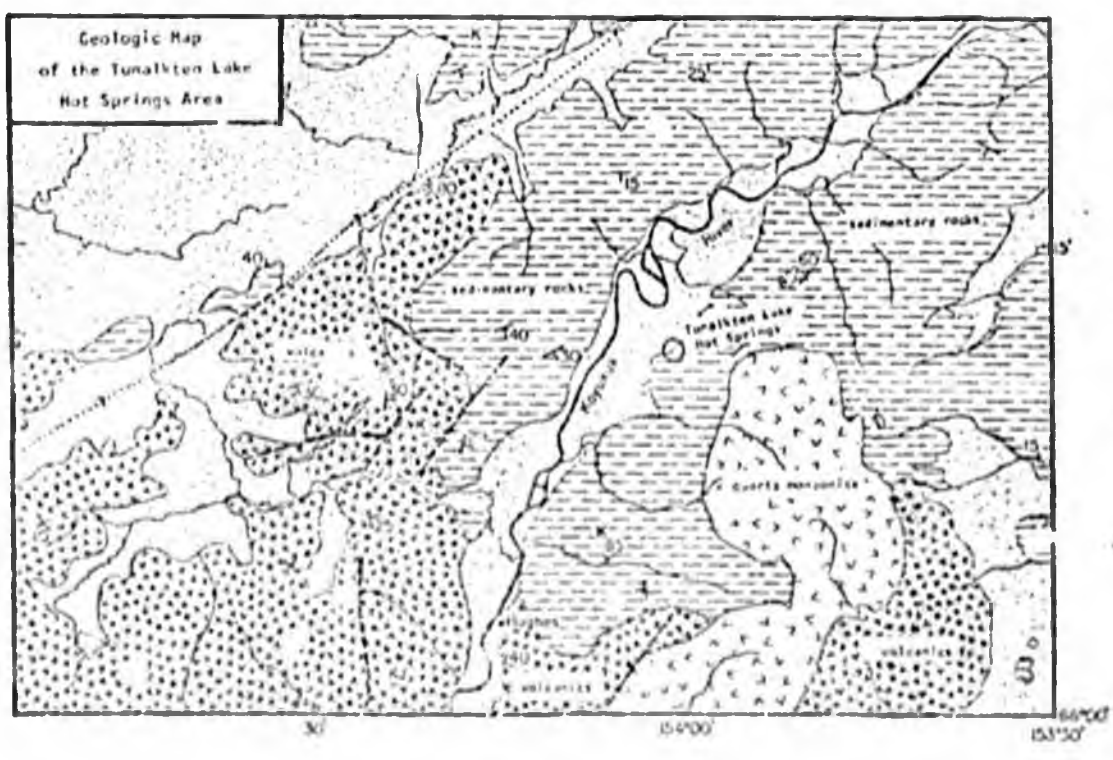

Figure 12b: Geologic map of the Tunalkten Lake Hot Springs area.

Both of these springs exceed the salinity threshold of acceptable potable water, and are potentially troublesome in terms of corrosion of casing, pipe and other hardware.

Utilization of Alaskan Thermal Springs

The thermal springs of Alaska were first utilized and developed by early stampeders and entrepreneurs. For example, Circle and Chena Hot Springs, in the Fairbanks District, were used by early prospectors for bathing and recreation; and subsequently, roadhouses and small settlements appeared. In these early cases, primitive engineering techniques were used, and the applications were limited to bathing pools, hot tap water, and space heating, using hot water convectors. At Manley Hot Springs, the utilization of thermal waters was more advanced, as spring water was used to heat greenhouses, animal barns, and a 60-room hotel, in addition to that used in the bathing pools and the hot water system. Agriculture also became an important part of the activity at Pilgrim Springs during the Nome gold rush in the early 1900's.

These early attempts to utilize the energy of thermal springs passed with the wave of gold seekers, but the energy remains. If properly utilized, such energy sources could play an important part in the economic and cultural life of many rural communities.

The ideal utilization of a geothermal resource in a rural Alaskan community would provide the following:

(1) Heat and electricity for the entire community, to reduce and perhaps eliminate the dependence on imported fossil fuels, and

(2) Energy for local industries which would aid the economy with minimum impact to village culture and lifestyle.

The following sections discuss the more promising applications of thermal spring resources to rural needs.

Electricity: There are many techniques for producing electric power from geothermal resources. Unfortunately, most of these are very complex and require vapor phase reservoirs or high temperature waters which can only be reached by deep drilling. Such techniques are not economically feasible, if very small amounts of power are needed, as in the case of a small Alaskan village.

Techniques must be found to produce relatively small amounts of electricity from geothermal resources with as little impact on the environment as possible. The most promising of these resources in Alaska are the thermal springs. The Geophysical Institute, University of Alaska, has been investigating a method that might be used to produce electricity directly from hot spring water, which utilizes the organic Rankine cycle and the temperature difference between the spring water and the ambient air. An experimental plant, utilizing this technique is now operating at Paratunka, Kamchatka, USSR, and uses water at a temperature of 81.5°C (Facca, 1970).

The Geophysical Institute, University of Alaska, has been working informally with Ormat Turbines Ltd. of Israel, to determine whether or not one of their organic Rankine cycle turbines could be coupled to thermal spring water as an energy source. Ormat has determined that one of their units could be so adapted and that useful, but small, amounts of power could be produced from waters with temperatures as low as 60°C, a temperature which is obtainable in many Alaskan hot springs. Shallow drilling to minimize dilution by ground water could increase the water temperature and enhance the efficiency of the Ormat turbine. Such drilling would not be cost prohibitive and could be easily accomplished by small rigs in remote locations.

Ormat engineers estimate overall efficiencies of approximately 5-1/2% which would require about 40 gpm of 60°C thermal spring water to produce 5 KW of continuous power. This efficiency would, of course, be increased if the temperature of the input water were greater. A schematic diagram illustrating the Ormat system as applied to a thermal spring source is shown in Figure 13.

The electrical system of the Ormat turbine produces a high frequency voltage at the generator which is rectified to DC, thus eliminating the need for costly speed control equipment. The DC output can then be inverted to AC, or it can be used to charge batteries. Such a system could be integrated with wind-generating equipment and circuitry. The combined use of alternate energy sources such as wind power and geothermal energy is especially attractive and should be evaluated in demonstration experiments.

While Rankine cycle power generation at small temperature differences is not very efficient, compared to conventional steam plants, the continuous free supply of the geothermal "fuel" makes it attractive. But in addition to fuel savings, the Ormat turbine has advantages which make it well adapted to use in remote regions:

1. The synthetic organic working fluid allows for low working pressures and temperatures. This results in the elimination of sophisticated pressure vessels and the need for elaborate safety equipment;
2. The entire vapor system is closed, eliminating the need for constant monitoring of the working fluid;
3. The only moving part is the common, turbine-generator shaft. Lubrication is provided by the working fluid which contains a lubrication agent;

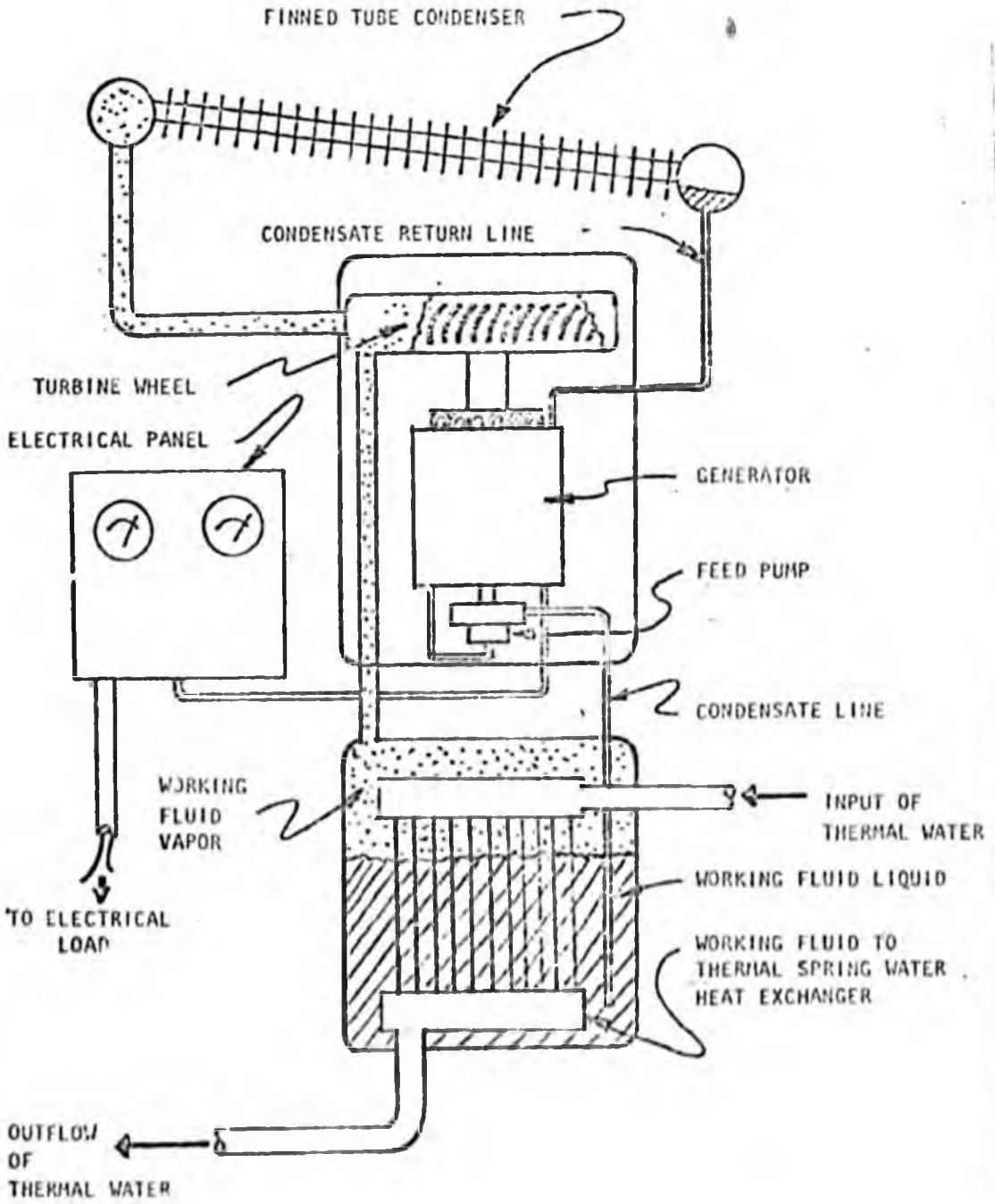

Figure 13: Diagram of Ormat system applied to thermal spring heat source.

4. The working fluid-air condenser is of the free convection type which makes cooling fans and similar devices unneccessary; and

5. The turbo-generating system is hermetically sealed and Ormat claims a 20-year operating life without maintenance.

All of these factors, as well as the previous experience of Ormat Turbines Ltd. in manufacturing organic Rankine cycle systems for the communications industry in other arctic and subarctic areas, make the Ormat system ideally suited for rural Alaska. If an optimum system for a rural Alaskan village could be found, it would be one in which:

1. A local fuel could provide the basic energy input.

2. No maintenance was necessary, and the system could operate unattended for extended periods.

3. The system would be simple enough to be operated by personnel with basic technical skills, and without extensive formal training.

4. The cost would be low.

An Ormat type system appears to meet most of these criteria, but the system has not been demonstrated in the field. If a successful demonstration is achieved, cost factors will fall with increased demand. To date, the largest Ormat unit of this type is a 15-KW unit. However, Ormat engineers are now working on a 100-KW system. Hopefully, the production of this size unit could coincide with the final phase of a successful small-scale feasibility demonstration of a geothermally-powered Ormat turbine.

Ormat Turbines Ltd. has agreed to work with the Geophysical Institute on a co-sponsored research and development investigation. Ormat has agreed to design and construct a 2500-W test unit with a hot water-to-working fluid heat exchanger suitable for the experiment.

Space Heating: The cost of home heating in Alaska is high. In many rural villages without local fuels such as wood or coal, imported fuel oil is the only source of heat. Presently, No. 1 stove oil costs are as high as $1 per gallon in some remote villages and recently have risen to over 50¢ per gallon in many Alaskan cities. At this rate, $900 would be an annual cost for home heating that many village residents can expect to pay this year. With the typical head of a household making less than $3,000 per year, the heating bill alone would constitute about 30% of the family's annual income. Under these conditions, the burden of heating costs alone can seriously depress the potential for economic growth of rural communities.

The heating of buildings with thermal spring waters is one of the oldest and most basic applications of geothermal energy. In areas where thermal springs exist, obvious benefits could be realized by the construction of a geothermally-powered municipal heating system. Figure 14a shows a simple system in which thermal waters from the spring would be directly circulated through convectors in homes. Since many thermal springs contain dissolved salts and other minerals which are corrosive to piping, binary systems as shown in Figure 14b could be constructed which would limit the corrosive effects to a heat exchanger which could be built of stainless steel, or other non-corrosive material.

Various methods could be employed to circulate the thermal spring water. Thermal siphons could help reduce the required pump work. This particular method was used at Pilgrim Hot Springs, Alaska, during the 1930's when the waters of the spring were used to heat buildings at the Catholic mission school.

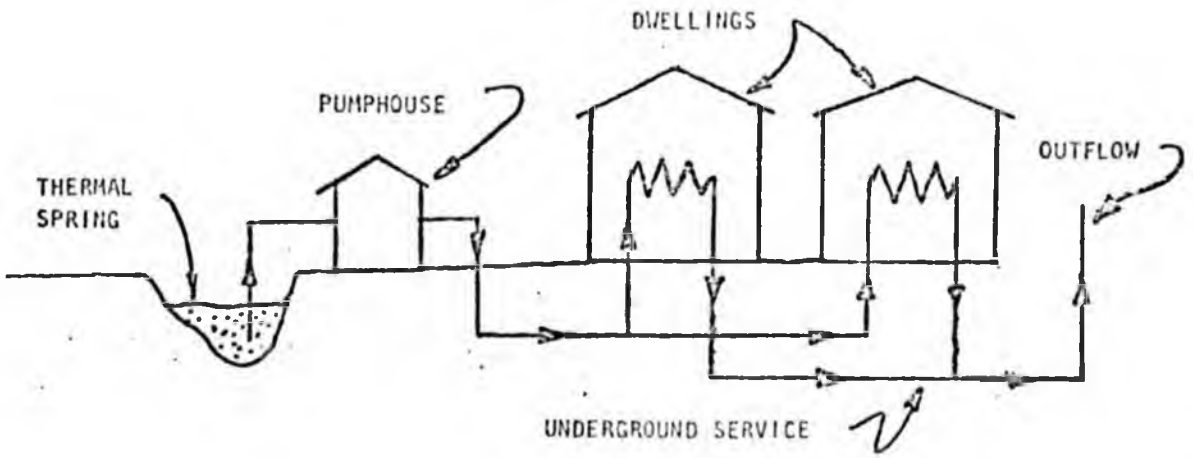

Figure 14a: Primary space heating system.

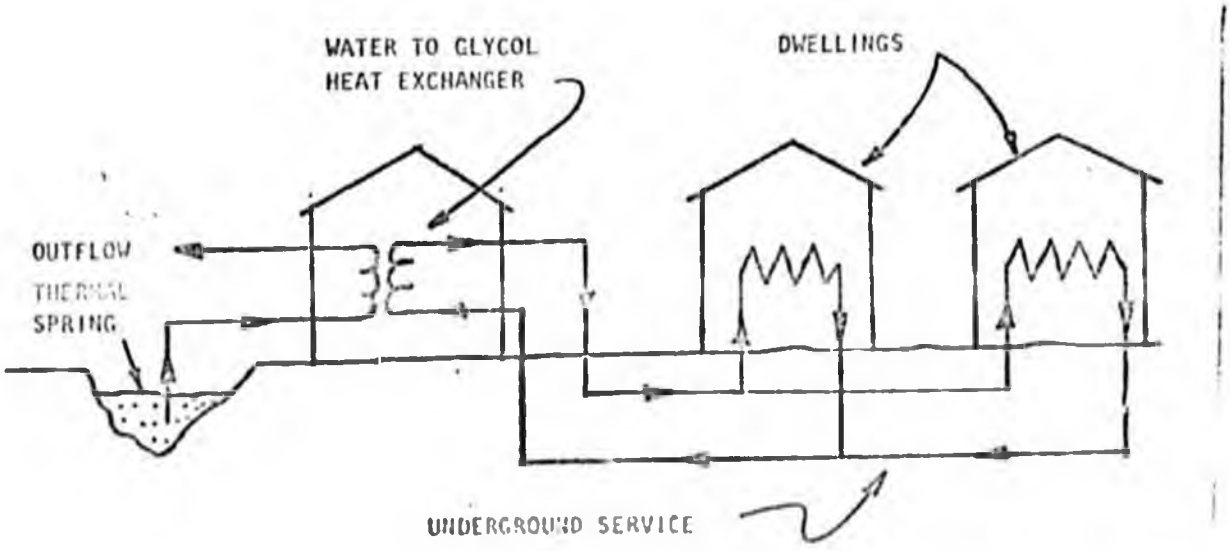

Figure 14b: Binary space heating system.

Space heating techniques are not new and probably do not require further experimental development. A careful literature and design investigation should be made, however, to gain full advantage of existing equipment which could be applied to Alaskan needs.

Refrigeration: Several villages such as Elim and Mary's Igloo on the Seward Peninsula, and Manley in Interior Alaska, could benefit greatly from low-cost refrigeration systems. Small coastal villages cannot presently take full advantage of commercial fishing opportunities due to the lack of cold storage facilities. The reindeer industry is another example of the need for cold storage or freezer facilities as such facilities could eliminate the need for immediate sale and shipment of meat after the reindeer are harvested.

Transmission of Geothermal Energy

Since geothermal resources often exist in areas which are some distance from the location where they could be best utilized, the transmission of this energy becomes an applications engineering problem. If electricity was the only concern, it could be transmitted from the generating site to the users by the usual transmission lines. But since we are also concerned with non-electric applications and the total utilization of the available energy, the problem is more complex.

High Temperature Pipelines: To date, no large reservoir geothermal systems have been discovered in Alaska; thus we are not immediately concerned with the transmission of large quantities of energy. If such a discovery should be made, however, pipeline transmission of hot water might present formidable problems. The Icelandic operations are the most valuable model that we currently have for hot water transmission

technology. The Alaskan climate is more extreme, however, and hot water pipelines will face the same environmental problems that confronted the trans-Alaska oil pipeline. High moisture content permafrost is a costly handicap, and non-stable soil problems can offer many challenges to pipeline engineers. This report does not contain a complete economic analysis of hot water pipelines in Alaska, but we believe that the cost would be highly prohibitive, unless a great number of people could be served, and there was a large magnitude energy potential.

Low Temperature Pipelines: Low temperature waters such as those emitted by many thermal springs, offer similar transmission problems to those which would be encountered by high temperature water pipelines, with the added hazard of lower outflow temperatures due to heat loss.

Pipeline transmission of low temperature thermal waters (60°C or lower) is not practical in permafrost terrane for distances over two or three miles. Where low temperature springs are to be utilized, it is more feasible to move the user to the source than to attempt pipeline transmission of the water.

SPACE HEATING AND INDUSTRIAL APPLICATIONS

Space Heating

Alaska should be an ideal place for the use of geothermal space heating because of the large number of days per year that heating is necessary; thus the "on line" factor would be high. Temperature extremes might require supplemental booster heating for a cost efficient system.

The use of existing hot springs is an ideal way to initiate this program, as the "front end" costs of exploration and drilling could be avoided. Small projects (a dozen to several hundred homes) should be proposed and implemented as soon as possible. A survey should be conducted at the earliest date to determine which communities are amenable to space heating by hot spring sources.

It does not seem practical to use wind power for space heating, unless heat pumps could be integrated into the system.

The Industrial Belt

The possible applications of geothermal or wind power in the industrial belt should be investigated in the near future. Fairbanks is potentially interesting since it is already known that 100°C temperatures exist at 10,000 feet in the subsurface, and that the present heating methods cause serious ice fog problems.

The New Capital Site

The working group felt that in spite of the possible adverse political effects, the possibility of heating the new capital with geothermal heat should be again pointed out to the Capital Site Committee. After a site

is picked, the possibility should again be studied. At least the town should be planned to be centrally heated so that such a heat source could be used later, if developed.

Industrial Applications

The following is a list of possible industrial applications:

1. The use of geothermal energy to make electricity for the aluminum or fertilizer industry using the apparently large resource along the Aleutian Chain. Wind energy might be a good candidate for this use also.
2. The use of geothermal steam in the southeast for pulp processing. This is being done in New Zealand with appreciable success.
3. The use of geothermal hot water to allow gold mining year-round, as is done in Siberia.
4. The use of geothermal hot water for other mining processing, for instance at Lost River.

Recommended Projects

Specifically, a few projects should be started as soon as possible:

1. A survey of all rural Alaska villages should be conducted to determine where wind and/or geothermal energy might be competitive with present energy sources.
2. Based on that survey, a number of projects should be initiated to demonstrate the practicability of such applications.
3. The needs of larger population centers should also be evaluated, in terms of municipal wind power and geothermal applications.

Environmental Hazards

Chemical Pollution: Steam brought up from subsurface reservoirs contains about 0.5-5% noncondensible gas which is principally carbon dioxide with varying amounts of hydrogen sulfide, methane and ammonia.

These gases are released directly from the condensate in cooling towers. Condensates usually contain trace amounts of boron, arsenic and other volatile elements which can be hazardous in excessive concentrations. Hydrogen sulfide is a dense gaseous pollutant which can be dangerous to human and animal life.

Most geothermal steam fields are the wet rather than the dry type (vapor dominated) and contain approximately 80% water at the wellhead. The water often contains higher concentrations of trace elements than the steam. The most common dissolved constituents include carbonate, silica and sodium chloride.

Some of the liquid-dominated systems are characterized by brines which contain very high concentrations of sodium, potassium, bromine and heavy metals. Such brines are extremely corrosive, and potentially hazardous to plant and animal life if released into the environment without treatment.

Noise Pollution: When superheated water flashes to steam, an intense ro-- is produced which is very offensive to workers, residents and nearby communities.

Thermal Pollution: Hot water which is wasted from geothermal power plants and other uses is potentially troublesome if it is allowed to

flow into streams, rivers, lakes or ground water tables. The chemical effect on the ecosystem may be far less in some cases than the thermal shock created by the inflow of hot water.

Anti-Pollution Measures

In the case of steam fields, water and condensates may be reinjected into another drill hole. Acoustic problems from flashing steam can be solved with silencers.

In the next few years, a technology will no doubt be developed for desalinization systems which will extract valuable salts and metals from brines, after steam has been extracted for the turbines, with a final outflow of potable water (Figure 15).

Environmental Vulnerability of Alaskan Thermal Springs

The utilization of thermal waters emitted from springs is not beset by some of the hazards associated with geothermal steam operations. Thermal waters which well up from the springs flow into streams which are part of the same ecosystem. The chemical composition of the spring waters should not be greatly changed by the planned demonstrations and experiments, as only the heat will be extracted....and concentrations of dissolved constituents are not high enough to cause accelerated precipitation during the cooling process. The water can be rechanneled into the same outflow streams with relatively little environmental impact.

If shallow drilling at Pilgrim Springs should indicate a possible geothermal steam reservoir, with more highly concentrated brines as the liquid phase, adequate protection measures will have to be taken before proceeding to demonstrations involving deeper drilling and the possible release of steam and condensates at the wellhead.

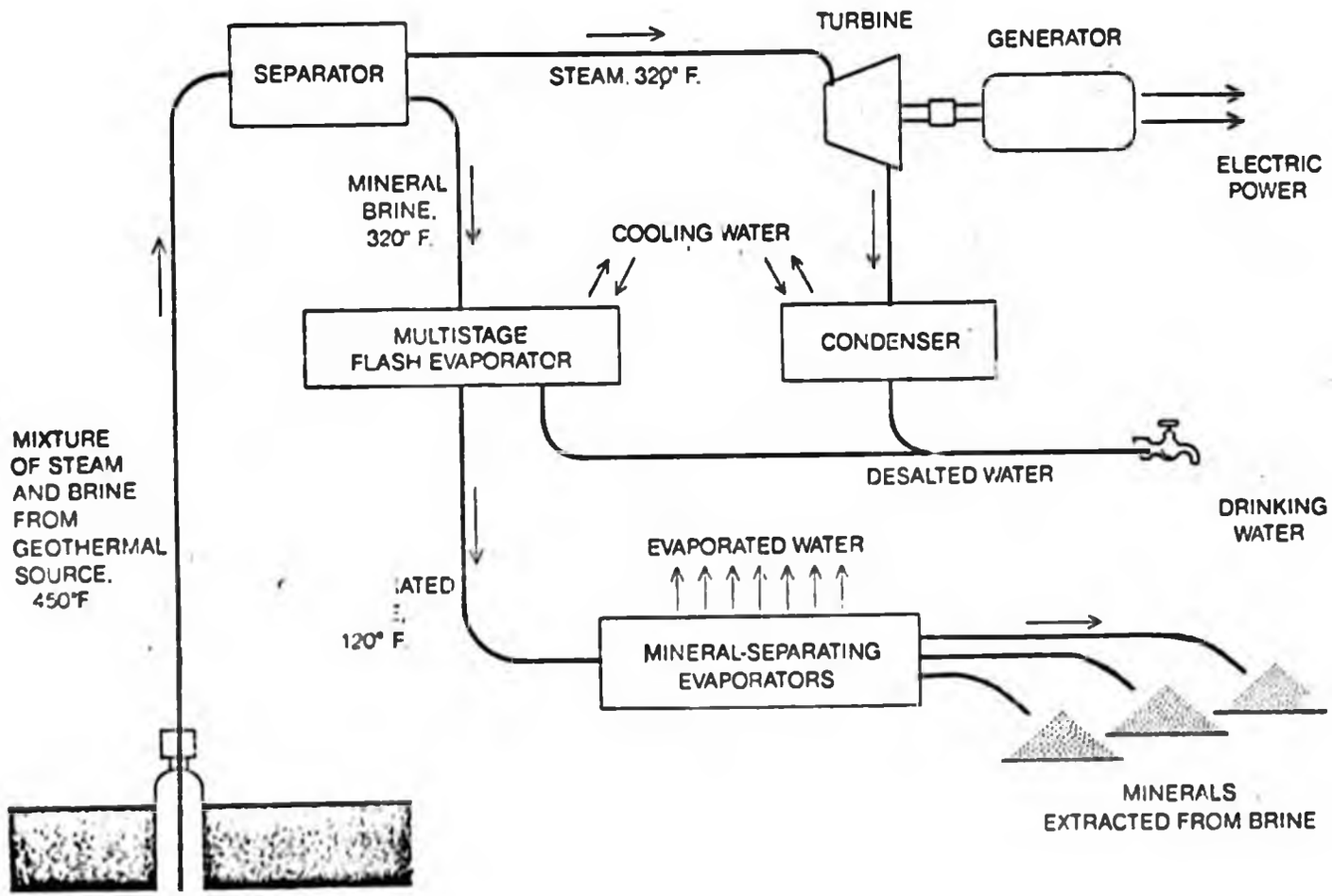

Figure 15: Multipurpose geothermal system, as designed by the UN and the Government of Chili. From "Geothermal Power" by Joseph Barnea. Copyright January, 1972, by Scientific American, Inc. All rights reserved.

Some concern has been voiced for thermal springs and the adjacent terrane as possible island ecosystems surrounded by a hostile arctic environment. It has been suggested, for example, that such ecosystems and the accompanying microenvironment (unless destroyed by man) may contain relict biological populations which have survived glacial episodes, dating back to Pliocene time. Although it remains to be proved, the reported presence of vigorous earthworms in the warm soil around Pilgrim Springs is of more than passing interest....even though the earthworms may have arrived via plants which were imported during the Nome gold rush.

Manley and Pilgrim Springs have been thoroughly overprinted by the works of man. Channelways, pools and seeps have been reworked and altered by several generations of residents. Indeed, it would be difficult, or perhaps impossible, to reconstruct the original setting. Nevertheless, each of these microenvironments should be carefully assessed and evaluated so that future developments can be accompanied by attempts to restore the former biological equilibrium, if possible.

Clear Creek Springs will be a more sensitive site, as it has not been obviously altered or disturbed by the white man. It would be prudent to conduct a thorough biological assessment of these springs and the surrounding terrane during the reconnaissance studies.

WIND POWER POTENTIAL OF ALASKA

Wind Power Potential Defined

Wind power potential can be defined in several ways, including the available wind energy (in a meteorological sense), and wind energy that can actually be converted to useful work at a given site. The meteorological wind power potential of Alaska is high. However, due to the high cost of installing windmills versus marketing the exported energy, the economic climate is poor in uninhabitated places like Amchitka and Cape Thompson where near-surface wind speeds are almost ideal for large wind-driven power plants. Alternately, Cold Bay, with its excellent harbor and wind resources, is a promising location for the utilization of wind-derived power.

In Alaska, the availability of wind-derived energy, and the attendant practical wind power potential, will be limited by economics for some time to come. The economics will be influenced greatly by the huge land area, much of it not settled, and the dispersed population outside of the few major cities. In the area of the two largest cities, Anchorage and Fairbanks, fossil fuels and hydro-electric power will be more than competitive with wind. However, an underlying concern in all wind power investigations is that what appears to be economic folly now may be an attractive proposition or even a necessity in the year 2000 (only 24 years away).

The wind energy of the entire atmosphere is really not of interest here. Rather, the central question seems to be what power (or power flux) is available for windmill purposes in the atmospheric layer ranging from the earth's surface to about 1100 meters. Sellers (1966) and

Flohn (1966) separately estimated that the dissipation of energy by the worldwide combination of winds, waves, tides and currents ranges from 250 to 2500×10^{12} watts. We estimate that 1130×10^{12} watts are generated and dissipated in the same layer. On an areal basis, 3.4×10^{12} watts are dissipated over Alaska. These power flux and power estimates are shown in Table 9. Kung (1966a, 1966b) has published extensively on the kinetic energy generation and dissipation of the atmosphere, based on data from about 120 weather stations throughout the entire United States and most of Alaska and Canada. Thus, computed values of the kinetic energy in various atmospheric layers are available for most of North America. Below 1100 meters these power fluxes are (Kung, 1966b) about 2.21 watts/m^2. (In his earlier paper, Kung (1966a) estimated 1.8 watts/m^2.) Additionally, Kung concludes that despite the difference in land and ocean surface roughness, the dissipation rates in the boundary layer are about the same over land masses and the oceans.

Thus, we can assume here that 2.21 watts/m^2 represent the mean worldwide annual power flux for dissipation and generation in the lower boundary layer (defined here as the first 1100 meters of the atmosphere). Our estimate for the world surface area (1.965×10^8 mi^2 or 5.10×10^{14} m^2) of the wind energy in the boundary layer is 1130×10^{12} watts.

We can also conclude that in the Alaskan boundary layer (area = 5.86×10^6, or 0.30% of the earth's total area), the available kinetic energy is 3.4×10^6 megawatts.

If we arbitrarily assume that 1/1000 of the kinetic energy in the first 1100 meters of air above Alaska could be extracted by windmills, then the practical annual mean wind power potential of Alaska is

TABLE 9

FRICTIONAL POWER FLUXES IN THE EARTH-ATMOSPHERE INTERFACE AND ESTIMATES OF POWER OF DISSIPATION POTENTIALLY AVAILABLE FOR WIND POWER.

Author (year, ref.)	Frictional Power flux watts/m^2	World-Wide[+] "Wind Power"* in 10^{12} watts
Flohn (1966, 12)	1-2	510-1020
Sellers (1966, 11)	0.49-4.9**	247-2470**
Hubbert (1972, 6)	various, averaged	370
Kung (1966, 7)	1.8	-
Kung (1966, 8)	2.21	-
von Arx (1974, 13)	-	1
Wentink (this work)	Used 2.21	1130 (3.4 for Alaska)

*In a near-surface boundary layer, about 1100 meters thick, originally wind-driven and eventually dissipated by energy sinks like waves, surface currents, and (in part) convection.

**Computed by Hubbert[9] from Seller's 1-10 langleys/day; 1 ly/day = 0.485 watts/m^2.

[+]Earth total surface area = 1.97×10^8 mi^2 = 5.10×10^{14} m^2.

about 3400 megawatts. This is six times the present electric power generation capability of all Alaskan utilities. Clearly, a renewable resource with a power generation potential of this magnitude warrants closer examination.

Wind Power Calculations

The discussion of wind power involves several wind speed (V, for velocity) quantities. It is important to differentiate these quantities as instantaneous wind speed (V), average or mean wind speed ($\bar{V}$), and rated wind speed (V_R). The latter is the wind speed necessary for maximum power output of a given windmill or wind energy conversion system (WECS). Thus, for example, a particular windmill may have V_R = 32 mph to develop a 6 KW power output. As described later, however, that particular machine will produce an average power ($\bar{P}$) output of only 0.8 KW to about 4 KW, for a range in $\bar{V}$ of 10 to 25 mph. The latter average is only attained in very unusual situations, such as that recorded on Amchitka in January.

Hence, the determination of the average wind velocity ($\bar{V}$) of a site is important. Also, generally, V increases with height, so increasing tower heights are important (recommended 40 to 60 feet for small windmills). In the ($\bar{V}$) tables presented in this report (Tables 10, 11), it is important to note that the height of wind measurement varied from about 13 to 100 feet above ground, and in all cases the station data were acquired for purposes other than the evaluations of wind power.

While the following discussion deals mostly with $\bar{V}$, frequency (duration) data are also important (i.e., the amount of time that various winds reach or exceed V at a given site). For our purposes in this paper the comparison of $\bar{V}$, as measured for Alaskan sites, is adequate.

Meaningful Variables: The average or arithmetic mean wind speed ($\bar{V}$), the variance of the wind speed (V), and the vertical profile of V are the most important variables in the evaluation of a site for wind power generation.

The instantaneous power in kilowatts (P) depends on the windmill disc area (A), and the cube of (V), with a constant (K) for the unit system and the air density. These relations have been treated extensively in most publications on wind power. Thus:

$$P(KW) = K \, A \, V^3 \tag{3}$$

K is about 3.1×10^{-6} for an ideal windmill, and in actual practice, is obtained by multiplying P by the actual efficiency, which usually ranges from 50 to 70%. The mean power $\bar{P}$ does not vary with $\bar{V}^3$ in the same way, but we will show the importance of using $\bar{V}$ to compute $\bar{P}$.

The vertical gradient of horizontal wind speeds is an important design and operating parameter. Data on the gradient are essential in determining optimum tower height in order to optimize energy productivity and to cope with the difference in forces on the turbine blades at the top and bottom of the swing of the rotating blades.

The relationship between the wind velocity (V) at a height above the ground (h) is given by:

$$V_u V_l = (h_u / h_l)^P \tag{4}$$

where u and l refer to the upper and lower heights. Here p can vary from 0 to 1. For estimation, p of 0.15 to 0.30 is useful.

We have examined the wind speed data from other sources such as the National Weather Service, from various heights, and for several stations

in an attempt to establish the vertical gradients of horizontal wind speed (see calculations for Cold Bay, Table 11 in Wentink, 1974). These attempts have failed, for various reasons. Our strong conviction is that further such attempts are not worthwhile, unless simultaneous measurements at various heights are made on the same tower. Long-term mean values of V do not serve the purpose. In the case of Cold Bay, subsequent and extensive simultaneous measurements did indeed reveal a well-defined vertical wind velocity profile.

Alaskan Wind Data

The collection of Alaskan wind data has been a formidable task, as the National Climatological Center (NCC) lists 90 Alaskan land stations for which some wind data are available. There are data from other stations which have not yet been reduced to usable form, such as those from the Arctic Distant Early Warning radar stations (DEW line). Reed (1975) has published wind data for 63 Alaskan sites taken from an NCC computer tape. There are several different climatological provinces in Alaska as defined and separated by extensive mountain ranges. This report emphasizes mainland coastal Alaska, including the Alaskan Peninsula, the Aleutian and other offshore Alaskan islands.

Wentink (1974) covers 10 sites in the Aleutian Islands (west of False Pass and Cold Bay); 4 sites on the Alaska Peninsula; and 3 sites on the northwest coastal mainland. In more detail, these sites are listed on the next page.

Aleutians	Alaska Peninsula	Northwest Coast
Shemya	Cold Bay	Kotzebue
Amchitka	Port Moller	Tin City
Adak	Port Heiden	Cape Lisburne
Atka	King Salmon	
Nikolski		
Fort Glenn (Cape AFB)		
Driftwood Bay		
Dutch Harbor		
Cape Sarichef		
St. Paul Island		

Data from additional locations are also included in this report, including:

"Panhandle" and Gulf of Alaska	West Coast	North Coast	Interior
Annette Island	Cape Newenham	Barrow	McGrath
Juneau	Cape Romanzof	Barter Island	Fairbanks
Yakutat	Bethel		
Cordova	Northeast Cape*		
Middleton Island	Nome		
Kodiak	Koyuk		
	Moses Pt.		
	Cape Thompson		
	Pt. Hope		

*St. Lawrence Island

Most of these locations have considerable potential for wind power installations of various sizes. It is important to remember that none of the wind data from these sites analyzed by us were taken at locations that had been previously selected as possible wind power installations; on the contrary, the anemometer positions had been selected, and often moved, to favor aviation observations. Thus, mean wind speeds given in Tables 10 and 11 probably represent conservative lower limits for estimation of wind energy.

In general, a $\bar{V}$ of 12 mph (10.4 knots) or more at expected propeller heights is desirable for satisfactory windmill performance.

TABLE 10

NEAR-SURFACE YEARLY MEAN WIND SPEEDS AT VARIOUS ALASKAN LOCATIONS

General Area	Station	Yearly Mean Speed* (knots)	Data Period	Anemometer Height (feet)**
Aleutian Islands	Shemya	16.2	1950-72	184-20
	Amchitka	18.3	1943-50	?
	Adak	13.1 (sh)	1942-65	75-15
	Atka	10.9 (sh)	1942-45	?
	Nikolski[a]	14.0	1959-69	30-13
	Ft. Glenn[a]	13.6	1942-48	?
	Driftwood Bay[b]	8.3 (sh)	1959-69	?
	Dutch Harbor[b]	9.6 (sh)	1946-54	33
	Cape Sarichef	13.7	1952-56	?
	St. Paul[c]	16.0	1962-71	42
Alaska Peninsula	Cold Bay	14.9	1956-72	88-21
	Port Moller	8.9 (sh)	1959-59	30-20
	Port Heiden	12.8	1942-67	29
	Ugashik	Under measurement by us		
	King Salmon	9.6	1956-72	38-20
Alaska "Panhandle" and Gulf of Alaska	Annette Island	9.5	1942-70	33-20
	Juneau	7.4 (sh)	1948-70	32-37
	Yakutat	7.0	1941-70	59-20
	Cordova	4.4 (sh)	1946-70	36-20
	Middleton Isl.	11.9	1945-63	30-20
	Kodiak	8.9 (sh)	1941-69	60-16

TABLE 10 (cont'd.)

General Area	Station	Yearly Mean Speed* (knots)	Data Period	Anemometer Height (feet)**
Kuskokwim and Yukon Rivers and Deltas	Cape Newenham	9.8	1953-70	30-13
	Cape Romanzof	11.7	1953-70	15-11
	Bethel	11.2	1958-72	69-20
	McGrath[d]	4.3	1949-73	26
Norton and Kotzebue Sounds, Seward Peninsula	Koyuk	9.5	1944-45	?
	Moses Point	10.6	1945-67	?
	Nome	9.5	1955-73	75-21
	Northeast Cape[e]	11.0	1952-69	30-13
	Tin City	14.9	1953-70	?
	Kotzebue	11.1	1945-70	31
Northwestern and Northern coasts	Cape Thompson	17.4	1960-61	?
	Pt. Hope	10.7	1945-48	?
	Cape Lisburne	10.5	1953-70	13
	Barrow	10.6	1945-68	39-31
	Kaktovik[f]	11.2	1945-70	27-20
Fairbanks (interior)	Fairbanks	4.3		

** Last value is usually the most recent height. Large horizontal shifts may also have occurred.

*(sh): pronounced topographic shielding effects may be involved.

a: Umnak Island
b: Unalaska Island
c: Pribilof Island
d: Interior location
e: St. Lawrence Island
f: Barter Island

Ranking of Wind Power Sites

In Table 11, 67 Alaskan sites have been ranked on the basis of measured mean yearly wind speeds and/or the yearly average potential wind power. These stations are representative of more than 100 Alaskan sites. The means are taken from data acquired during our literature survey, and the wind power figures are from the excellent compilation by Reed (1975). Readers who refer to this table should realize that:

1. None of the data involve optimization of wind instrument location for wind power surveys.
2. No attempt has been made to correct for the changes in anemometer location (vertically or horizontally) over extended observation periods.
3. Close agreement should not be expected when average powers derived from our $\bar{V}$ are compared to Reed's watts/m^2, because:
   a. In some cases the recording periods for the two sets of data are different; and
   b. Reed's power fluxes are means for long time periods derived by averaging monthly power fluxes (Reed, 1975).
4. The wind power fluxes are high in terms of what can be extracted by presently available windmills. The theoretical Betz (1966) extraction limit of 59.3% for unshrouded windmills is not included, and neither are the normal mechanical and electrical efficiencies taken into account. Also, the cut-in speed and the power limiting at higher velocities (25 knots or 12.9 m/s), as planned for present windmill design, are not included.

Nevertheless, simple conversions may be applied to Reed's results in order to estimate the actual power obtained from a particular windmill at a specific location. For example, the "Elektro WVG-50G" 6KW machine (disc area 19.9m^2) gives a factor f=0.59 (Betz limit x 10^{-3}KW/w x 19.9m^2 = 1.17 x 10^{-2}/w). An empirical factor K (0.39) seems to express the machine versus wind speed characteristics when coupled with the speed duration curves. It may be considered a composite "shape factor"; it includes variables such as cut-in speed, practical efficiencies, and calms. Then, for this particular windmill, fk = 4.5 x 10^3 KW-m^2/w. As shown in Table 12, fk, when multiplied by Reed's values, leads to useful estimates of the yearly mean power which compare well in most cases with our results, derived from computed power productivity curves.

TABLE 11

RANKING OF ALASKAN WIND POWER SITES

RANK	[1]Average yearly wind velocity ($\bar{V}$)	$\bar{V}$ yearly, meters/ sec.	Site	[2]Wind Power watts/m^2	Remarks
1	18.3	9.41	Amchitka Is.	1025	Uninhabited
2	17.4	8.95	Cape Thompson		Uninhabited
3	16.2	8.33	Shemya Is.	633	Restricted area
4	14.9	7.66	Cold Bay	574	Prime test site
5	14.9	7.66	Tin City	549	
6	16.0	8.23	St. Paul Is.	547	
7	13.7	7.05	Cape Sarichef (Unimak Is.)		
8	13.6	7.00	Cape AFB (Umnak Is.)	498	
9	14.0	7.20	Nikolski (Umnak Is.)	482	
10	12.8	6.58	Port Heiden	430	
11	13.1	6.74	Adak Is.	405	
12	11.7	6.02	Cape Romanzof	381	
13	11.9	6.12	Middleton Is.	377	
14	11.3	5.81	Attu Is.	369	Site probably shielded; V low should rank near #3.
15	11.2	5.76	Kaktovik (Barter Is.)	341	
16	11.0	5.66	Northeast Cape (St. Lawrence Is.)	329	
17	10.9	5.61	Atka Is.		$\bar{V}$ probably lower limit
18	10.7	5.50	Point Hope		

TABLE 11 (cont'd.)

RANK	[1]Average yearly wind velocity ($\bar{V}$)	$\bar{V}$ yearly, meters/sec.	Site	[2]Wind Power watts/m^2	Remarks
19	10.5	5.40	Cape Lisburne	315	
20	11.1	5.71	Kotzebue	292	
21	11.4	5.86	Unalakleet	265	
22	9.8	5.04	Cape Newenhar	242	
23	10.6	5.45	Mos.s Point	241	
24	NA*	-	Golovin	241	
25	9.6	4.9	Dutch Harbor (Unalaska Is.)	233	Shielded instrument site (?)
26	9.5	4.9	Nome	218	
27	8.1	4.2	Big Delta	216	
28	9.5	4.9	Koyuk		
29	9.5	4.9	Annette Is.	199	
30	10.6	5.45	Point Barrow	193	
31	9.6	4.9	King Salmon	191	
32	8.9	4.6	Kodiak	189	
33	8.9	4.6	Port Mollor	172	
34	11.2	5.7o	Bethel	172	
35	NA*	-	Flat	172	
36	7.9	4.1	Haines	147	
37	8.3	4.3	Driftwood Bay (Unalaska Is.)		
38	NA*	-	Craig	129	
39	7.4	3.8	Juneau	116	
40	7.0	3.6	Yakutat	115	

* = Not yet available.

TABLE 11 (cont'd.)

RANK	[1]Average yearly wind velocity ($\bar{V}$)	$\bar{V}$ yearly, meters/ sec.	Site	[2]Wind Power watts/m^2	Remarks
41	5.7	2.9	Gulkana	81	
42	NA*	-	Ruby	79	
43	6.0	3.1	Umiat	76	
44	6.6	3.4	Kenai	75	
45	5 6	2.9	Tanana	73	
46	5.4	2.8	Indian Mtn.	70	
47	5.6	2.9	Fort Yukon	65	
48	4.7	2.4	Sparrevohn	64	
49	NA*	-	Manley Ht. Spngs.	63	
50			Anchorage (Int. Apt.)	61	
51	6.4	3.3	Galena	59	
52	NA*	-	Ketchikan	58	
53	NA*	-	Kaltag	57	
54	6.6	3.4	Valdez	53	
55	5.8	3.0	Bettles	49	
56	5.6	2.9	Homer		
57	5.0	2.6	Nenana	42	
58	4.6	2.4	Anchorage (Merrill Field)	38	
59	4.4	2.3	Cordova (Mile 13 Apt.)	37	Shielded instrument site (?)
60	5.7	2.9	Anchorage (Elmendorf AFB)	36	

* = Not yet available.

TABLE 11 (cont'd.)

RANK	[1]Average yearly wind velocity ($\bar{V}$)	$\bar{V}$ yearly, meters/ sec.	Site	[2]Wind Power watts/m^2	Remarks
61	6.6	3.4	Sitka	33	
62	7.9	7.9	Petersburg	33	
63	4.3	2.2	Tatalina	31	
64	4.2	2.2	Northway	29	
65	4.3	2.2	McGrath	28	
66	4.3	2.2	Fairbanks (Int. Apt.)	27	
67	3.8	2.0	Wiseman	24	

Notes:

(1) Taken from Wentink (1976).

(2) As taken from Reed (1975); these values are the averages of the 12 mean monthly wind powers calculated from unsmoothed duration curves.

TABLE 12

YEARLY MEAN POWER* FOR SPECIFIC ALASKAN SITES AND WIND MACHINE "X"

Site	Annual average wind velocity (V) mph	Annual average wind velocity $(\bar{V})$, m/s	watts/m^2 (Reed)	Mean Power $(\bar{P})$ in KW Reed x fk (1)	Mean Power $(\bar{P})$ in KW Wentink (2)
Amchitka Island	21.1	9.43	1025	4.7	3.27
Cold Bay	17.4	7.78	574	2.64	2.70
St. Paul Island	17.1	7.64	548	2.52	2.59
Umnak Island	15.6	6.97	498	2.29	2.25
Middleton Island	13.7	6.12	377	1.73	1.79
Cape Romanzof	13.4	5.99	381	1.76	1.90
Kotzebue	13.2	5.90	292	1.34	1.63
Cape Lisburne	12.1	5.41	315	1.45	1.62

*Not optimum power, which also depends on site selection and machine height.

(1) $f = 1.17 \times 10^{-2}$ KW m^2/w; $k = 0.39$ (empirical).

(2) From machine power vs windpseed characteristics and actual mean yearly speed duration curve.

Present State of Technology

As of March 1976 the actual availability of "WECS" is in a state of flux. Foreign windmills that can be ordered "off the shelf" are rated at 2.5 to 6 KW, but delivery to the U.S. and Alaska is often delayed and erratic. U.S. production is almost nil, although many tens of thousands of 3 KW units were sold during the period 1930-1955. In the late 1976-early 1977 period, U.S. manufactured units in the 6 to 15 KW range are expected to appear on the market. Many small companies are developing prototypes, but development and production have been somewhat retarded by lack of an assured market. Paradoxically, however, the market is not developing rapidly due to the lack of field tested, cost acceptable windmills.

Table 13 lists some small windmills that are possibly available to the consumer, and which may be of specific interest to individuals or small, remote communities. Most of these have not been tested in Alaska.

Table 13 does not include the large (100 KW or greater) WECS that are under development by the Energy Research and Development Administration (ERDA) and the National Aeronautics and Space Administration (NASA). We believe that in Alaska a complex of several small units is preferable to one large machine (i.e., four 25 KW WECS instead of one 100 KW WECS). Windmill farms offer redundancy, reduced erection and maintenance problems due to lower tower heights and the technical advantage of proved WECS in the lower power output range.

TABLE 13

Some Small (0.2-15 KW) Windmills Currently or Potentially Available

Manufacturer	Model	Propeller Disc Diameter, ft. (Note 2)	P_{max}, KW (Note 3)	V_R, mph (Note 3)	Voltage Output (Note 4)	Approximate Cost, $(1976) (Note 5)	Remarks (Note 1)
Grumman Aerospace Corp.	Windstream 25	25 (3b, vp, dw, nt)	15	26	115	20,000 (?)	Available mid-1976 (?) Prototype in test.
Zephyer Wind Dynamo Co.	Zephyer	17 (3b, fp, dw, nt)	7.5 (to 15)	22 (30)	250	3,500	Prototype in test; limited production pending.
Elektro GmbH (Swiss)	Various; data for WVG-500	16.5 (3b, vp, wt)	6.1	32	115	6,500	In production; long history.
Aerowatt (French)	Various; data for largest.	3[illegible]1 (2b, vp, wt)	4.1	17	220	23,000 (?)	Limited production; excels in low V regimes.
Jacobs Wind Electric Co.	Various (pre-1955)	14 (3b, vp, wt)	1.5 (to 3.0)	18	32 or 110	2,500 to 5,000	Prices for reconditioned machines; long history of excellent performance. (Note 6)
Quirks (Australian)	Various	13 (3b, vp, wt)	2.5 (3.0)	25 (30)	24 to 110	3,000 (?)	Rated at 2KW continuous Long history of proven performance. In production.
Sencenbaugh Wind Electric	750-14	12 (3b, fp, wt)	0.8	20	14	1,400 (kit, 1050)	In production.
Windcharger	1222H	6 (2b, fp, wt)	0.2	23	14	450	Long production history; cost includes stub tower.

Notes:

1. Inclusion in this list, or omission from it, does not imply any recommendation. A question mark means only our uncertainty of lack of current information. All information is to the best of our knowledge, mostly from vendor literature or private communications.

2. b = number of blades; vp = variable pitch; fp = fixed pitch; dw = downwind pusher type; nt = no tail boom; wt = with tail boom.

3. Power output P_{max} achieved at wind speed V_R; limiting by various means then occurs; at some larger V controlled shut-down usually occurs.

4. Nominal voltage or generator of alternator; larger voltages (within design limits) are often encountered.

5. f.o.b. manufacturer or dealer locations and without tower.

6. Jacobs may announce new models in 1976 or 1977; for reconditioned units inquire elsewhere.

The Use of Mean Wind Speeds

The instantaneous power output (P) of a given wind turbine (treated elsewhere) depends on the cube of the wind speed:

$$P(KW) = K \, A \, V^3$$

where with (V) in mph and the area (A) in ft^2, (P) is in KW. However, as pointed out previously, the cube of the average (mean) wind speed of a site is appreciably different from the mean of the cubes of various wind speeds, i.e.,

$$\bar{V} = \frac{i}{n} \sum_i V_i$$

where n is the number of V_i data and

$$\bar{V}^3 \neq \sum_i V_i^3 \text{ and } c\,\bar{V}^3 \approx \sum_i V_i^3$$

For instance, a Lockheed study (1975) shows that c of the last equality is about 1.73 (for a 3 km height above ground). Of course, this c factor will be different for near-surface winds, and 1.73 also is not directly applicable to the problem of wind turbines having a threshold cut-in speed above zero and probable power limiting at some specified velocity. In most any case $\bar{V}^3$ is an approximate and usually pessimistic lower limit in estimating the absolute power of a WECS in a given $\bar{V}$ regime. However, $\bar{V}$ is still a very useful parameter, (Wentink, 1976).

Evaluation of Available WECS Units

The output of a given windmill can be predicted for a given location, if one has the necessary wind data for that location, even though only average wind speeds are known. In the latter case, synthesized

(calculated, wind duration curves can be used instead of measured field wind duration curves (Wentink, 1976). This approach is useful, in that economic analyses and predictions can be made, including estimated costs of wind-derived electricity and resultant savings in fossil fuel consumption for various WECS and locations.

Grumman WS25 Prototype: We co led the manufacturer's preliminary power (P) versus wind speed duration cves, using synthetic V duration curves computed from our "Planck" distribution function (Wentink, 1976). These calculations gave curves of P versus time. The integral of each curve gives the energy produced during the period of wind measurement that yielded the duration curv .

The average energy $\overline{E}$ (and $\overline{P}$) are a linear function of $\overline{V}$ up to about 22 mph; above the 22 mph limit, the energy productivity starts to decline since the WS 25 limits quite abruptly at 26 mph (V_R). Where $\overline{V}$ is 12 or 17 mph, the $\overline{P}$ would be 2.3 or 5.8 KW, respectively, for 15 KW-rated WECS.

The Elektro WVG50: The evaluation included the same analytical procedures, with the application of measured V duration curves and two different models for synthetic (artificial) V duration curves. Also, preliminary results based on hand and desk computer calculations, used for the previous section (the WS25), were extended by IBM 360 machine computations.

As shown in Table 14 and Figure 16, it appears that very reasonable values for the average monthly and annual power from a given windmill, in this case the 6 KW Elektro, can be estimated from reliable knowledge of the $\bar{V}$ encountered at the hub of the windmill propeller. The agreement of the analytical data with the field data is remarkably good, lending support to our contention that a long-term measured $\bar{V}$ can be used to predict, for WECS, $\bar{P}$ in the absence of long-term V frequency (i.e., velocity duration) data.

The considerable time spent on the Elektro 6 KW windmill and calculations does not imply any endorsement of this machine or the manufacturer; it merely reflects the fact this machine was used in the Ugashik tests. (The Elektro 6 KW is the highest power rated windmill presently in production.) Other machines may be more desirable, especially for Alaskan use.

The Aerowatt 4.1 KW: We considered in a preliminary way the French Aerowatt Model 4100FP7, rated at 4.1 KW output at V = 16 mph. It has a claimed superiority at low wind speeds, mostly due to large (30.7 feet diameter) light blades. However, it is apparently very rugged, with a claimed survival wind speed of 115 knots (132 mph).

The power characteristic shown in Figure 17 was deduced from Aerowatt sales literature. An empirical $\bar{P}$ vs $\bar{V}$ curve from the fit to 46 field points, as described for the Elektro unit, is given in Figure 18.

The computed values are higher than Aerowatt claims, given as points on Figure 18, but they are still in good agreement. While the productivity at low $\bar{V}$ is indeed excellent (39% of maximum at $\bar{V}$ = 16 mph), the high cost ($23,000) is discouraging. The Elektro 6 KW seems to be as productive as the Aerowatt 4.1 KW at $\bar{V}$ = 21 mph, but of course few locales have a $\bar{V}$ of 21 mph. To date, we know of only one

TABLE 14

MEAN POWER FROM ELEKTRO WVC50 (6 KW rated) WINDMILL, USING MEASURED AND SYNTHETIC (F3) SPEED DURATION CURVES (Six Alaskan Locations)

$\overline{V}$,kts	$\overline{V}$,mph	Site, Month (Note 1)	$\overline{P}$,KW (q-meas) (Note 2)	$\overline{P}$,KW (calc) (Note 3)	Δ,% (Note 4).
22.9	26.4	A, Jan.	4.07	4.07	0
21.9	25.2	A, Dec.	3.98	3.92	1.5
21.1	24.3	A, Feb.	3.78	3.80	0.5
20.7	23.8	A, Mar.	3.84	3.73	3.4
19.4	22.3	A, Nov.	3.57	3.49	2.2
18.9	21.8	A, Oct.	3.46	3.41	1.4
18.7	21.5	A, Apr.	3.48	3.36	3.6
18.3	21.1	A, Annual	3.27	3.28	0.3
17.8	20.5	SP, Feb.	3.38	3.19	5.6
17.4	20.0	SP, Dec.	3.28	3.09	5.8
17.0	19.6	SP, Jan.	3.19	3.02	5.3
16.6	19.1	SP, Nov.	3.06	2.92	4.6
16.5	19.0	SP, Oct.	3.05	2.90	4.9
16.4	18.9	A, May	2.98	2.88	3.6
16.4	18.9	A, Sept.	2.85	2.88	1.1
16.3	18.8	SP, Mar.	2.96	2.86	3.4
15.1	17.4	CB, Annual (1a)	2.71	2.58	4.8
15.1	17.4	CB, Annual (1a)	2.70	2.58	4.4
15.1	17.4	SP, Apr.	2.65	2.58	2.6
15.0	17.3	M, Dec.	2.58	2.56	0.8
14.9	17.1	SP, Annual	2.59	2.51	3.1
14.8	17.0	M, Jan.	2.58	2.49	2.7
14.7	16.9	M, Nov.	2.49	2.47	0.8
14.6	16.8	A, Aug.	2.53	2.45	3.2
14.1	16.2	A, June	2.36	2.32	1.7
14.1	16.2	A, July	2.34	2.32	0.9
13.5	15.5	SP, Sept.	2.23	2.16	3.1
13.4	15.4	M, Oct.	2.15	2.13	0.9
13.4	15.4	SP, May	2.19	2.13	2.7
12.4	14.3	SP, Aug.	1.87	1.87	0

TABLE 14 (Cont'd.)

$\bar{V}$,kts	$\bar{V}$,mph	Site Month (Note 1)	$\bar{P}$, KW (q-meas) (Note 2)	$\bar{P}$, KW (calc) (Note 3)	Δ,% (Note 4)
11.9	13.7	M, Annual	1.79	1.72	3.9
11.8	13.6	B, Nov.	1.70	1.70	0
11.8	13.6	B, Oct.	1.69	1.70	0.6
11.5	13.2	K, Aug.	1.62	1.60	1.2
11.4	13.1	K, Oct.	1.62	1.57	3.1
11.4	13.1	SP, June	1.53	1.57	2.6
11.3	13.0	K, Sept.	1.57	1.55	1.3
11.1	12.8	K, July	1.49	1.50	0.7
10.7	12.3	SP, July	1.34	1.37	2.2
10.6	12.2	M, Sept.	1.38	1.34	2.9
10.5	12.1	B, May	1.26	1.31	4.0
10.4	12.0	K, June	1.32	1.29	2.3
10.0	11.5	B, Apr.	1.19	1.15	3.4
9.9	11.4	B, Dec.	1.22	1.13	7.4
9.3	10.7	K, May	1.10	0.93	15.5
7.7	8.9	M, July	0.68	0.40	41.1
				Mean (all points)	3.7
				Mean (omit last 2 points)	2.6

Notes:

1. A = Amchitka Isl., B = Barrow, CB = Cold Bay, K = Kotzebue, M = Middleton Isl., SP = St. Paul Isl.; 1a = separate 5-year periods at CB.

2. q. meas. or q.m. = quasi-measured; from measured wind data and manufacturer's power vs. wind speed curve.

3. From Weibull Function (k=2) and manufacturer's power curve.

4. $\Delta = 100\ (\bar{P}_{qm} - \bar{P}_{syn.})/\bar{P}_{qm.}$

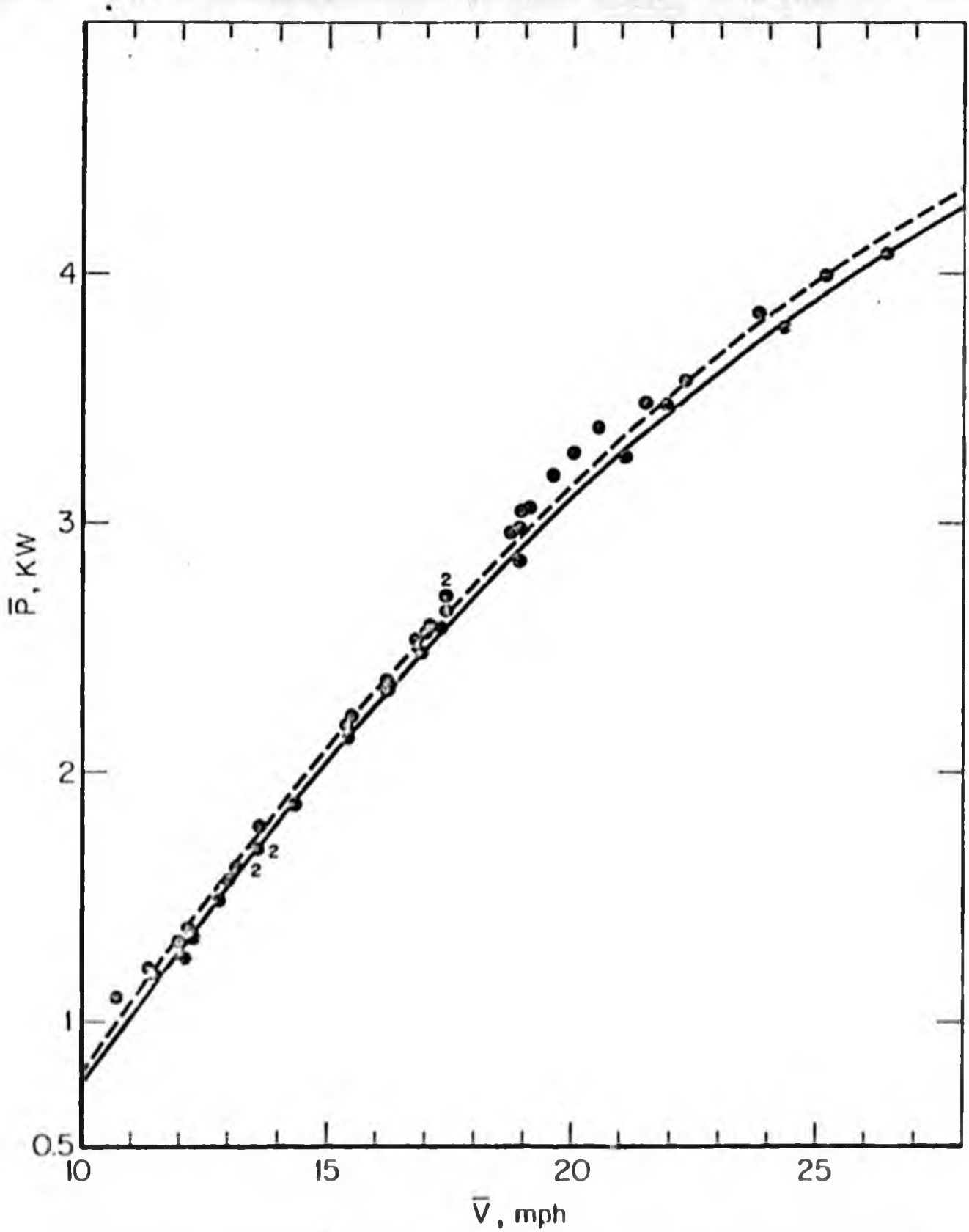

Figure 16: Mean power from an Electro WVG50 (6 KW at 33 mph) Windmill for measured and analytically-predicted duration curves. (Points from measured winds; dashed curve best fit to them. The 2 on graph means duplicate points. Solid curve is quadratic polynomial calculated from F3.)

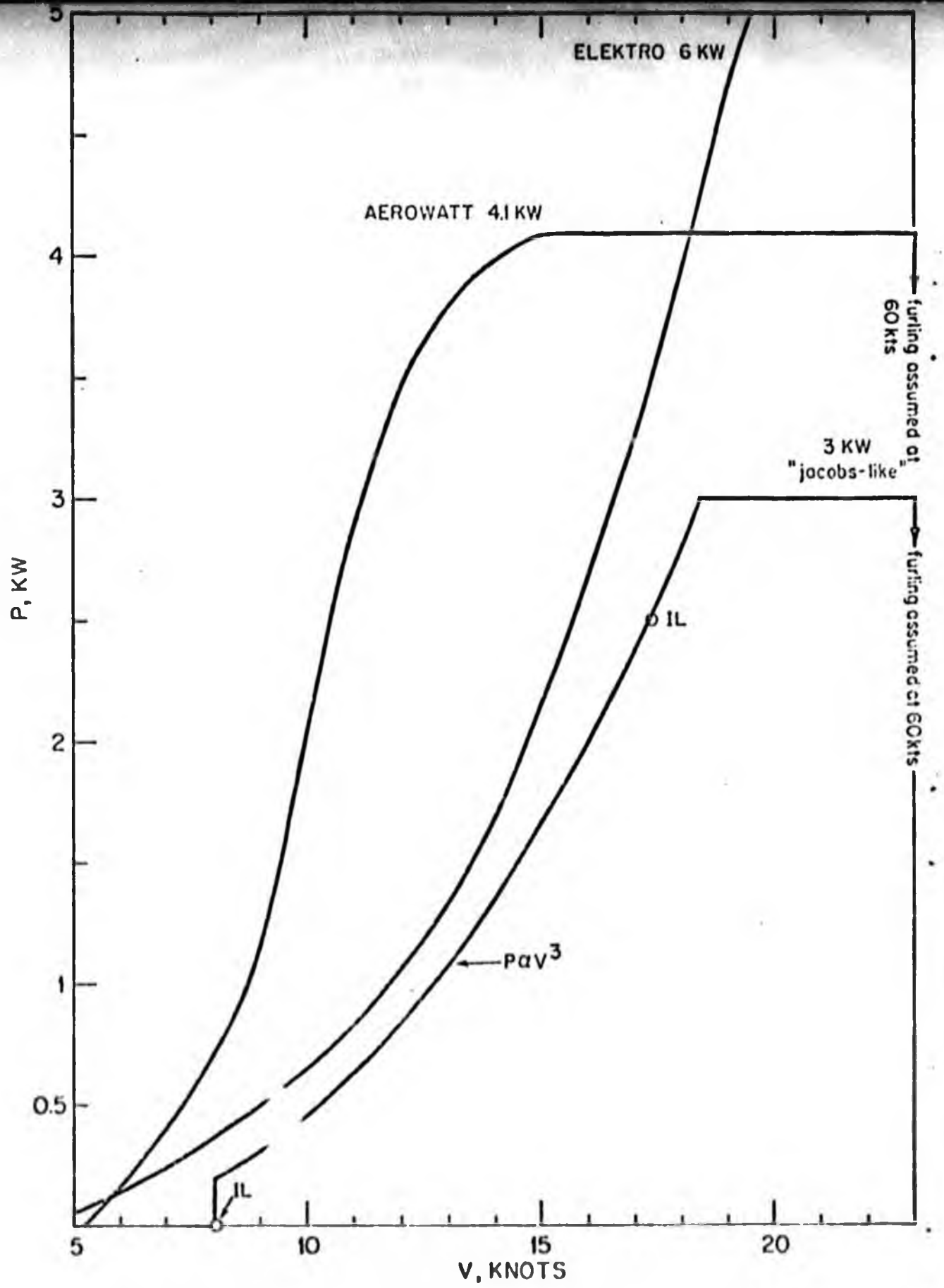

Figure 17: Power characteristics for Aerowatt 4.1 KW, Elektro 6 KW, and Jacobs-like 3 KW windmills.

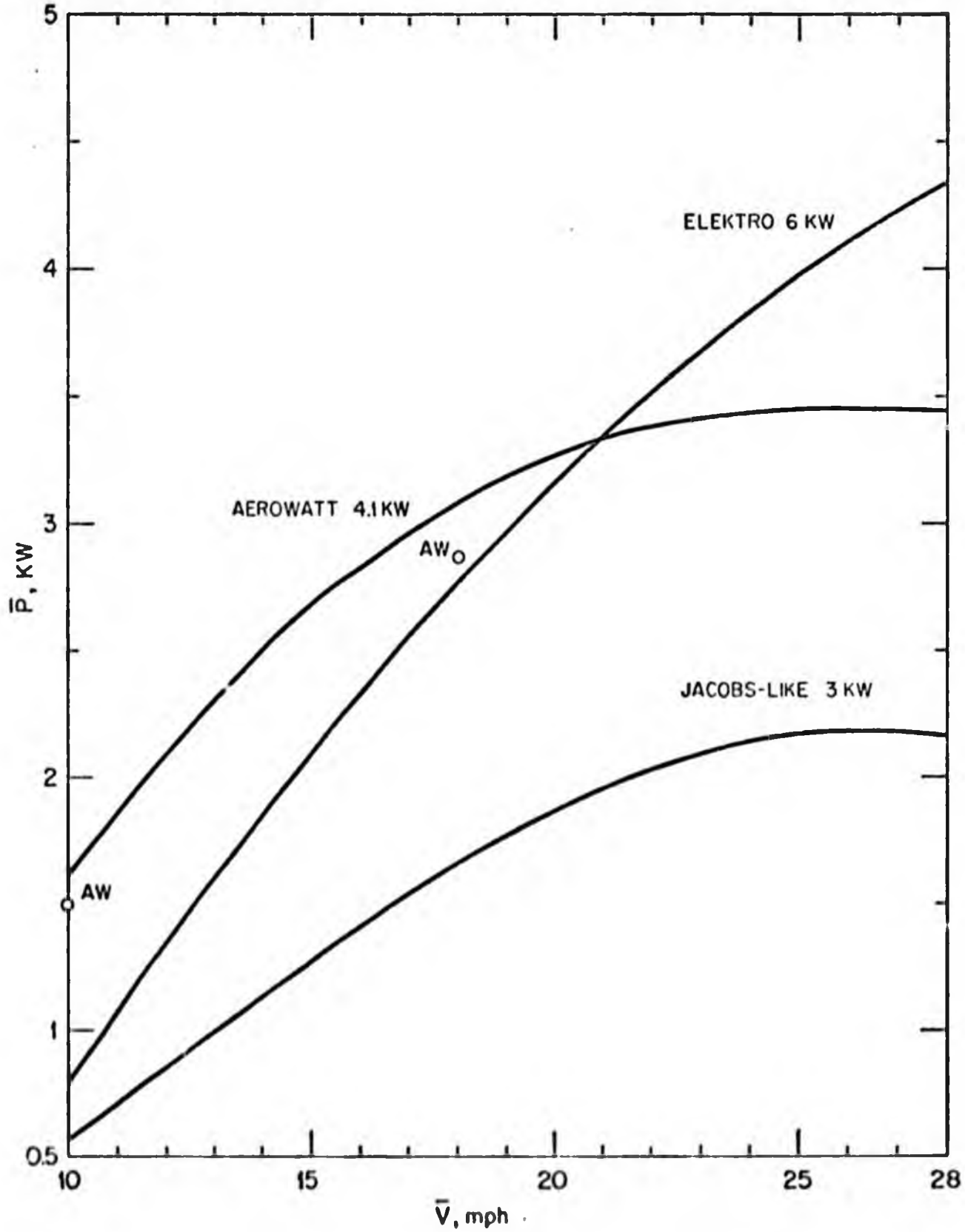

Figure 18: Average power vs. average wind speed for three small windmills in Alaskan wind regimes. (All from best fit to polynomials, each based on 46 long-term duration curves. Points marked AW from Aerowatt literature.)

Aerowatt 4.1 KW machine in use, in Norway; and we have no details.

A Jacobs-like 3 KW WECS. The Jacobs 1 to 10 KW machines (thousands of units) have a long history of very successful operation, with high reliability and energy yields. Our studies and Jacob's substantiated claims (1974) indicate that these machines are probably the most successful electricity-producing small windmills ever produced in quantity. It is regrettable that the 1930-1957 units are no longer manufactured, and are only available as rebuilt items. Jacobs may produce newer designs and hardware in late 1976 (6 to 10 KW?).

Jacobs, to the best of our knowledge, never published a formal power characteristic curve. We deduced such a curve from Frenkiel's (1964) Iliat data. We call our characteristic, shown in Figure 17, the Jacobs-like 3 KW; and of course M. Jacobs is not responsible for any of the conclusions drawn from our curves.

The $\bar{P}$ vs $\bar{V}$ curve for the Jacobs-like 3 KW plant is also given in Figure 18. This is based on 46 measured duration curves. This is not in good agreement with Frenkiel's result, for one or more unexplained reasons. However, his machine power characteristic may have been appreciably different than our necessary estimate, especially at low $\bar{V}$ (10-12 mph). He also intentionally limited the maximum power to 2.5 KW. Furthermore, he computed his expression from $\bar{V}$ data spanning only the 10 to 16 mph range.

The reader can draw his own conclusions. A major hindrance in comparisons, for example, between a Jacobs-like 3 KW and an Elektro 6 KW ($\bar{P}$ same at $\bar{V}$ = 15 to 20 mph), is the absence of present cost data for any vintage Jacobs units, or for comparable newly-produced windmills.

Energy Productivity and the Height Effect

Assume an Elektro 6 KW windmill installed at Ugashik on a 40 ft tower. Take $\bar{V}$ there as 12 knots (13.8 mph), from the better known long-term $\bar{V}$ values (and varying quite smoothly along the Alaska Peninsula) at King Salmon (9.9 knots), Port Heiden (12.9 knots) and Cold Bay (15.1 knots). The airline distances from Ugashik to those places are, respectively, 80, 60 and 263 statute miles.

We then estimated the energy power and energy productivity at 40 feet, the oil-savings equivalent, and also the effects of variation in tower height between 30 and 100 feet (see Table 15). A major assumption was that only one-half of the energy yield of the windmill was useable. This assumption is based on our knowledge of Alaskan bush energy habits and wind patterns, and the experience of other workers. For instance, the wind-derived voltage might often be less than the battery bank voltage, or the batteries might be fully charged, with no load to use the wind energy. Also, considerable energy might be lost due to windmill shut-down (for safety) during sustained gales.

There are other assumptions, which may be questionable for the long term, including such things as 1975 prices for typical towers and constant oil costs of 75¢/gal at Ugashik. Nevertheless, it appears that tower heights in the 40 to 60 feet are most cost-effective. In this range the yearly oil-equivalent of the useful energy is 20 to 24 drums (53 gal, not 42 gal drums), with an energy cost savings of $800 to $940/year. The improvement in average power, relative to that at 40 feet, is 18% at 60 feet and 26% at 70 feet. However, the accompanying savings in oil and costs at these heights are not great. Thus, the cost of tall towers appears to off-set the increased energy yield obtained, as others have noted. Hence, for the Ugashik area, we would question the worth of tower heights above 60 feet.

TABLE 15

ESTIMATED ENERGY PRODUCTIVITY (10 years) OF AN ELEKTRO 6 KW WINDMILL AT UGASHIK, ALASKA, FOR VARIOUS HEIGHTS WITH SOME RELATED COSTS

height/ft	$\bar{V}$,mph (N-1,4)	$\bar{P}$,KW (N-2)	10 year $\bar{E} \times 10^5$ kwh (N-2)	$\bar{E}/2$ = Drums of Oil (N-3)	10 year $\Delta\bar{E} \times 10^4$ kwh (N-4)	Oil Equiv. Savings in $ (N-5)	Tower Cost $ (N-6)	h increase Savings (or drums) (N-4)
30	1.29	1.58	1.384	176	-1.93	6996	990 (645)	-724 (-18d)
40	13.8	1.80	1.577	201	0	7990	1260 (800)	0
50	14.5	1.98	1.734	221	1.57	8785	1560 (1000)	495 (12d)
60	15.1	2.12	1.857	237	280	9421	1935 (1250)	756 (19d)
70	15.7	2.26	1.980	253	4.03	10057	2470 (1600)	857 (22d)
100	17.0	2.54	2.225	284	6.48	11289	?	-

Notes:

N1. For mean p = 0.23 in V vs h relation; equations (3).

N2. From Figure 16, before battery bank.

N3. Assumes 1/2 of windmill productivity is usable, and alternate energy source generator yields 7.4 kwh/gal; then 10^5 kwh =255 drums oil.

N4. With reference to h = 40 ft value.

N5. As for N-3, with constant 10 year cost of 75c/gal or $39.75/drum, delivered (questionable long term assumption).

N6. Delivered at Ugashik, including cost of footings, with no provisions for labor or interest; (price fob Seattle).

Engineering Design Factors

Power Coefficient and Efficiency: The power coefficient C_p, as we use it, is the ratio of the actual windmill power output to the power in the wind. The efficiency of an actual single disc windmill, as we define it, is the power output of the actual mill relative to an idealized windmill. The latter is limited, through the Betz (1966) formulation, to the extraction of 59.3% of the power of the wind.

Cut-in Speeds and Calms: The energy (power x time) productivity versus the costs determine the utility of a windmill system. Important factors include the starting or cut-in wind speed, the wind speed required to reach rated power, and of course, the mechanical integrity. The time of power generation is as important as the power rating. While our wind survey results reveal many desirable locations for windmills in Alaska, design innovations should be directed toward decreasing the wind speed necessary for attaining the rated power of the generator, compatible with mechanical integrity. In our opinion, emphasis should be placed on blade design, reliable speed controls, reduction of the generator power overrating, and the cost and weight of the generator. The French Aerowatt windmill (full rating reached at 17 mph for their 4 KW machine) and the NASA/Lewis-Plum Brook projected 100 KW windmill (full rating at 18 mph) show considerable promise in this respect.

Productivity Curves: Productivity is best estimated by combining the machine power versus wind speed curve with the wind velocity duration curve. In this way, one can generate productivity curves like those in Figures 18 and 19.

One aspect of curves such as those shown in Figure 19 is that wind machine output characteristic curves are almost always given

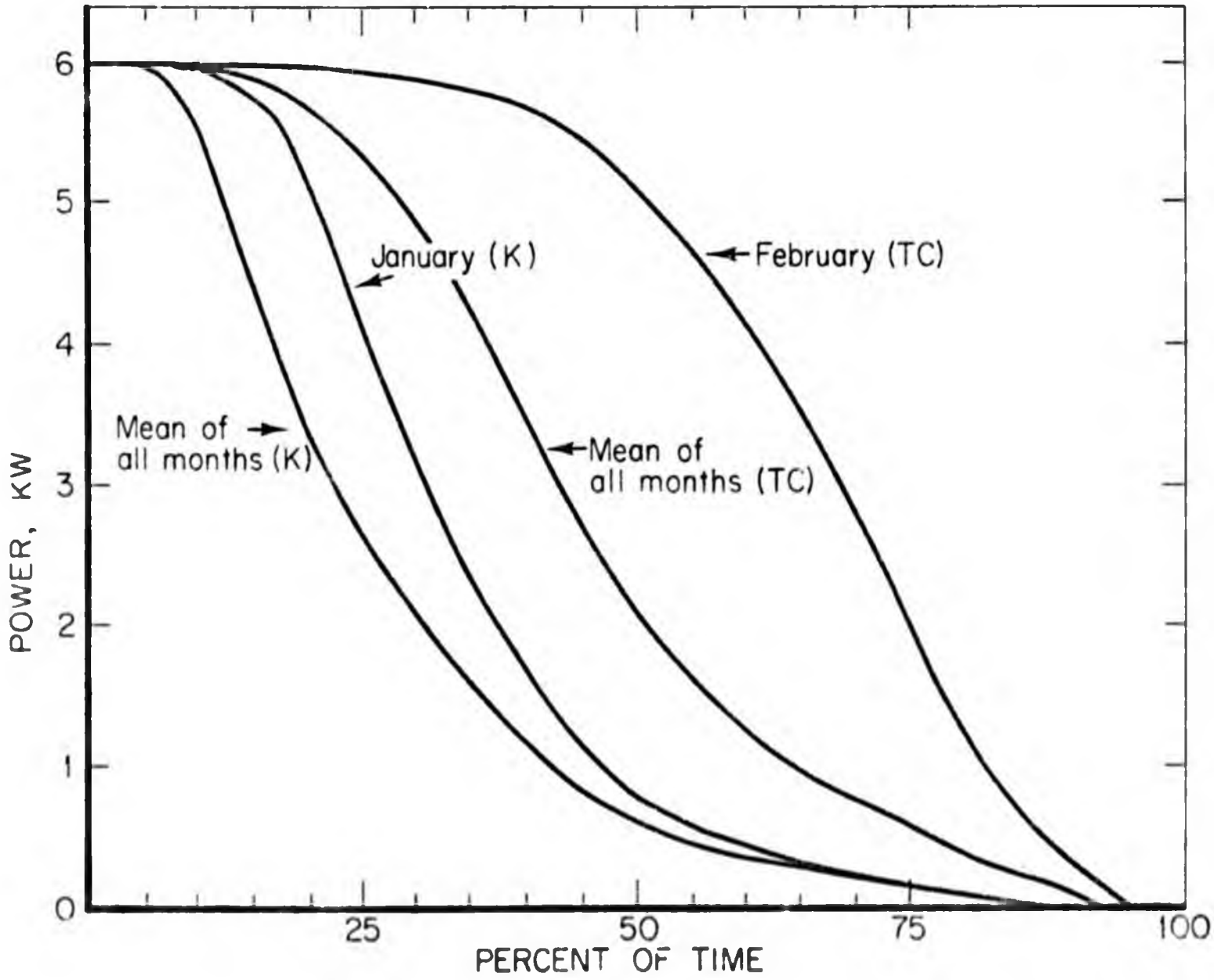

Figure 19: Monthly Power Productivity at Kotzebue (K) and Tin City (TC), Alaska, from a 6 KW Rated Windmill (areas under the curves give the energy produced each month or year).

in terms of power, not voltage, output. In the absence of such published voltage versus wind speed curves, it can be concluded that for resistive loads the voltage quickly drops below acceptable levels for lighting and other loads requiring voltage regulation, as wind speed drops. Furthermore, as in the case of wind-charged battery banks, the generator output is insufficient for battery charging, unless elaborate switching is used. In such cases, a considerable part of the total energy is available only if diverted to low-level energy reservoirs, such as hot water tanks.

Icing Problems and Blade Coating: The icing problem relates to tower integrity, blade strength (survival), and possible mechanical damage to the generator assembly through vibration. Putnam's (1948) experience with the large wind machine on Grandpa's Knob (Vermont) seemed to indicate that the best de-icing technique was to run (cautiously) the windmill during icing conditions, as blade flexure usually shed the ice. Putnam said:

> "Although ice several inches thick was observed on the stationary structure several times, the maximum thickness observed on the rotating stainless-steel turbine blades was about 1/2 inch thick on the leading edge. As this skin of ice began to peel off, the unit would begin to run rough and was usually shut down for this reason."

Experience suggests that major icing problems are also caused by the unequal thawing of blades that accumulated ice during shut-down periods. A start-up under these conditions results in excessive vibration which can destroy the main bearings very quickly.

Some information has been gained from interviews with users or observers of windmills in Alaska. At Barrow, for example, icing problems

were not encountered, and the most serious operational problem was charge limiting, and destructive overcharging of the batteries. In the Alaskan interior (Livengood), packed snow behind the blades acted as a brake, but blade icing was negligible.

Location, of course, is important. Australian mills were said to have iced up in tests in Australian mountains, but they encountered little trouble in Antarctica. It is said that Swiss mills used in the Alps do not ice up.

Usually blade protection from normal weather is obtained from paints, such as urethane. The French Aerowatt Company offers fluorocarbon coatings as a protection against heavy icing. We had also advocated this approach to the problem, but later indicated that teflon coatings are most probably not worthwhile (Wentink, 1976).

DC Versus AC Rural Systems and Inverters

We recognize that modern windmill systems are often engineered to yield controlled frequency AC over large power and wind speed ranges. However, in view of our experience in rural Alaska, it appears that DC outputs may still have a considerable role, especially where the wind-derived power is generated close to the user. DC is advantageous because:

(a) DC-AC inverters are expensive, and increase the capital investment in wind-powered systems by 30 to 70%.

(b) Incardescent lights, motors, heaters (for water, fish smoking, etc.) work well on DC.

(c) DC motors offer some advantages over AC motors, such as increased tolerance to changing line voltage, in variable

speed control, and in starting characteristics. Also, there are numerous inexpensive DC motors on the surplus market, especially in the 28 volt DC range.

(d) Batteries, when used in an energy reservoir, can supply large short-term loads, which are usually well beyond the safe surge capability time of many inverters.

Inverters used with battery bank storage in small WECS should include refinements, such as those available in the Soleq and modified Topaz units. The efficiency is often good (80 to 90%) at higher loads, but poor under light loads or on idle. For instance, 3-KW rated inverters often have a no-applied-load power consumption of about 200 watts (5 KWh/day). This can be significant during long calms. However, a load sensor, such as that in the Soleq unit, switches off the main inverter circuit on the DC side when there is no AC load; and power drain of the load sensor is negligible. Voltage controls to protect the battery bank and the inverter at low and high DC levels are also available and should be installed.

WECS Foundation Requirements

The foundation footings for towers need special attention in Alaska, due to break-up (thawing) and solifluction conditions. Tower vibration can also be a problem, in addition to high mechanical loads experienced during icing conditions or gales.

Environmental Impact

Currently, we do not foresee any major environmental problems associated with the use of wind power plants. However, there are two

potential problem areas that should be checked, involving the movements of migratory birds and possible disturbances in navigational radio aids.

Possible Bird Kills: The possibility of large bird kills by windmills during annual migrations should be further evaluated. However, shutdowns during these rather brief and predictable migration periods could be utilized for maintenance and repair, and this possibility does not appear to be a serious problem, with proper checks and planning.

Communications Interference: The reflection and diversion of radio waves from navigational aids by windmills could be troublesome near airports, runway approaches and repeater stations. All-metal blades, such as those on the Grumman Windstream 25 propeller (25 ft or 7.6 m disc diameter, 2 ft or 61 cm blade chord), could be potent reflectors and modulators and/or erroneous redirectors of navigational signals in critical locations. Even the wooden blades of the Elektro 6 KW (16.5 ft or 5 m disc, 6 in or 15 cm chord), if coated with metallic paint could be sources of reradiation. This effect would be accentuated by oscillations of the windmill in response to variation in wind direction.

Generator noise could also be a problem. All of these effects need further evaluation.

Weather Modification: Although the question of detrimental weather modification by large windmill farms has been raised repeatedly, the effects do not seem to be of serious concern.

Even though we were to install five 1 megawatt-rated mills per square mile at Cold Bay, where wind conditions limit the power extraction to about 3 megawatts/mile^2, both atmospheric horizontal mixing and

energy replenishment from the upper layers should quickly smooth out any energy unbalance. Also, of course, there is no particular need to crowd the machines in most areas that are candidates for windmill farms.

Mechanical Risk and Liability: A propeller fragment in free flight could cause serious damage. The Smith-Putnam windmill threw a 65-foot, 8-ton metal blade 750 feet, which landed in one piece on its tip (Putnam, 1948). When our Ugashik windmill was destroyed in 1975, the 8-foot wood blades were completely fragmented before they struck the ground. There was no wooden debris at the tower base, and fragments were found over a radius of 1/4 mile. No property or personal damage occurred in these cases, but the implications are obvious.

Wind Versus Fossil Fuel-Generated Power

Wentink (1976) has recently published a cost analysis of a small windpower installation at Ugashik, Alaska, including a 6 KW maximum rated windmill with controls, tower, small battery bank (25 KWh capacity at 50% discharge limit), and a 4 KW DC-AC inverter yielding 60 cycle/115V AC. Today, this plant could be delivered to Ugashik at a cost of approximately $10,000. Assuming free labor, and no interest payments, the installation cost would be about $1,670/KW.

These costs may seem excessive when first compared with the $450/KW installed capacity of large fossil or nuclear utility plants, and the target of $500/installed KW for projected new and larger windmills. If these costs are compared to those of diesel fuel-generated kilowatts in rural Alaska, however, wind power-generated electricity may be competitive over longer production periods.

Economic viability of a WECS is based on the energy cost in $/KWh, not the installed power cost in $/KW. If we apply the AVEC system-wide factor of 7.4 KWh/gal of fuel to Ugashik (where there is no central utility), and consider the present cost of fuel delivered to Ugashik (70¢/gal), the fuel production cost of electricity would be 9.5¢/KWh. The actual sale price by AVEC (elsewhere) is currently 22¢ to 12¢/KWh (Table 16).

If we derate the windmill system further because of wind conditions, so that the average system productivity is only 2 KW, power output would be 1460 KWh/month or 17520 KWh/year. Corresponding costs for electricity

TABLE 16

(Spring 1975)

RECENT RATES FOR ELECTRICAL ENERGY IN ALASKA

Location	Monthly use KWh range	Residential cost, ¢/KWh	
Boston Area (September '74)	First 15	12.9	$1.94 monthly min.
	Next 35	5.6	
	Next 50	3.5	
	Next 150	3.2	
	Next 200	2.9	
	Next 500	1.5	
Fairbanks (GVEA, 1975)[a]	First 150	8.0	$10 monthly min.
	Next 550	3.9	(Rates out of city
	Next 800	2.2	slightly higher)
	Over 1500	1.9	
Nome (1974)	Flat Rate	15.	
Kotzebue (1974)	First 50	21.5	
	Next 50	12.5	
	Next 400	11.0	
	Over 500	10.5	
AVEC[b] (same for all 47 villages 1974)	First 75	20.[c]	$15 monthly min.
	Next 225	15.	
	Next 700	12.	
	Over 1000	9.	
Bethel (1975)	First 50	12.	$5 monthly min.
	Next 200	10.	
	Over 250	7.5	
Cold Bay (1975)	First 50	11.5	$10 monthly min.
	Next 650	9.5	
	Over 700	7.5	

a: Golden Valley Electric Association

b: Alaska Village Electric Cooperative

c: For 1975 a 2 to 3¢ /KWh fuel surcharge is in effect. Surcharges are also present in most of the other rates.

derived from oil would be $139/month or $1664/year (at 9.5¢/KWh). Using actual AVEC customer prices to purchase 1460 KWh/month, we estimate consumer costs of $204/month and $2449/year.

So, for users presently using electricity at only 9.5¢/KWh, the small windmill system would establish a ratio of $9864/$1664/year, which would require 5.9 years to pay off through fuel oil savings. However, a typical "AVEC customer" could anticipate an earlier payoff in only 4.0 years.

We cannot assume that the cost of fuel oil in rural Alaska will remain at 70¢/gal (recall our earlier comments on current village fuel costs up to $2.15/gal). The control of domestic crude oil prices will make wind power even more attractive. The actual savings from the use of wind power will depend on variations in wind conditions and logistics. Although the initial cost of wind power plants will remain higher than those for diesel power plants for the foreseeable future, the soaring costs of fuel oil will permit rapid (4 to 6 years) payback of capital costs of wind plants through savings on fossil fuel costs alone.

Industrial Applications

One possible use of large scale wind power could be the production of electricity for processing other chemically-reactive materials or the production of reactive materials (e.g., compressors or hydrogen, respectively). Thus, wind could either drive pumps to transport hydrogen, or release hydrogen from water.

Ammonia Production: Consider one of the present methods for ammonia (NH_3) production. Purified natural gas (CH_4) is reacted with steam in

a catalytic reformer to eventually yield carbon monoxide (CO) and H_2. The overall reaction (some steps omitted) is:

$$CH_4 + H_2O \rightarrow CO + 3H_2.$$

Further processing, requiring compressors and other energy using steps, produces the reaction:

$$3H_2 + N_2 \rightarrow 2NH_3.$$

For WECS applications we would propose using H_2 from water and N_2 from the air.

The economics of scale dictate that modern NH_3 plants must operate at output levels above 600 tons NH_3/day; many plants actually produce above 1000 tons/day. We think that the case for smaller fertilizer plants (100 tons/day or less) should be re-examined, when the user is nearby and when wind and water are used rat er than natural gas.

A 1 MW rated (installed capacity) WECS in a suitable wind regime (50% power productivity) could generate enough hydrogen to produce 1.7 tons of NH_3/day. Thus, an ammonia plant of 100 tons/day capability (admittedly a small plant) would require a windmill complex of at least 59 MW for the necessary H_2 production. The capital cost (without interest, etc.) at $500/installed KW would be about $30,000,000, which is the same order of magnitude as the cost of a large modern transport aircraft.

At $100/ton or NH_3 and 300 days/year of plant operation, more than 10 years of production would be required to return the capital investment of the WECS. At present, this is economically unattractive. However, there are several other factors that need to be considered:

(1) the plant lifetime, (2) the need for fertilizer, (3) the price the market will bear in 1980-90, (4) the availability of natural gas and (5) the cost of gas if available. Also, the cost of the reformer in present NH_3 plants which use natural gas is large, and these troublesome units are often plagued with excessive down time. These reformers break down the natural gas (CH_4) to yield CO and H_2 and also consume significant gas to heat the reformer chambers and to produce steam. We have no firm information on the initial and maintenance costs for reformers, but we estimate that reformers may account for nearly 30% of total plant costs.

The long-term cost of natural gas is not clear. For estimating purposes, we note that the cost of CH_4 for a 100 ton/day NH_3 plant at $1/Mcf would be near $3,200/day (at ideal conversion), or $948,000 for a 300-day op rating year. Hence, replacing natural gas with water as a raw material would amount to a savings of about a million dollars each year which could be applied to the amortization of WECS costs.

Urea and Methanol Production: The production of urea and methanol require a carbon source, such as coal. Consider the Alaska Peninsula region, where coal and wind power are available, and where ice-free harbors exist. This coal could be combined locally with electrolytic hydrogen and then ammonia to yield urea (H_2NCONH_2) or methanol (CH_3OH), which are readily shippable chemicals.

In the case of methanol, there are two possible routes that deserve consideration. The first route would be to power the plant machinery with windmills, to produce so-called process gas ($CO+H_2$) from the reaction:

$$C + H_2O \rightarrow CO + H_2.$$

In further reaction, to produce:

$$2\ CO + 2\ H_2 \rightarrow CH_3OH + CO.$$

In this case there would be excess CO which could be burned later (perhaps yielding undesirable side products other than methanol). An alternate route would be to react the process gas with a stoichiometric amount of H_2 from wind-powered electrolysis units, as in the properly-catalyzed reaction:

$$CO + H_2 \rightarrow CH_3OH$$

Mining: The Alaskan mining industry is expected to grow during the next decade. The Lost River (Seward Peninsula) fluorite-tungsten-tin mine shows promise for future development, and the Seward Peninsula may also contain economically-important copper deposits. Tin City is already known for its wind potential. (The long-term yearly average wind speed at Tin City is 17.1 mph.)

Wind power could be exploited by the mining industry in several ways, including power (lighting, machine power, the generation of compressed air -- an attractive energy storage device), possible ore reduction with electrolytic hydrogen, and metal refining by electroplating. Windmills delivered to remote sites by helicopter might be economic at interior localities in the early phases of exploration development.

Agriculture

Alaska has relatively little agriculture due to high costs, late planting dates, low soil temperatures, and early frost, even though much of Alaska is blessed with long days during the summer growing season.

We do not think wind-derived electricity is best used for soil warming on a large scale. However, there seems to be real merit in