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TRANSPORT AND STORAGE OF ENERGY

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Abstract

An overall view of the situation is given of energy transportation and storage today, with some historical trends and an attempt to project them into the future.

The importance of the properties of the fuel or energy form in determining the properties of the distribution system are analyzed.

Since what is consumed is not energy but negentropy, the possibility of transporting it, dissociated from energy in a technically acceptable system, is briefly described as a means for overcoming the problem of thermal pollution at the usage point.

Introduction

The subject of transport and storage of energy is a very broad one, and only a brief outline can be given within the confines of this paper. I will try to do that by looking at the problem with a physicist's eye.

Transportation and storage can be visualized as devices for adding spacial and temporal flexibility to the use of energy--impedance matching, so to speak.

Bacteria feeding on decaying leaves, e.g., cannot transport or store the energy they are feeding on, so their life cycle is quite rigorously bounded, in time and space, by the condition of amount and distribution of their food.

Superior animals and plants have already made a great leap forward by developing storage means, in form of starch, fats and waxes which happen to be quite efficient storage media. Starch has about 4000 kcal/kg, fat and waxes more than 9000 kcal/kg.

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Accumulation of starch gives plants quite a large degree of flexibility. Apart from the daily cycle of the sun, i.e. food input, e.g. biannual plants can spend a year accumulating energy, and during the next concentrate on the great show for efficient reproduction. More important, starch constitutes the energy dowry for the seeds to start a new machinery and a new life.

In the case of animals transportation is done the other way round. As for storage, fat is very efficient in weight and volume, and without unduly reducing mobility, permits overcoming the seasonal cycle and extending the habitat of many species to regions where e.g. the hardness of winter would make their survival impossible.

This biological image has many point of contact with the structure our society has developed to manipulate energy. The pile of logs near the country house keeps the house going the year round in spite of the cyclic and dislocated accumulation of energy in the nearby woods and the vagaries of weather. The fuel in the jet plane crossing the Atlantic strongly resembles, in chemistry and distribution, the fat of a bear crossing Greenland to its winter quarters.

In Table 1 a list of the more important energy forms is given, with the most common transportation and storage modes. As can be seen from the second column, chemical free energy is by far the most important form, and the chemical products most used are very near those used in the biosphere. In evolutionary terms society has advanced very little with respect to biological systems.

In the secondary energies, however, things start to move. Electricity is widely used in animals to carry signals, but very little for power (except sometimes to kill). Negentropy in a pure state, i.e. dissociated from energy, as in concentrated vs. diluted solutions, is again used extensively by living organisms for chemical engineering purposes, but very little for transferring or storing energy. Also here, a considerable potential exists for designing original systems for the special needs which are developing for our society. I shall come to this later.

I should say that in one respect at least the energy system of living organisms is far superior to that of our society: at the final utilization level, i.e. at the level of the enzymes which perform energetic operations in the cell, energy appears always in the same form, in all the biosphere. The universal energy carrier is adenositriphosphate which is transformed into adenosindiphosphate liberating 9 kcal/mole of free energy.

A few years ago, I proposed a system which will finally lead to a similar situation. It is based on hydrogen as the sole energy carrier. All primary energies may be finally transformed into it, so that the increasingly complex machinery at the business end of the system will become decoupled from the specific characteristics of the input. As the scientific-technical community has already accepted the concept and is actively working on it, it is probable that evolution may be on the move also in this direction.

Transportation and the General Characteristics of the Energy Systems

Energy systems are strongly characterized by energy transportation and storage modes.

Two points need stressing for a better understanding of the internal mechanisms of their operation and evolution: economy of scale and learning curves. Economy of scale means the larger the operation the lower the unit cost. Over broad ranges equations of the type

$$C = aS^b \quad C = \text{cost} \quad S = \text{size} \quad a,b \text{ constants}$$

describe quite faithfully the relation between the cost and scale of a plant or an operation.

If we look at the evolution of the coefficient in time, we will see that it tends to decrease (for C in constant money) essentially because of the evolution of technology. $a(t)$ can be defined as the technological learning function.

The effect of scale is properly conveyed by b. Just to give an idea of the situation, e.g. for chemical plants b is of the order of 2/3. This is a very powerful incentive to go big. An order of magnitude increase in the scale of the operation means a reduction in unit costs of 50% (similar equations can be used for investment costs and for manufacturing costs).

For the nuclear island of a power station e.g., $b \simeq 0.5$ (for light water reactors). In this case an order of magnitude in scale brings a saving of around 70% in unit costs.

For a pipeline the transportation costs go approximately as the inverse of the pipe diameter and the amount transported approximately with the cube, so again $b \simeq 2/3$.

For supertankers $b \simeq 0.7$, and the same for an electrical power station, and so on. The narrow range of the values for b is simply astonishing in view of the great variety of techniques.

As to the maximum level of S, the scale of the operation, technologists tend to think the problem is essentially a technological one, i.e. that they hold the key to progress. There is some truth in that, in the sense that above a certain size b moves rapidly to 1 (see e.g. gas transportation costs by pipeline, Figure 1), but that certain size keeps increasing in time. A more precise analysis of causes and effects shows, however, that market demand defines the task for the technologist (who most of the time is able to comply).

A topical case is that of electric generators (and associated primary movers). The optimization of a certain net requires the power of the single generator to be not larger than 10% of that of the net. This figure emerges from the constraints on the externally imposed availability of the net, the expected availability of the single generator and the necessary standby to match the two. The optimization is done in economic terms, balancing the economies of scale with the diseconomies of larger standbys.

Now the power of a net depends on the spacial intensity of the utilization and on its extension (that can be measured by the mean distance at which electric energy is transported). The intensity grows roughly with the consumption of electricity (doubling every 10 years for most developed countries). The extension depends on the development of power lines and roughly doubles every 25 years. Combining the two factors one gets a doubling of the power of a net every 7 years.

Now it happens that since Edison's time the size of the generators, taking for each year the largest one installed, has increased by five orders of magnitude with a doubling time of about seven years. This observation is very important because it shows at work the driving forces, and the constraints that the distribution system applies to the generating system which appears to be very strongly conditioned by them.

One of the consequences of this conditioning is that if the progress in electric energy consumption and transportation keeps the pace it had in the last hundred years, the size of the nuclear reactors that the system will demand will keep doubling every seven years, i.e. faster than the consumption of electricity. This means that the number of nuclear (fission or fusion) reactors devoted to the production of electricity will first rapidly grow, to saturate the market, then will slowly decrease. The same thing has happened for the conventional generators in the past. This means also that if new energy vectors are introduced with transportability larger or smaller than that of electricity, then the generators' size will tend to become larger or smaller accordingly.

The two possible examples, if we remain in the field of the nuclear reactors, are hot water and hydrogen. In the first case a reasonable mean range for economic transportation and distribution is 10 km (Figure 2), in the second it is 1000 km, as can be drawn from the statistics for natural gas, which has very similar transportation costs. The mean range for electricity is about 100 km, and it is interesting to note how this correlates with the relative portion of nuclear power stations and population centers, e.g. in Western Germany (Figure 3). This means that the optimum size of generators will tend to be, in equilibrium, about 1% of that for the electric system in case of the energy being distributed as hot water, 100 times that of the electric system if the energy is distributed as hydrogen.

For the sake of simplicity we have obviously assumed that the intensity of the market is the same in the three cases, a hypothesis that is actually true to within a factor of perhaps two or three.

As a kind of historical curiosity, I have shown in Figure 4 an ingenious system to transport mechanical energy. It was built by Heinrich Moser in Schaffhausen in 1866 and transported about 500 kW of mechanical energy using steel cables. The construction is elegant and efficient but ... the mean transportation distance is about 100 meters. One could have predicted little potential for market expansion, as proved to be case.

The impact of the transportability of the secondary energy vector on the scale, and consequently on the economy of the generator, is in fact dramatic. This is probably the main reason why all projects of hot water distribution are conceived as appendages to an electric generating unit which can by itself guarantee a minimum scale.

On the Historical Trends

Now let us take one step back and analyze, with the insight gained from the analysis of the previous "case history", the structure of the transportation system for the classical fuels: wood, coal, oil and gas.

Wood (for fuel) is handled today much as it was ten thousand years ago: chopped essentially by hand and carried by cart and logged in bundles. New technologies providing economies of scale were never developed. This may well be the main reason for the penetration of coal. The question of availability of the primary resource does not seem really relevant; it certainly was not at the time the substitution took place, a century ago, and even today proper management of forestry could provide all the energy necessary for our society [1]. One may say that the best forests are in strange and scarcely accessible places, the steaming tropics or the frozen Arctic. But the same is true for oil and gas.

Coal did beat wood, presumably gaining from the weakness of the wood business. The difference by a factor of two in energy density does not appear really decisive. Industrial management and ad hoc technology that rapidly developed at the coal mine and in the transportation system appear more credible causes.

A similar situation seems to have developed between oil and coal. Certainly the cause of the success of oil was not the exhaustion of coal resources; nor was it really a change in the structure of demand. As oil has widely demonstrated, demand requirements can be finely matched by proper processing. My interpretation is that the pipeline, the tanker, and all the economies of scale that a system operating on fluids can achieve, played a central role in the substitution.

Figure 5 visually supports this hypothesis. It depicts a coal sea terminal. The tiny dots are 30,000 large coal wagons. An oil terminal is not worth a picture, it is just a thin bunch of pipes.

Figure 6 shows the evolution of the scale of oil transportation technology on the sea with that of the oil market. The correlation is striking, and shows again the very strong control of the market forces over technological achievements. But I know technologists are not ready to think of themselves as the tail wagging the dog, and I will go into this point in more detail.

Oil, however, has a weak point. The final distribution, from the refinery to the consumer, is still done "by hand". A vast fleet of trucks and an incredible number of gas stations bear witness to that. Not much economy of scale is to be expected there, but just increasing costs and confusion.

Natural gas is largely superior on that point. An inconspicuous and efficient net of underground pipes provides an ideal system for the economies of scale to be reaped, with a minimum of disturbance to the rest of the infrastructure. Natural gas is somewhat weaker in long distance transportation overland, as the gas pipeline is not so economical as the oil pipeline. This did not, however, prevent the development of nets over large chunks of continents. It is certainly much weaker in transportation over the sea. Only recently have LNG tankers become a commercial reality. This has so far prevented natural gas from becoming a world commodity with a world net, as oil has done thanks to the supertanker.

But time works to change the situation. We spoke before of economies of scale and technological learning. When we look synthetically at the evolution of a certain technology, the two are best combined in a "learning curve" where the cost of a certain operation (in constant money) is plotted (log-log) versus the integrated amount of the commodity produced or manipulated. Figures 7, 8, and 9 give three interesting examples for production of fuels and energy manipulations. The straight lines of the trends indicate that a constant reduction in price occurs every time the total amount of the commodity manipulated e.g. doubles. This puts a premium on newcomers having a short history behind them and presumably a fast rate of growth, so that the doubling of totals comes up at the faster rate, and a marginal price advantage that may have started the game may rapidly become a very consistent one that makes the penetration of the old market by the new product a matter of time. This seems to be the case with the Liquid Natural Gas Tanker, a triumph of macrocryogenics, which is undergoing a fast development toward streamlined technology and large sizes.

What seems to be still lagging, in the sense of new technology "called in" by market demand, is the very large pipeline. The largest pipelines now have diameters ranging in the 1.5 meter region. They can carry gas economically over distances of the order of 2000-3000 km. Assuming we can extend the economy of scale rule, e.g. to pipelines of 10 m Ø, their economical range would reach ≈ 15,000 km, i.e. they could cover whole continents (e.g. Eurasia) with a single net.

The potential of the gas fields in Siberia and the Middle East, and the size of the markets in Europe, Japan and the U.S., make such development very likely. The Russians in fact are moving in that direction by stretching current technology to pipelines of 2.5 meters Ø, and are busy debugging the system. A new technological concept might be necessary, however, for a real jump ahead.

As the energy for the next century will most probably be of nuclear origin, it will not be unwise to tie the nuclear system to the winning horse. In that sense, the concept of the hydrogen economy, where nuclear heat is used to produce secondary energy carriers, electricity and hydrogen--but mainly hydrogen--appears perfectly fit, as it can use the transportation (and storage) technology of natural gas.

On the System Properties of Storage

So far the question of energy storage has been touched only occasionally. The main purpose of storage is to improve the utilization of the generation, transportation and transformation systems.

In a typical case where storage does not exist, that of electricity, the effects of this absence are apparent (Figure 10). The utilization factor of the electric system is in the order of 50%. This means that all this complex and expensive equipment that constitutes an electric utility simply sits idle 50% of the time. With energy systems becoming increasingly capital intensive, the evolutionary advantage of systems with storage capability will be very great indeed.

For wood and coal the usual storage is in form of a heap. It may seem simple and cheap but it is not. With humanity consuming a few km^3 of coal, these heaps take a lot of space and the coal is quite rapidly oxidized by bacteria. Furthermore the interface with the transportation system is clumsy.

For oil the almost universal form of storage is a metallic tank; this at all the hierarchical levels of storage, down to the tank in the car or in the house. All this tankage turns out to be very expensive, from perhaps 50$/ton for very large tanks at the port to perhaps 300$/ton for the family tank. As most tankage is used predominantly on a seasonal basis it adds substantially to the cost of energy.

Gas again has an ace to play. Exhausted gas fields, or underground porous structures such as aquifers, can provide large space at very low unit cost for storing it. Figures 11 and 12 show how this is done and Figure 13 shows the trends in use of this technique for the U.S. Figure 14 shows the potential for Western Germany in the form of identified structures suitable for that purpose.

The gas system very naturally provides the hierarchy of storages. The piping itself, with variations in pressure, may have a time constant of hours, the local aquifer of a day, the large one of weeks, and the great gas fields used as storages, of months and years. On top of that, everything is done underground with a minimum of physical and visual interference with the world we live in.

As Professor Häfele [2] and the author [3] have pointed out, this vision of the properties and trends of the energy system has led to the conception of the energy island, in a sense a synthetic substitute for the oil field. Transportation of liquid hydrogen with supertankers, and with large pipelines on land, in fact gives the system a world dimension. This will push to the technological limits the economies of scale. Actually normal system optimization will presumably lead to 10-20 islands to serve all the world. The unit for the energy manipulated in one of these islands will then be the Tw, almost three orders of magnitude above the present level of nuclear technology. I hope the colleagues in fusion, who have to prepare themselves for the market structure of the year 2020, will keep that in mind.

The great attraction of this concept comes from its position at the convergence points of various trends and developments. It will comply with the economic requirements through the economies of scale and via the development of LNG tankers and very large pipelines fostered by the gas industry.

It will comply with the diffuse and intense desire to see the nuclear system decoupled from the socio-system. The energy islands will be real islands in the ocean, and all the manipulation of radioactive materials will be done in the island, or even in the reactor building itself. In a cargo-cult vision the socio-system will see only tankers carrying fuel from nowhere.

It will comply with the ecological matching of the energy system, first by a choice of the island minimizing the climatic effects of heat release, second by producing a fuel which is almost 100% non-polluting at the transportation, distribution and consumption stages.

And What's Next?

As this paper deals mainly with system structure and trends, an obvious question is trying to guess what is going to come next. One may think that humanity will be happy for ever with the perfectly clean eco-mate, hydrogen so ending the scramble for life of the various energy vectors, and again reducing the system to the golden simplicity of the wood age. But hydrogen, alas, also has its Achilles heel. Like all other fuels used at present, it provides negentropy at the expense of the manipulation of a certain amount of heat. This heat will finally appear as an irreducible waste to be thrown into the ecosphere.

As man's activity tends to concentration--and the trend is toward more and more concentration [4]--the phenomena linked to what is called the "heat island" that are already plaguing many of our cities will assume unbearable proportions (Figures 15, 16, and 17). My colleagues in city planning asked me whether something could be done, and here is my proposal.

That what we consume is negentropy and not heat is obvious to all of us, although it may not come to mind first. (Fuels after all are paid on the base of their enthalpy and not of their free energy.) So I asked myself whether negentropy could not be transported, dissociated from heat.

The answer is yes, and the mechanism is very simple. When a gas is compressed isothermally, only its negentropy is modified, and is actually increased. Expanding it isothermally we then get work at the expense of ambient heat. When this work finally degrades into heat, the thermal balance of the local system is again zero. The machines are running, but no waste heat at the point where energy is used!

A conceptually straightforward implementation of that principle would be to have:

- An air compression system located where waste heat can be properly disposed of, e.g. on the ocean shore;
- A high pressure pipeline;
- A set of total energy centers, dispersed throughout the city where electricity, hot and cold fluids and air conditioning are produced, using compressed air to run the necessary machinery.

Simple calculations show that the negentropy density in the compressed air is somewhat too low to make the system really appealing, so I compromised a little on the purity of the concept, taking liquid air as negentropy carrier. Liquid air can actually be regarded as a handy compressed gas. It carries some frigories too, but that is an advantage from the point of view of the user as it allows the burning of a certain amount of fuel without releasing heat to the ecosystem.

Liquid air carries the equivalent of .2 kWh/liter (Figure 18), and, taking into account the potentially high quality of compressed air engines and total energy systems, it turns out that the amount of liquid air consumed per person could be more or less the same as the amount of water, a few hundred liters per day. Such a system has the essential function of centralizing waste heat, and may thus be looked on by ecologists with a slightly sour grin. So I overdid it to make them happy too.

My colleagues working at developing ocean thermal gradient power plants are doing a most thorough job, and I meant to take advantage of it in the following way: if you use the ocean thermal gradient to run an ammonia engine to compress a gas, what you finally do is to transfer, as negentropy into the compressed gas, the entropy of mixing waters of different temperatures. The thermal balance is zero.

If the compressed gas (or my negotiated compromise, liquid air) is carried on shore, and used to run the city, all thermal balances will be zero: no heat anywhere!

The system would in practice consist of floating stations, churning the ocean and producing liquid air, carried by tankers and pipelines to the final consumer: the local total energy system. Atmosphere will close the loop (Figures 19, 20, and 21).

I describe this system to show on the one hand that the evolutionary potential of energy systems may not yet be exhausted, on the other how market demand may unpredictably call for the deployment of systems inhomogeneous with present trends.

It is interesting to observe that what such system does in fact is to disorganize the ocean by altering the natural shape of the thermocline; the negentropy, i.e. information extracted, is then carried to the city and used to organize it. All energy systems work that way, but in this case the informational character of the operation appears in the purest form.

Conclusion

The attention of the public in general and of technologists in particular has been focused mainly on the problem of energy resources. What we have tried to show is that the logistics of the energy carrier, whether the primary fuel itself or not, plays a very central role in determining the evolutionary trends in the utilization of primary resources, in contrast to the current intuition that if a resource is there, it will be used.

The analysis of secular trends show transportation of energy in form of gaseous fuel as the most probable mode for the next century; developers of new energy sources should keep that well in mind.

Looking further into the future, a hint is given about a technology permitting transportation of (fairly) pure negentropy, in a sense dissociating energy use from heat release. Demand for such a technology may develop as a consequence of specially increased intensity in energy use, leading to troubles at the interface with the ecosystem.

Table 1.

	Form of Energy	Physical Nature	Mode of Transportation	Mode of Distribution	Mode of Storage	% Energy Budget (World 1970)
PRIMARY	Wood	Chemical Free energy	Bundle Cart Truck	Truck	Log heap	15% (with farm waste)
	Coal & Lignite	Chemical Free energy	Unit train Ship Slurry line	Truck	Heap	28%
	Oil	Chemical Free energy	Pipeline Tanker	Truck	Metallic tank	38%
	Gas	Chemical Free energy	Pipeline Cryotanker	Pipeline	Porous structures Cryotanks	17%
	Radiation	Electromag.	Space propag.	-	(High Q reson.)	-
	Mechanical	Mech.	Wires Ropes Bars		Flywheels	1%
	Heat	Thermod.				1%
	Negentropy	Thermod.	Cryotanker Pipeline	Pipeline	Hole in ground	-
Secondary	Oil products	Chem.		Truck	Metallic tank	35%
	Electricity	Electromag.		Wire	-	10% at consumer level
	Misc. chemicals	Chem.				

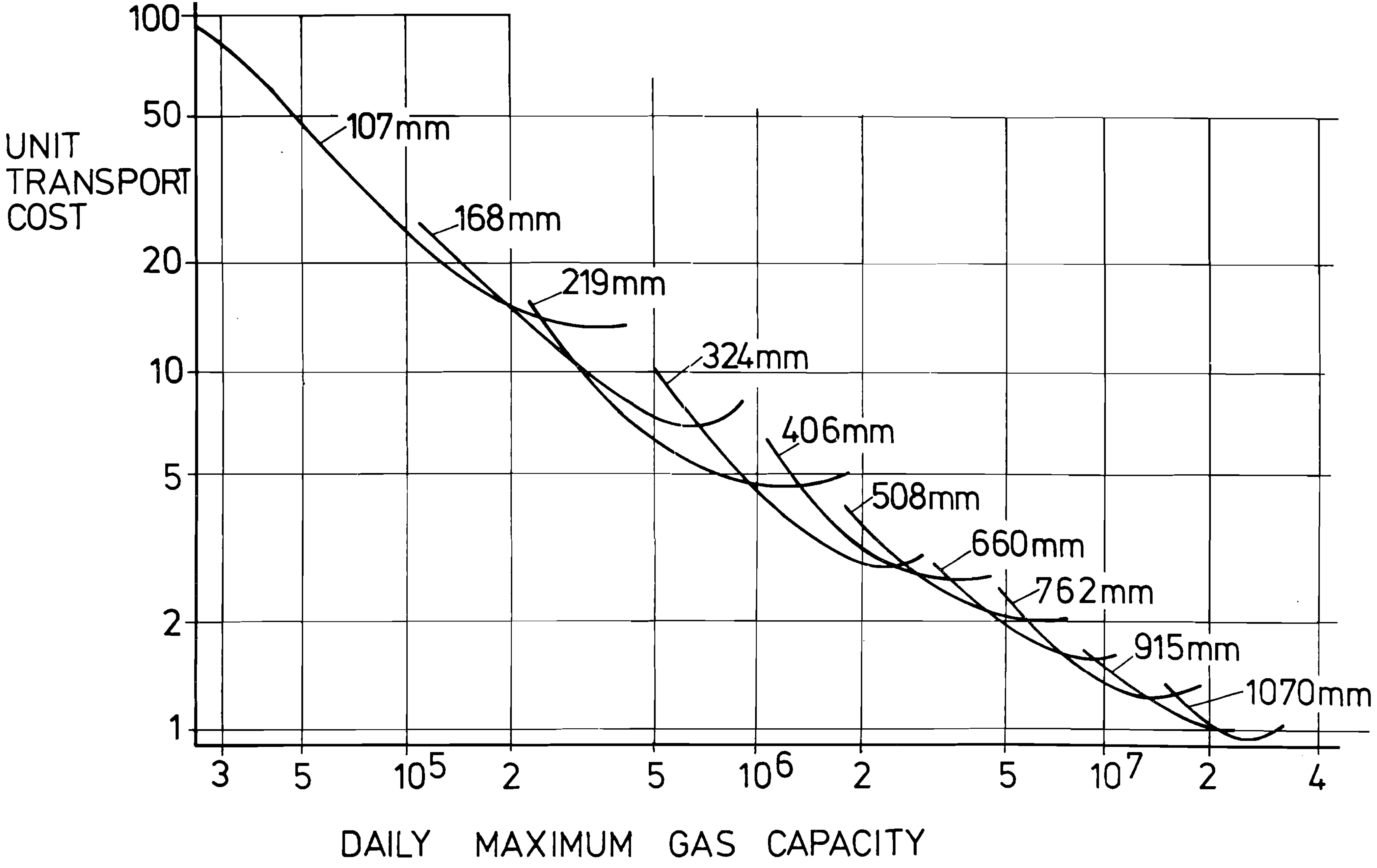


Figure 1. Cost curves of pipelines of various diameters.

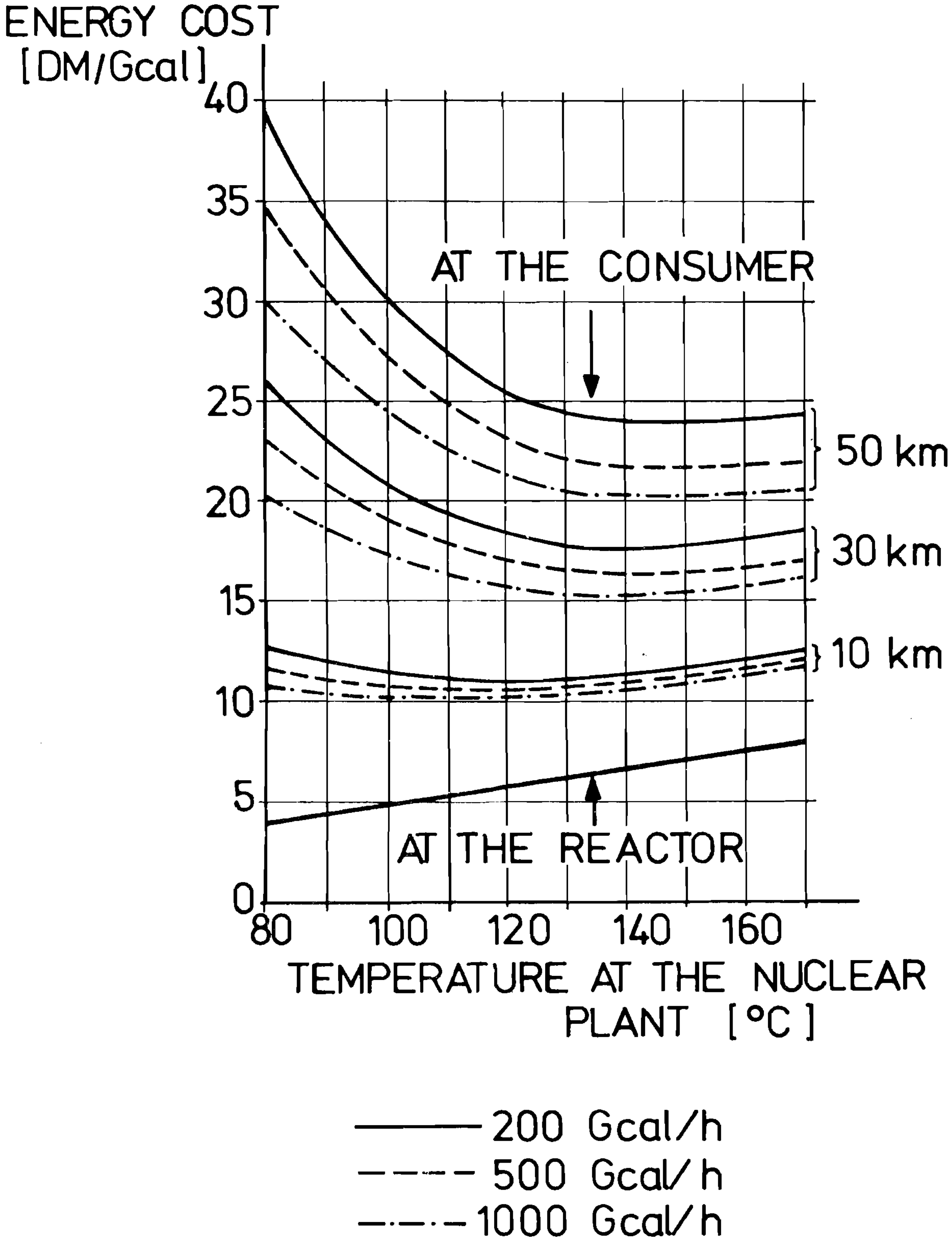


Figure 2. Transportation costs of hot water.

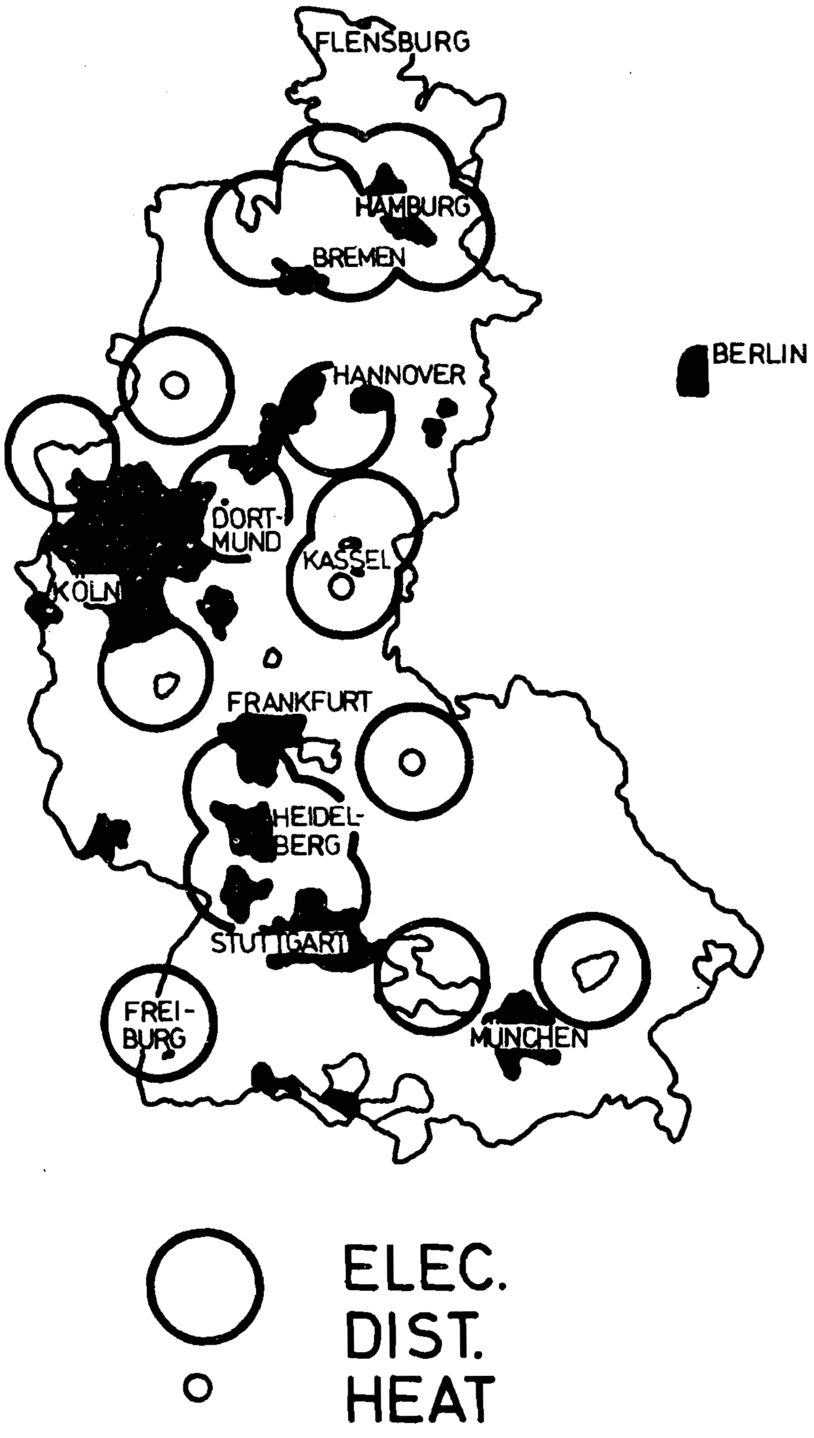


Figure 3. Predominant area coverage.

Figure 4. Cable transportation of mechanical energy - Schaffhausen 1866.

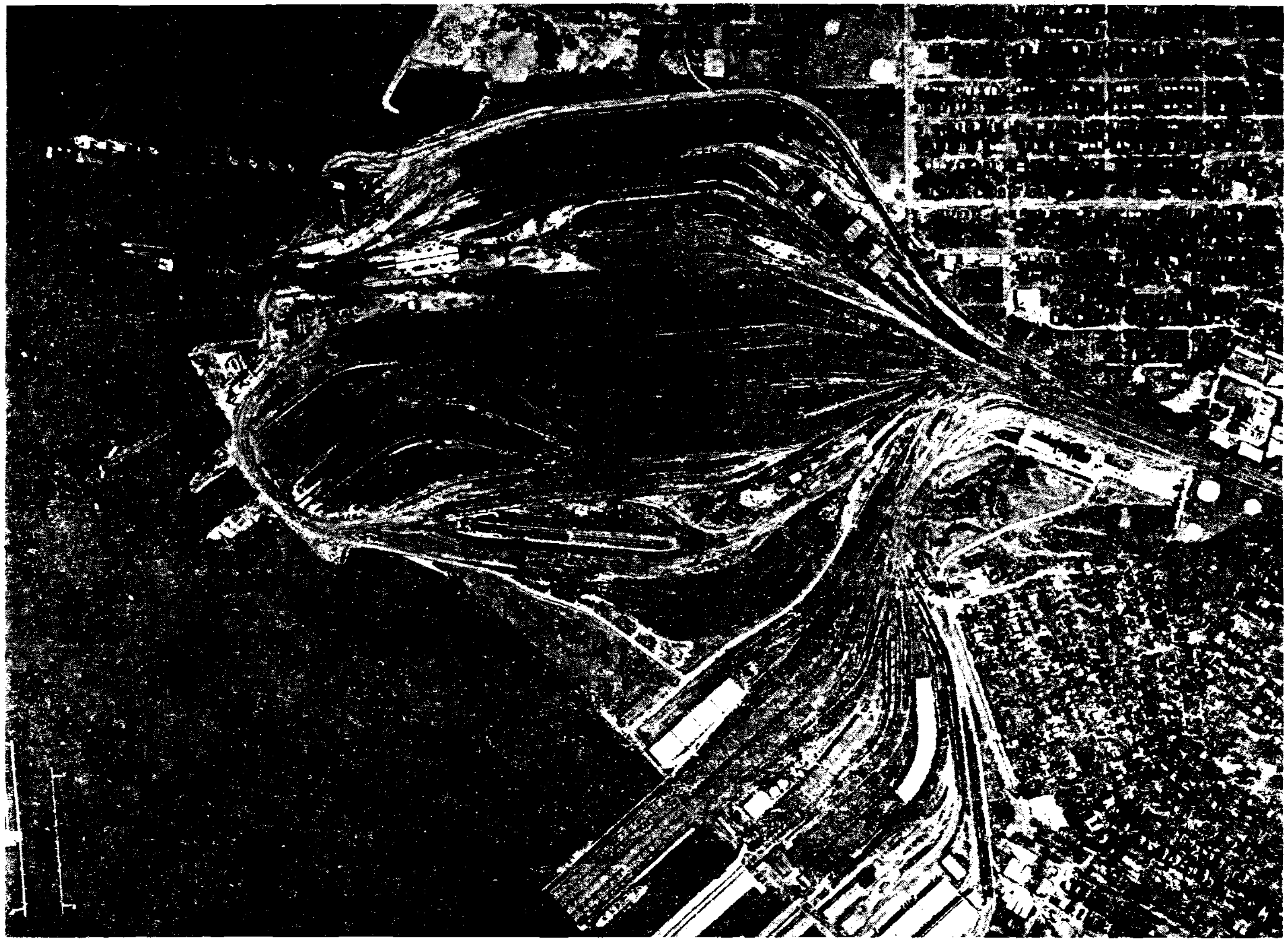


Figure 5a. Coal terminal in Norfolk, Virginia (USA). It can handle 8,000 tons of coal per day. (Source: Ref. [5])

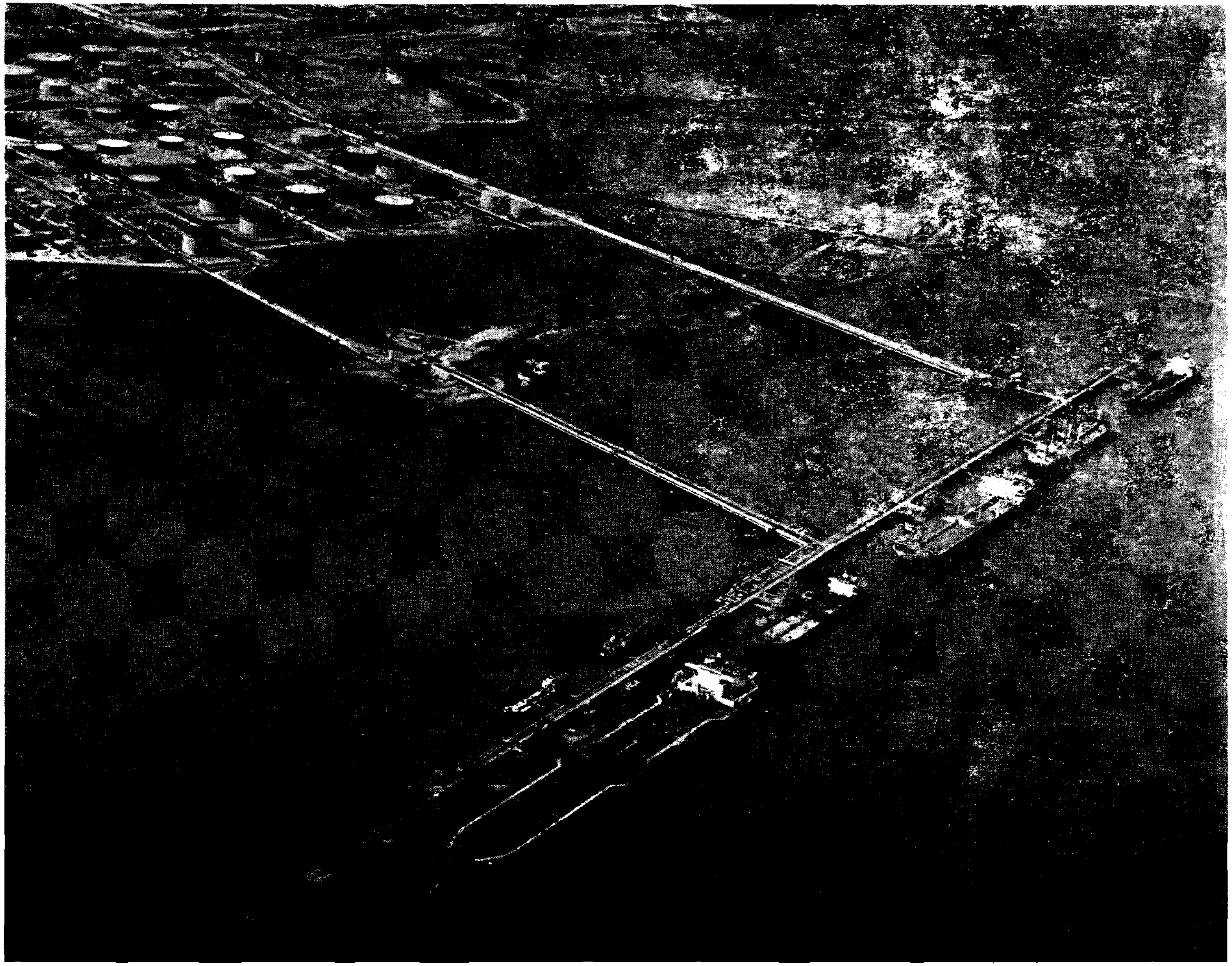


Figure 5b. ESSO oil terminal at Fawley, Hants., UK.
It can handle 100,000 tons of oil per day.
(ESSO photograph)

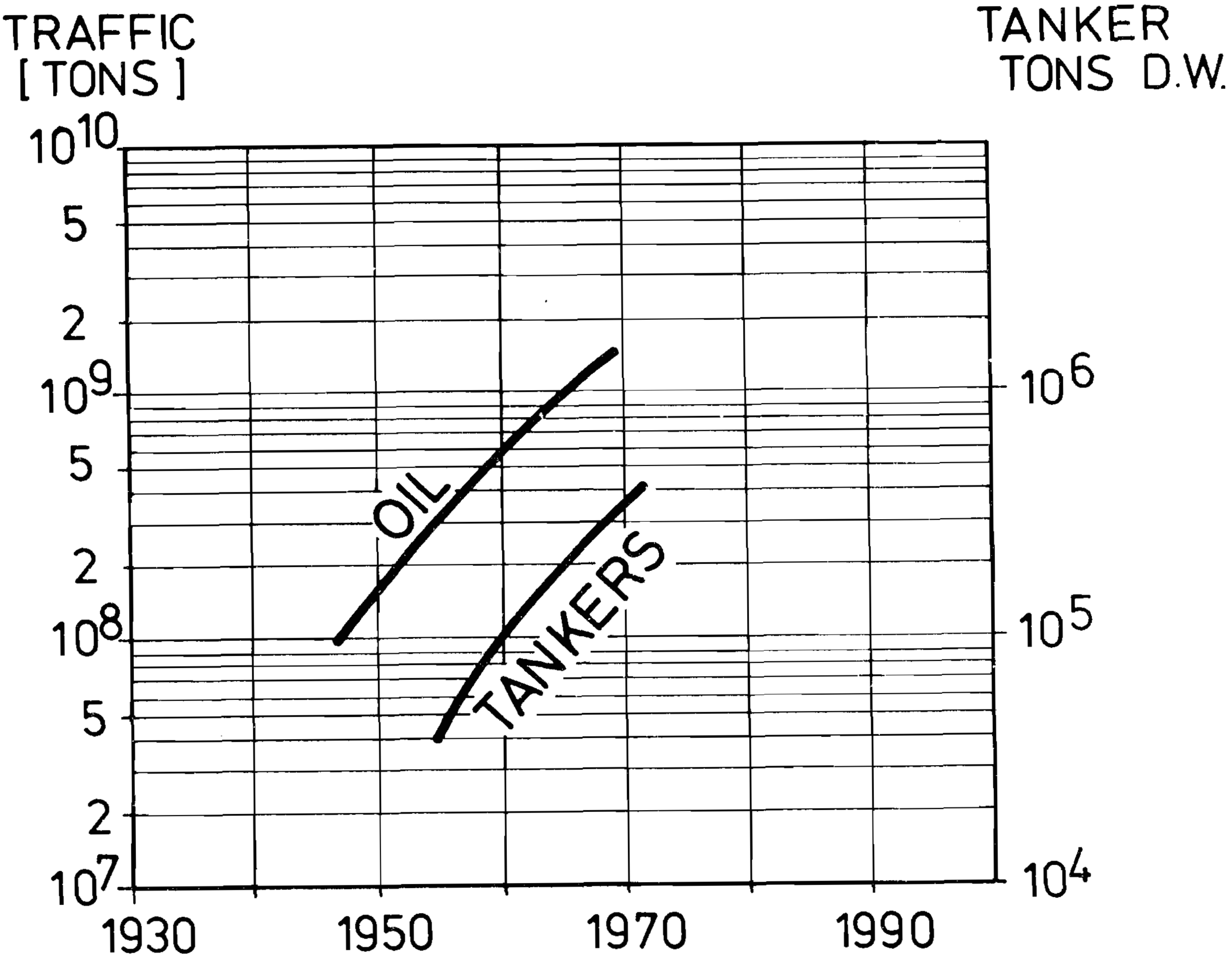


Figure 6: Correlations between size of tanker and oil traffic. (Adapted from Ref. [8])

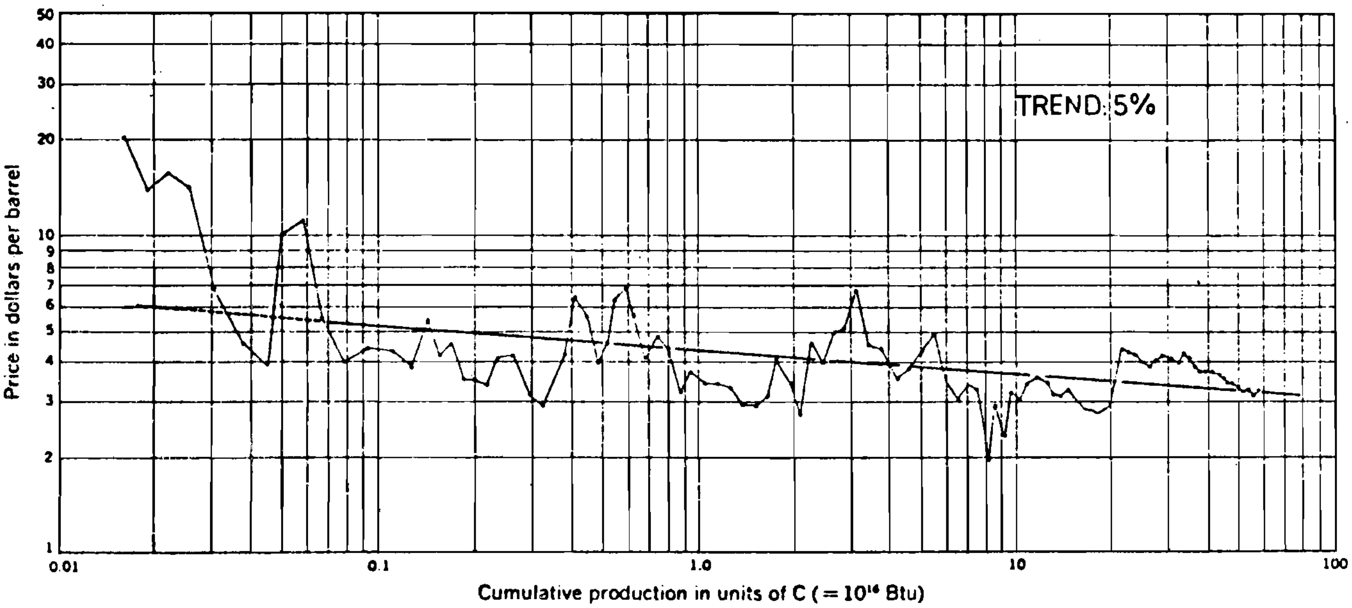


Figure 7. US wellhead oil-cost 1869-1971 (1970 dollars). (Source: Ref. [6])

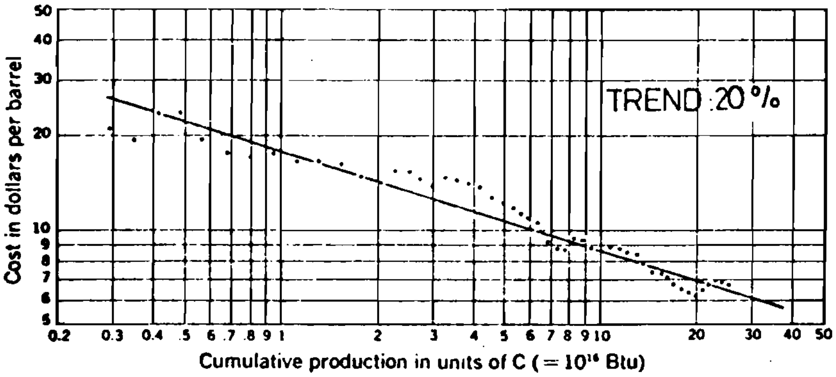


Figure 8. US manufacturing cost of petroleum 1919-1969 (Source: Ref. [6])

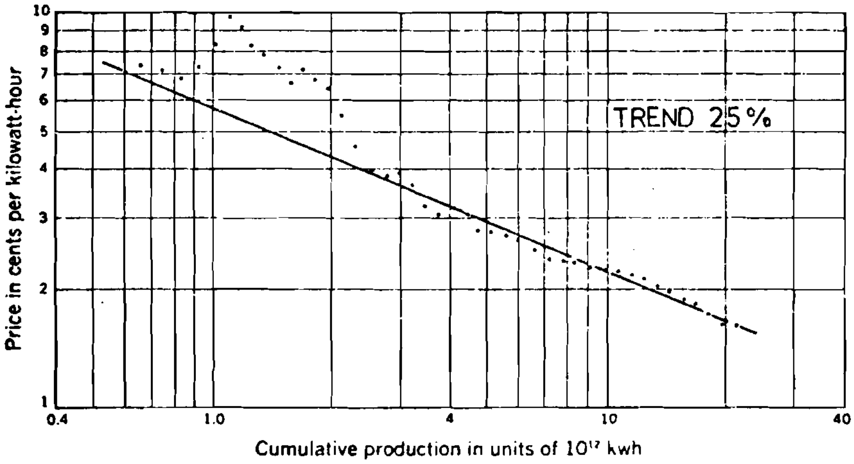


Figure 9. US electricity 1926-1970 (1970 dollars). (Source: Ref. [6])

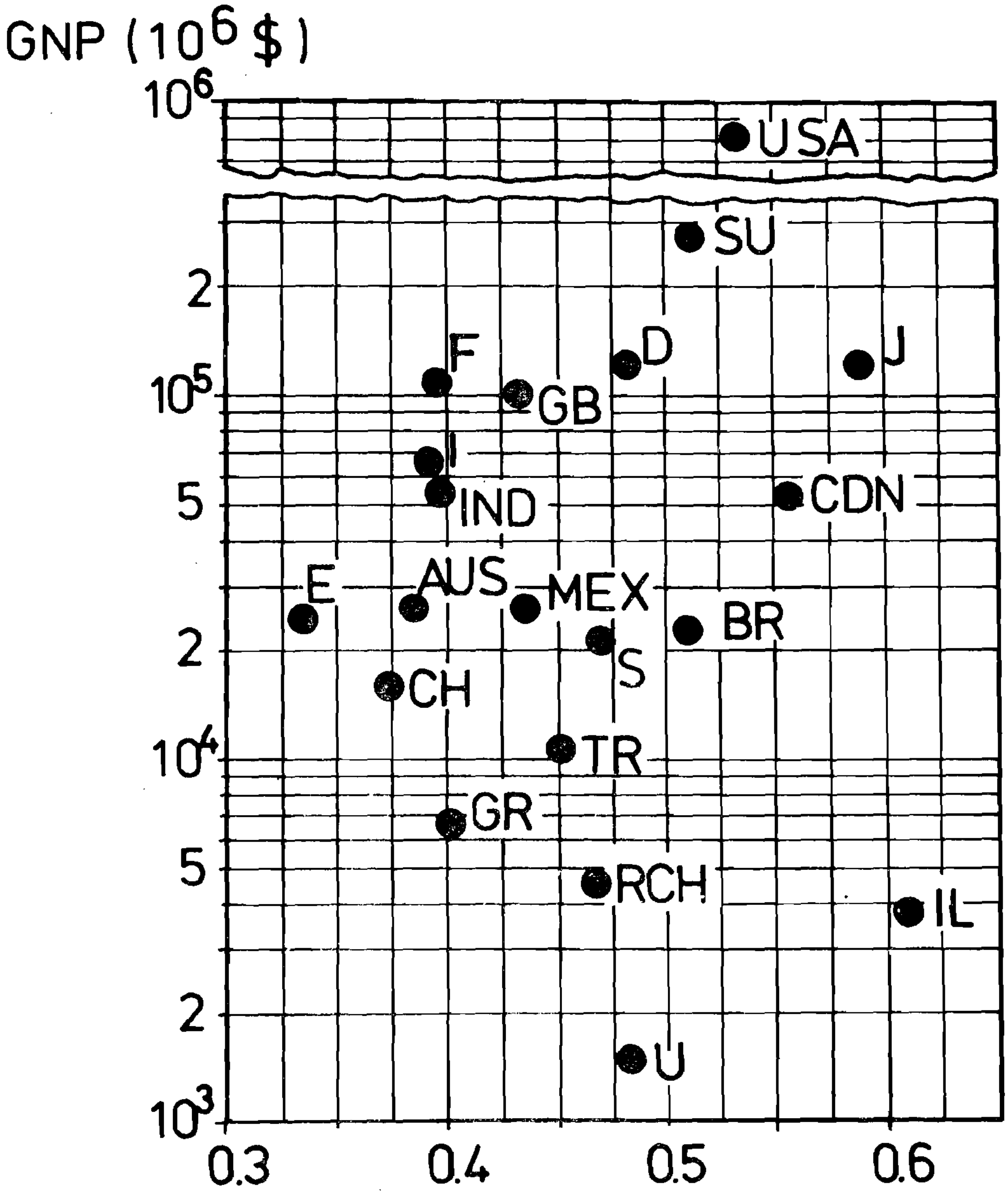


Figure 10. Electrical systems 1969 apparent load factor.

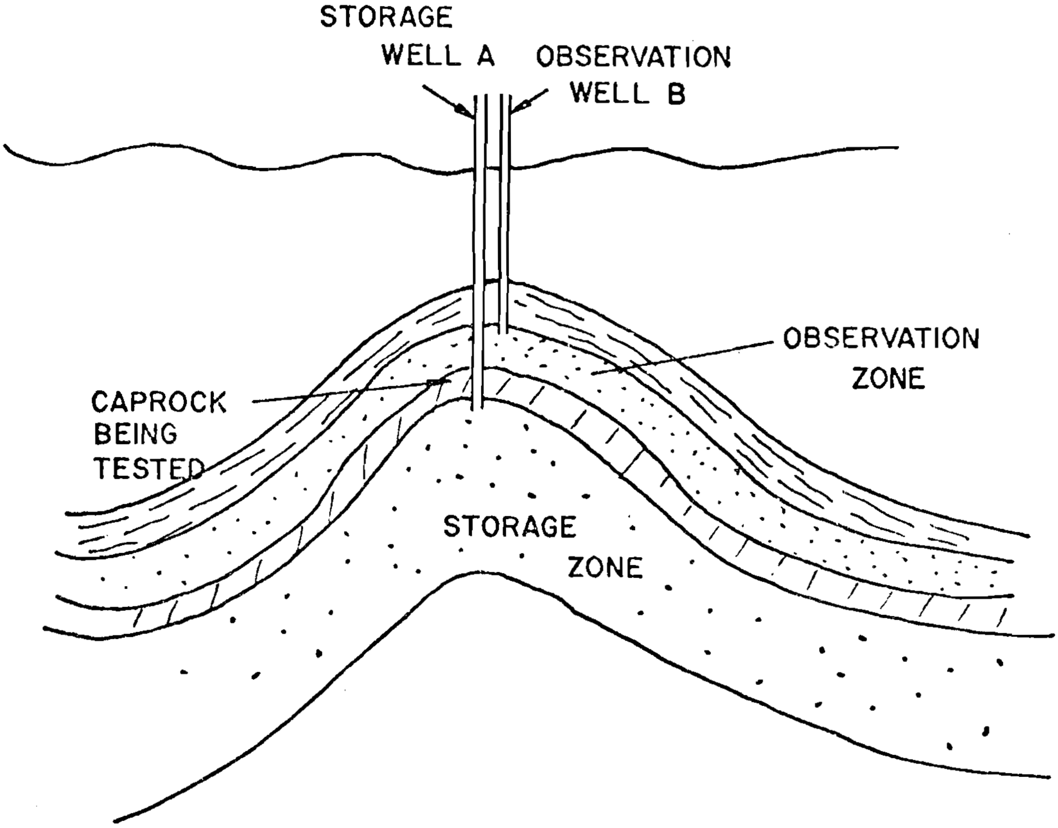


Figure 11. Principle of storage in an aquifer.

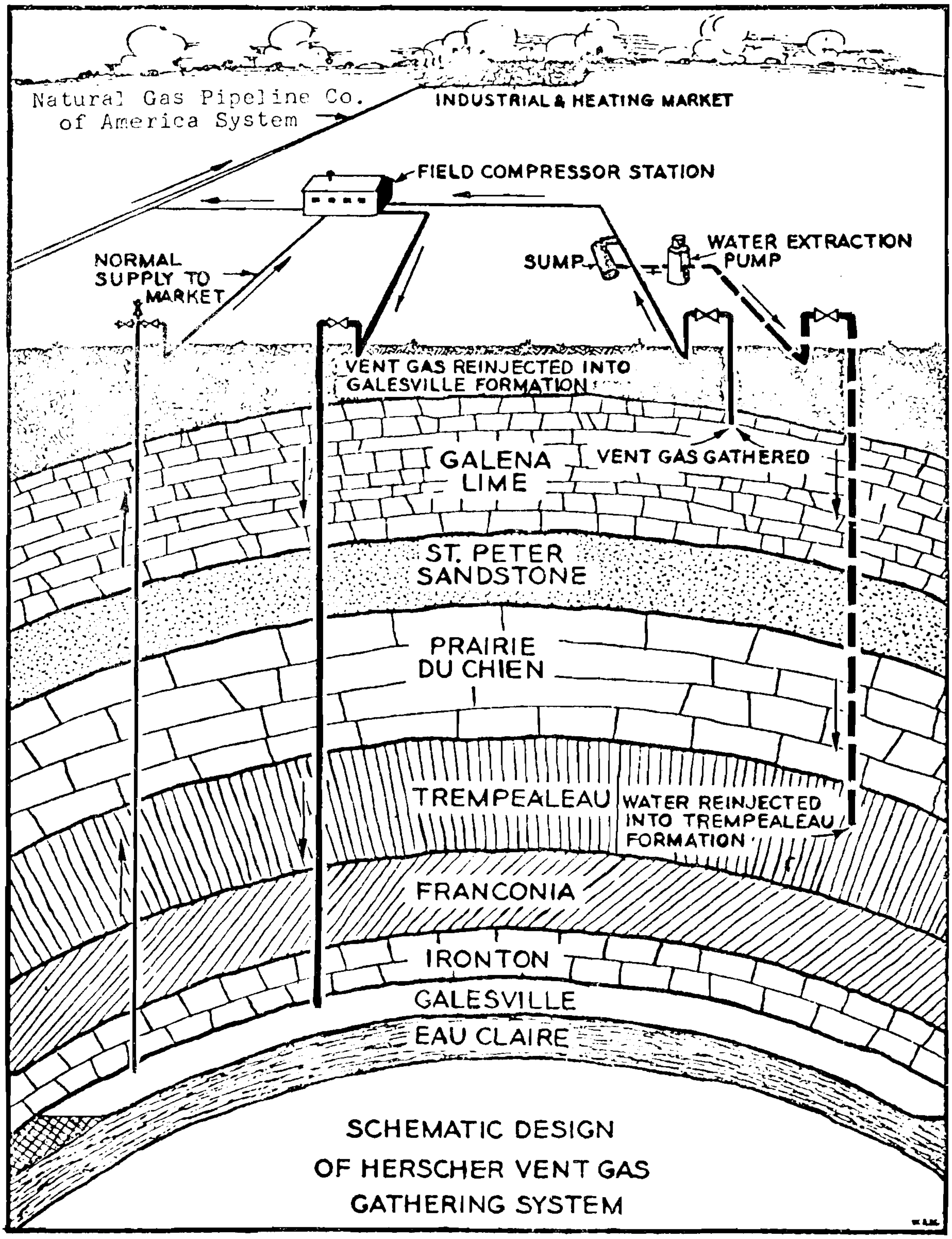


Figure 12. Artistic view of underground storage system.

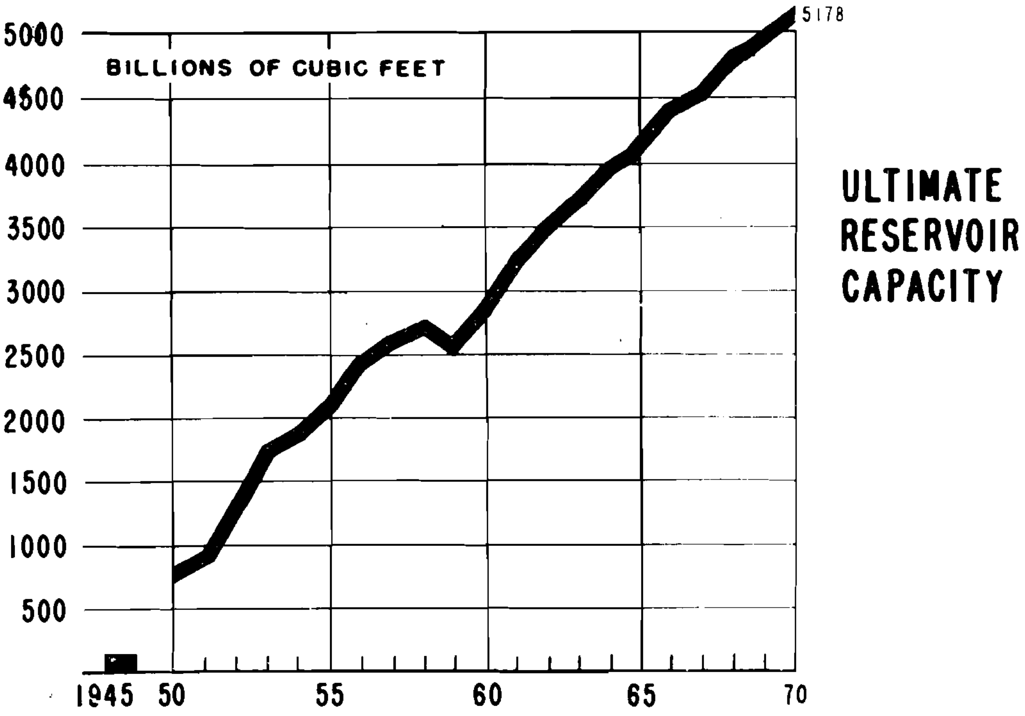


Figure 13. Ultimate reservoir capacity of existing underground storage fields and number of pools.

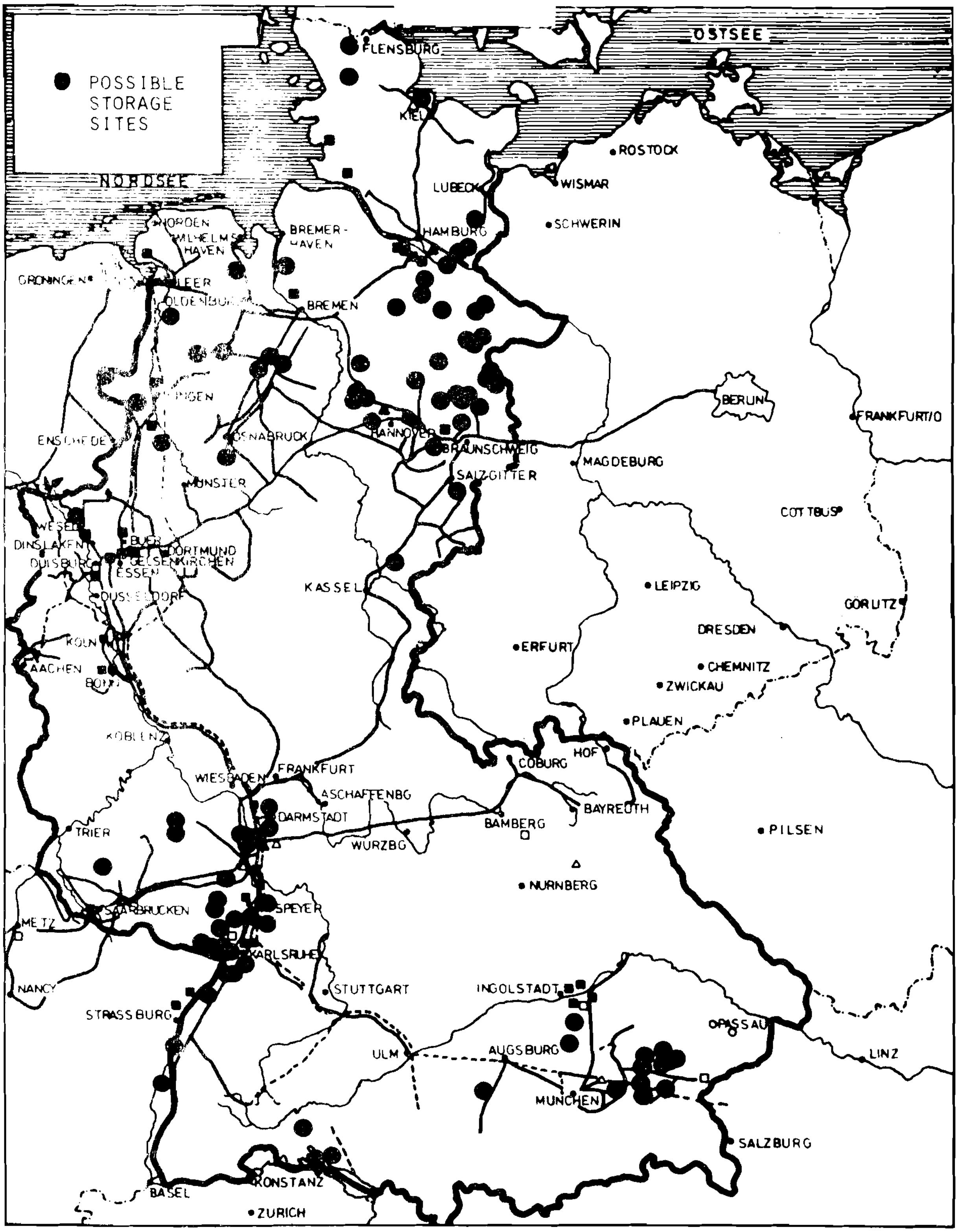


Figure 14. Identified natural sites for underground gas storage. (Source: Ref. (7))

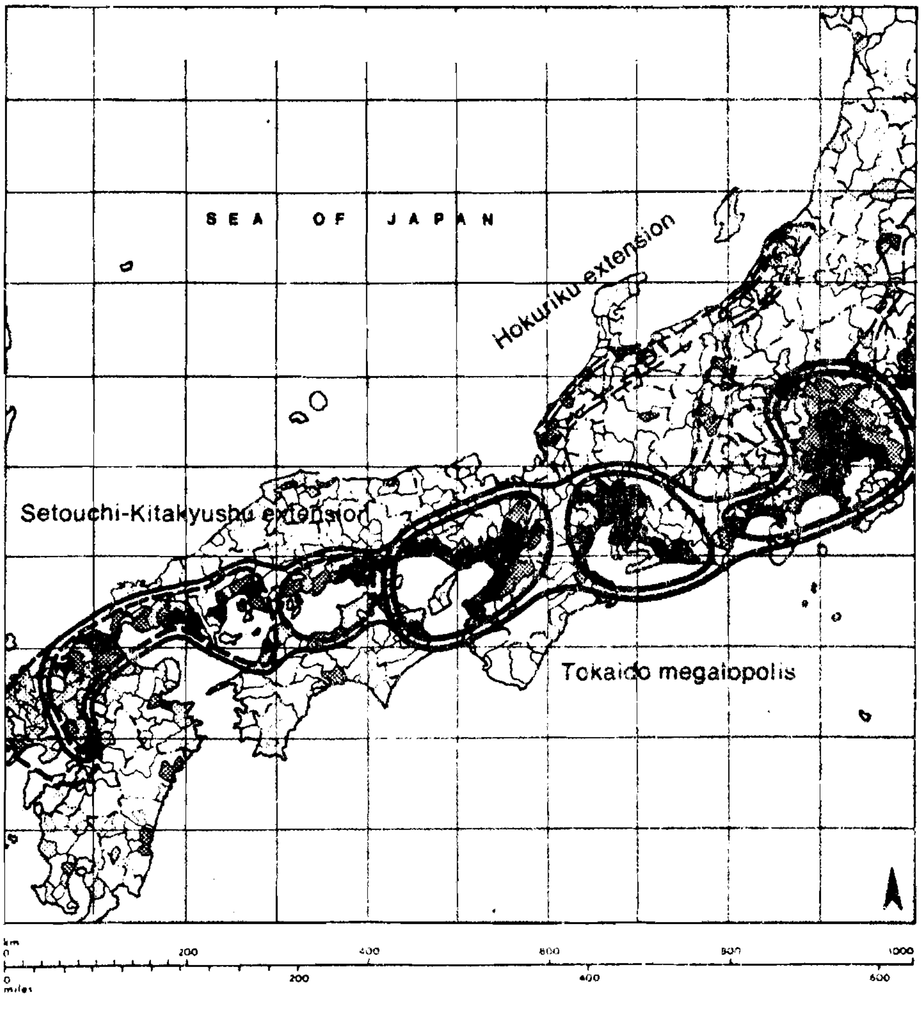
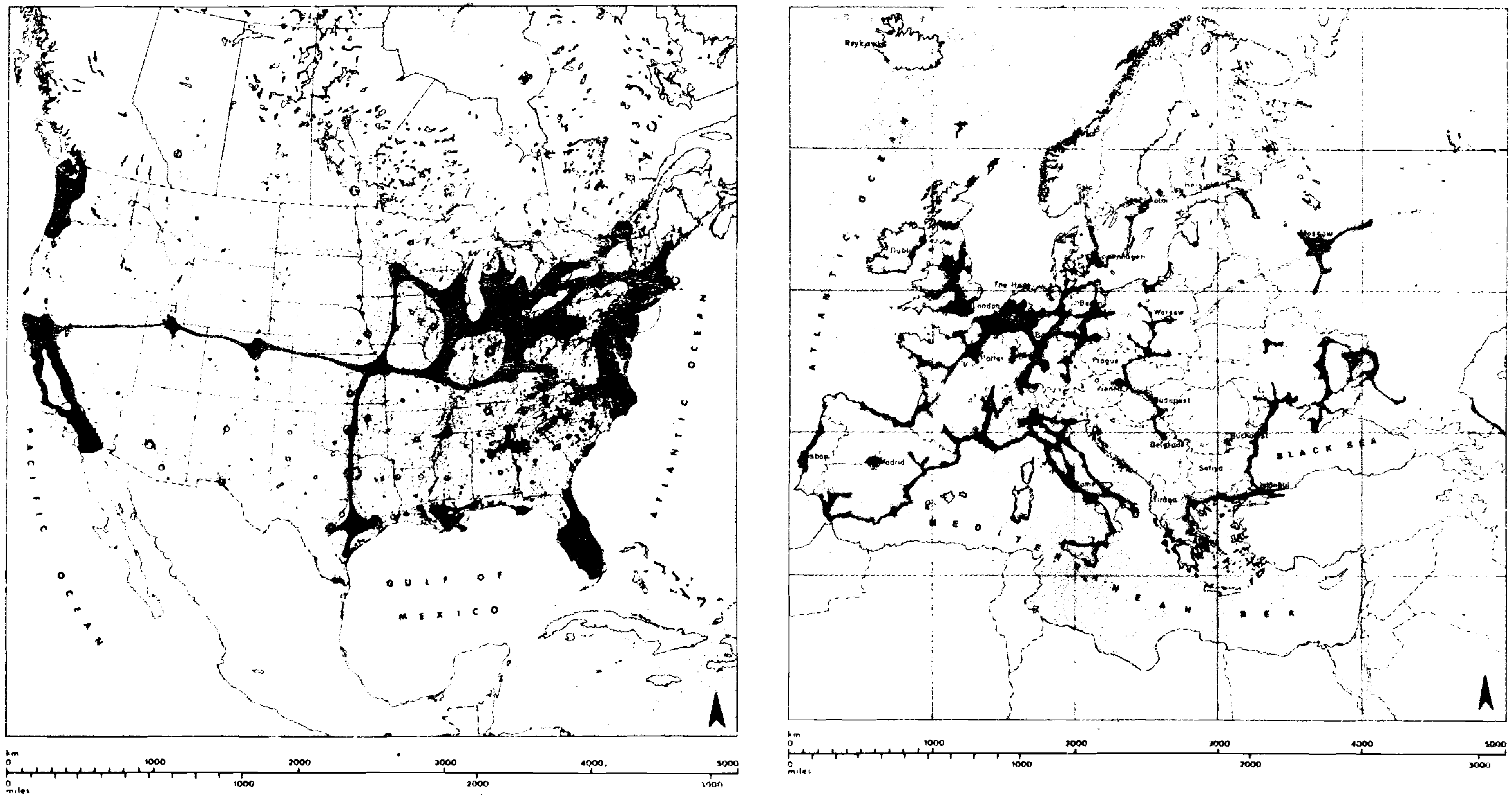


Figure 15. Ecumenopolis in formation: the linear megalopolis of Japan. (Source: Ref. [4])



Figures 16 and 17. Expected distribution of densely populated areas in USA and Europe as inferred from present trends. The long time constants characteristics of human settlements support such long extrapolation. (Source: Ref. [4])

THEORET. LIQUEF. ENERGY		(FROM 300°K)	~.2 KWh / kg
ACTUAL LIQUEF. EFFIC.			~50 %
ACTUAL COST OF		2[illegible]MW PLANT	620 $/KW
SCALE UP TO		1000MW PLANT x)	180 $/KW
LAIR	DENSITY		.88 kg/l
	TEMP.		~190 °K

x) SCALE UP FACTOR .7

Figure 18. Some data on lair.

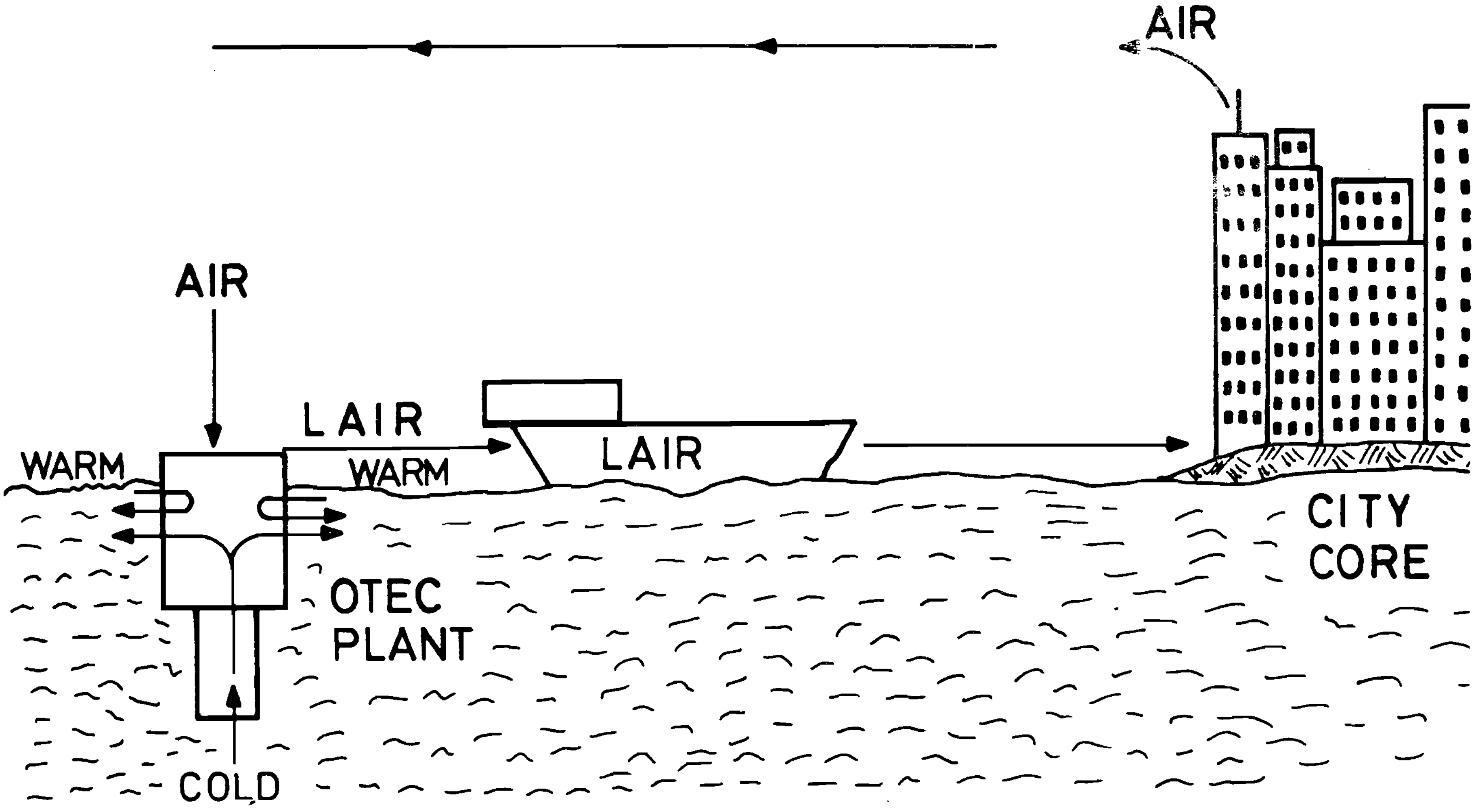


Figure 19. The lair cycle to carry negentropy to the urban core.

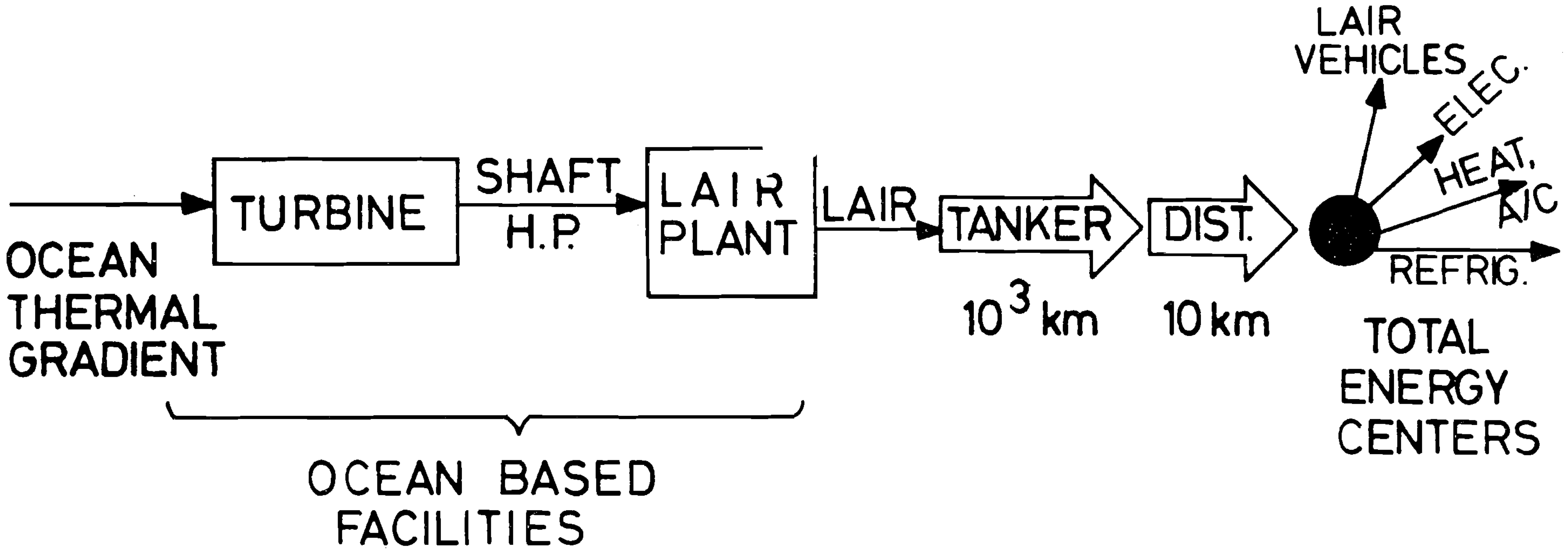


Figure 20. Negentropy system for the core city.

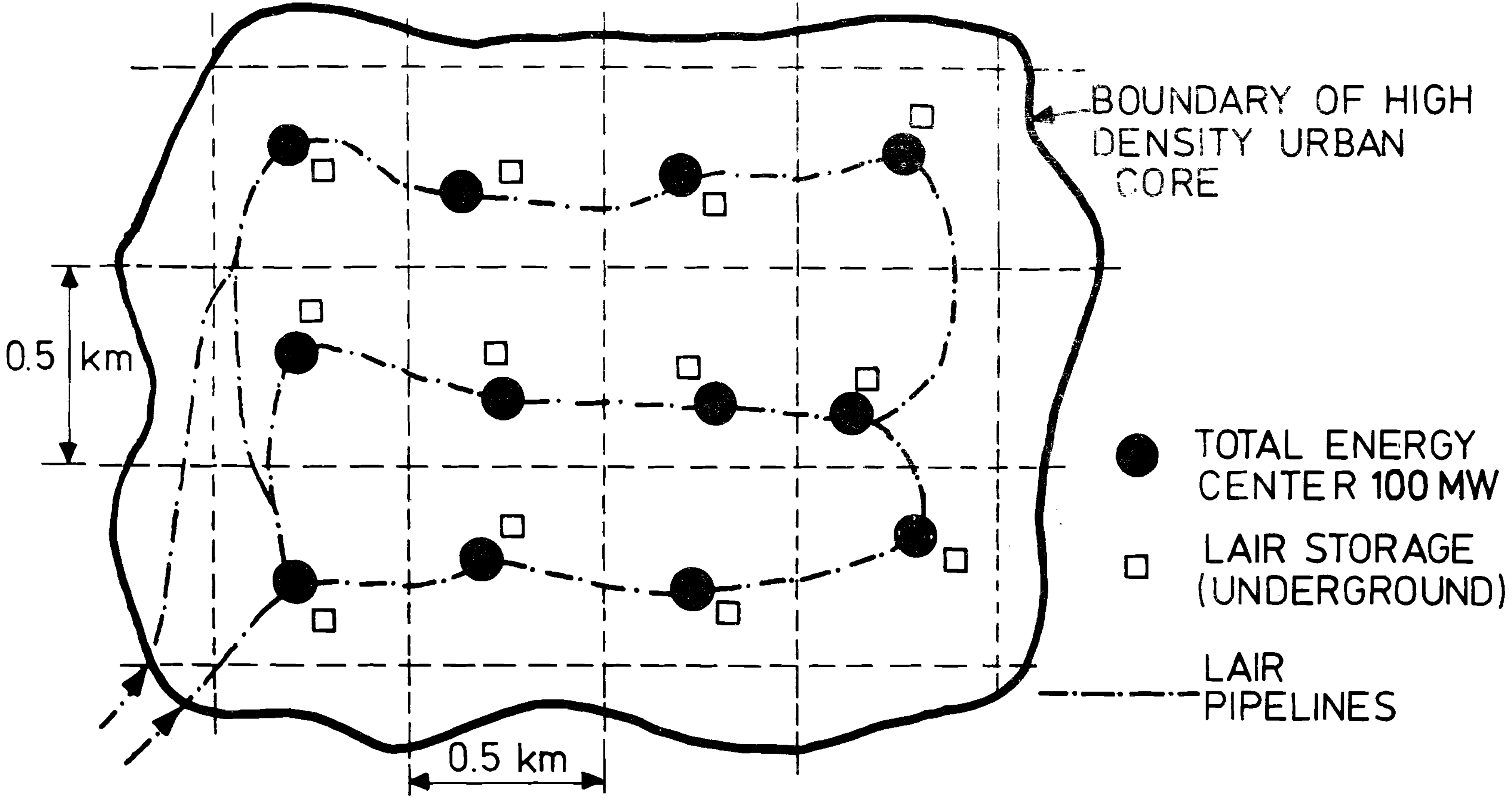


Figure 21. Total energy for dense settlements--liquid air concept.

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