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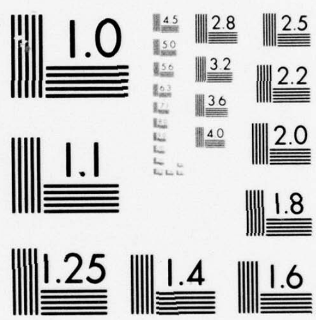

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SOME THOUGHTS ON OPTIMIZING LONG-DISTANCE HEAT TRANSPORT SYSTEMS AND THEIR STORAGE FACILITIES

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HANOVER, NEW HAMPSHIRE

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This document stems from the study of transport of heat produced in nuclear power reactors with a high enough rating to benefit by scale economy and relying on seasonal storage to flatten the production curve. It aims at optimizing such transport systems and is first of all a search for a simple mathematical method for determining immediately the optimal diameters and the corresponding costs.

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SOME THOUGHTS ON OPTIMIZING LONG-DISTANCE HEAT TRANSPORT SYSTEMS AND THEIR STORAGE FACILITIES

France in French Nov. 75 pp 1-46

[Article by P. Charroppin]

NOTE: 1 th (therm) = 10^{-3} Gcal = 1.16 kwh (th)

1 kth = 1 Gcal

[Text]

INTRODUCTION

This document is the fruit of a lot of thinking stemming from the study of transport of heat produced in nuclear power reactors with a high enough rating to benefit by scale economy and relying on seasonal storage to flatten the production curve.

It aims at optimizing such transport systems and is first of all a search for a simple mathematical method for determining immediately the optimal diameters and the corresponding costs. It translates into a straight-line chart whose points were established in a given economic context, but are easily transposable: the only condition for doing this is that, in the field involved, you can consider the mean investment cost for a transport pipeline as proportional to a power, α, of the diameter. It is demonstrated that at the optimum, there is a clearly defined ratio (35 percent) between pumping costs (amortization of the pumps + electricity consumption) and pipeline amortization. As we move along, there are several conclusions which emerge:

1. The same diameter is at once optimal for distribution with and without storage;

2. It is vital to push for pumping station design such that station power is highly controllable and readily adjustable to minute-to-minute needs;

3. It is possible to design a system which will remain optimum, to all intents and purposes, throughout a future increase in flow of 50 percent, without any significant penalization of the initial situation;

4. The decline in electricity rates further accentuates this flexibility;

5. Proper manipulation of summer-winter rates makes it possible to achieve a very marked reduction in transport costs. By separating the storage depots from the heat sources, in such a way that a good share of their customers will be along the route of the feeders which join source and storage facility, you can manage to have your most massive transfers fall in summer: if you do this, you are transporting marginal heat loads with marginal kilowatts, and you arrive at an overall production-transport-storage design with an overall minimization of cost, with each component, by reason of its existence or its placement, helping to squeeze the cost of the other two;

6. It is also demonstrated that in such a system you have no need, except in very rare exceptions, any need for standby (or peak) production facilities in consumption centers, and that for the very rare cases in which they might be useful, it would doubtless be prudent to consider building small above-ground or shallow weekly storage pits, which would normally be supplied on weekends or at night;

7. On a more prosaic level, we find that circulation speeds, flows, and load losses for the economic diameter are generally lower than those generally used, at least at present rates for the electrical kwh.

TABLE I

Diameters	Cost in francs per kilometer	A_o in francs per km	Cost in Fr/km (Professional data)
Diamètres	C en F/Km	A_o en F/Km	Coûts en F/Km (renseignements professionnels)
300	1.500.000	177.000	1.660.000
350	1.850.000	218.000	1.800.000
400	2.260.000	266.000	1.155.000
500	3.150.000	352.000	3.156.000
600	3.950.000	470.000	4.093.000
700	4.990.000	590.000	4.827.000
800	5.990.000	708.000	5.883.000
900	7.100.000	830.000	7.354.000
1000	8.300.000	982.000	8.291.000
(1200)	10.750.000	1.270.000	-
(1500)	14.600.000	1.740.000	-

This cost includes the delivery and return pipelines, the mains, the pipeline accessories (valves, carryoff apparatus), but not the pumps. It refers to economic conditions as of January 1975.

12. Establishing an Index

So as to allow for economic variations, take into consideration an overall index, i, for the total variation in the annual instalment for the pipelines, assuming that its value is independent of their diameter. Let i_o be this index under the economic conditions prevailing at the establishment of Table I, and the annual instalment is multiplied by i/io.

The choice of an index pinned to the annual instalment allows you to incorporate into it any variations in the conventional discount rate should it change.

For the pumping installations, we shall assume an overal average plant cost of 650 francs/kwh, or an annual amortization rate, a_o, of 76 francs/kw. In case of variations in economic conditions (or in the discount rate), a_o will become a. If necessary, it will be possible to use values of a better suited to a given problem.

One important factor is the cost of the electrical power for the pumps. We shall designate as p the price per Kwhe. Frequently the electricity rate is such that you will have to distinguish between a winter rate, pH, and a summer rate, pE, as well as a weighted mean price, pm.

The values for pH, pE, and pm to be used will be specified for each of the numerical examples.

1.13. Pumping Expenditures

The specific power consumption for pumping will vary considerably. The reason for this is the relationship between load loss, circulation speeds, and diameter, which, in the domain we are concerned with, is the Flament formula

$$j = K_1 \quad U^{1.75} D^{-1.25}$$

j = load loss

U = fluid velocity

K_1 is a constant depending solely on the units chosen (in general, in all that follows the Ks will denote constants).

If Q is the hydraulic or thermal flow:

$$j = K_3\ Q^{1.75} D^{-4.75} \text{ because } Q = K_2\ UD^2$$

As for the power of P of pumping per kilometer of pipeline, it is:

$$P = K_4\ j\ Q = K_5\ Q^{2.75}\ D^{-4.75}$$

We shall note that if j is stated in mm/m and Q designates the hydraulic flow Qh/m3/h and if the pumps have a yield of 0.7, we have P stated in kilowatts: $P = \frac{jQ_h}{125}$

$$P = \frac{jQth}{12.5} \times \frac{100}{\Delta T^o}, \text{ with Qth being the thermal output in k th/h}$$

ΔT= the temperature difference between outgoing and incoming steam.

For $\Delta T = 100^o$, the commonest solution,

$$P = \frac{jQth}{12.5}$$

When in a given pipeline there is a variable flow, the power needed for pumping is also variable, far more so than the flow.

If we use Q_N (the normal flow) to designate the flow corresponding to the installed power of the pumps, P_N, we can, for a given pipeline, define two annual schedules, H_1 and H_2.

H_1 is the annual schedule equivalent to full power of the pipeline flow ($H_1 = Q_{th\Delta}/Q_{thN}$ with

$Q_{th\Delta}$ = total annual heat flow

Q_{thN} = nominal hourly heat flow)

H_2 = the annual schedule equivalent to the full operating power of the pumps ($H_2 = C_p/P_N$ with C_p as the annual power consumption, and P_n = the nominal power of the pumps).

For a given diameter the instantaneous pumping power is linked with the instantaneous flow by the equation:

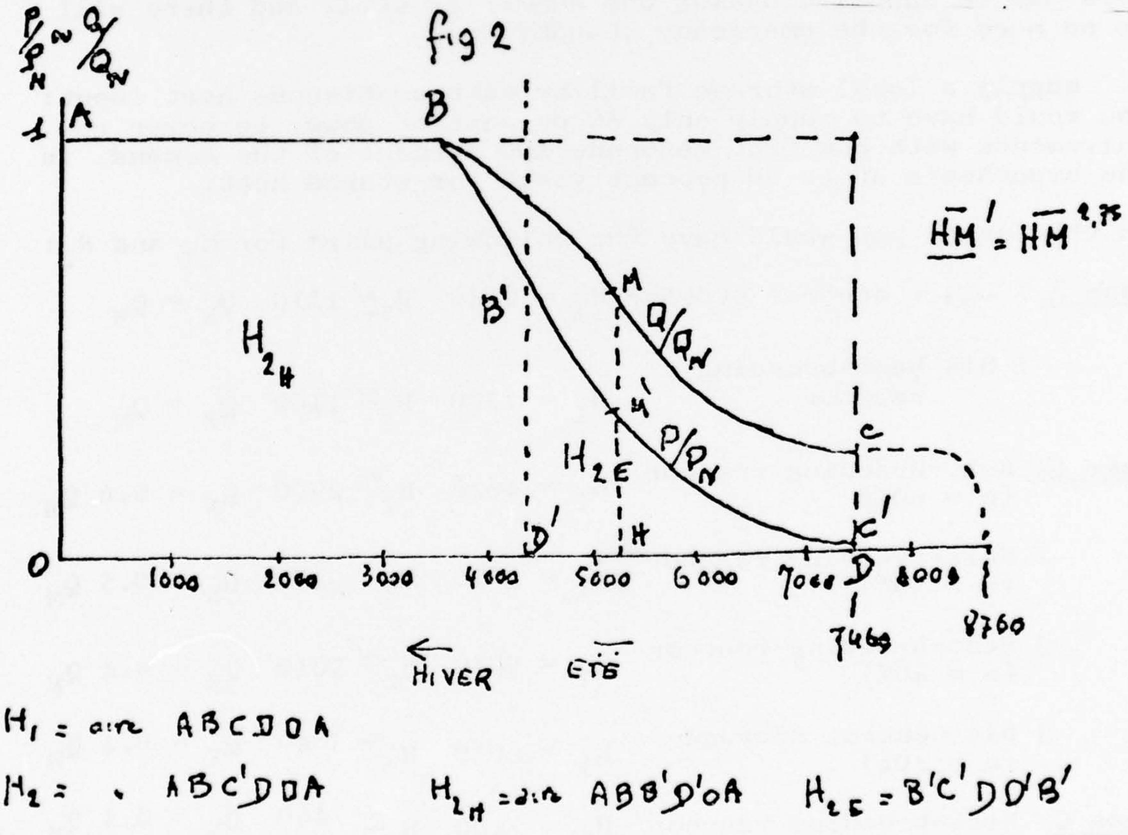
$$\frac{P}{P_N} = \left(\frac{Q_h}{Q_{hN}}\right)^{2.75}$$

If you have pumping stations installed in a sufficiently rational manner to be able to adapt P to Q_{th} (and hence to operate at a fixed ΔT)

$$\frac{P}{P_N} = \left(\frac{Q_{th}}{Q_{thN}}\right)^{2.75}$$

we see that as P/P_N is constantly lower than $\frac{Q_{th}}{Q_{Nth}}$, we necessarily get $H_2 \leqslant H_1$ (see Fig 2).

Knowledge of the H_1 H_2 pair characterizes the yearly mode of operation of the pipeline. We can establish certain relationships between H_1 and H_2.



These relationships are in essence a function of the mode of operation of the distribution system as a function of heat requirements. It depends upon, among other things, the monotones which define the latter.

If, for example, a feeder uses a source (a heat-breeding reactor or a storage pit) to supply a subdivision whose monotone looks like the one for C.P.C.U., you can design several modalities.

A. Supply and transport all the power and all the heat consumed except, in the case of the reactor, in periods of scheduled or accidental shutdowns of the reactor.

B. Supply and transport only n percent (40, 50, or 60 percent) of the maximal power, with backup on the coldest days provided by an independent local source (usually fuel oil heating) which would also provide heating during shutdown periods and in summer, and for emergencies. In the case of centralized storage, consumers can be supplied during the summer as well, and there will be no need for the emergency standby.

C. supply a local storage facility with continuous heat input: you would have to supply only 40 percent of power to cover requirements with the CPCU monotone 100 percent of the demand, in the hypothesis of an 80 percent yield for stored heat.

In this case, you would have the following pairs for H_1 and H_2:

<u>Case A</u>	1 bis - central storage	$H_1 = 2840$	$H_2 \simeq 1110$	$Q_N = Q_M$
	1 bis heat-breeding reactor	$H_1 = 2700$	$H_2 \simeq 1100$	$Q_N = Q_M$
<u>Case B1</u>	Heat-breeding reactor (n = 60%)	$H_1 = 4620$	$H_2 \simeq 2900$	$Q_N = 0.6\ Q_M$
2	Heat-breeding reactor (n = 50%)	$H_1 = 5070$	$H_2 \simeq 3400$	$Q_N = 0.5\ Q_M$
3	Heat-breeding reactor (n = 40%)	$H_1 = 5710$	$H_2 \simeq 5010$	$Q_N = 0.4\ Q_N$
3 bis	Central storage (n = 40%)	$H_1 = 6050$	$H_2 \simeq 5040$	$Q_N = 0.4\ Q_M$
<u>Case C</u>	Heat-breeding reactor	$H_1 = 7460$	$H_2 \simeq 7460$	$Q_N = 0.4\ Q_M$

Figure 2 shows cases B3 and C. The CPCU monotone has been limited to 40 percent of the total power required.

$$H_1 = \text{area A B C D O A}$$

$$H_2 = \text{area A B C' D O A}$$

The B C' curve is deduced from the BC curve with the equation:

$$\overline{H\ M'} = \overline{H\ M}^{\ 2.75} \text{ with } (\ A\ A = 1).$$

When you consider the case of A or B, the fact that $H_2 < H_1$ means that at equal normal power the specific energy consumption of pumping per therm distributed is less than that for case C; this may partially compensate, in the overyear balance, for the increase due to the fact that amortization is distributed over a smaller quantity of therms delivered, particularly if the Kwhe is costly.

1.13.1. Now we have the emergence of an important factor, <u>the seasonal nature of the price of the kilowatt hour</u>, which plays a part in the economic study: in the absence of storage, pumping energy consumption is essentially a wintertime thing. So, for case B3, of the 5,010 hours of H_2, at least 4,000 are wintertime hours, and summer consumption accounts for only 20 percent of the total. For case C, out of the 7,460 hours, there will be around 4,360 winter hours and 3,100 summer hours (see Fig. 2). Consumption at the reduced summer rate therefore represents 41 percent; if the summer price is half the winter price, this amounts to an effective cost cut per Kwh of 10 percent, because:

$$\text{Case } B_3 \quad p_{mP_3} = 0.80\ p_H + 0.20\ p_E = (0.90\ p_H$$

$$\text{Case C} \quad p_{mC} = 0.59\ p_H + 0.41\ p_E = (0.81\ p_H)$$

$$p_{mC} = 0.9\ pm_{B3}$$

We can imagine situations in which the great majority of transport would take place in summer. This is the case, for example, if you are supplying a subdivision V_2 from a storage pit nearby, supplied by a reactor located near or in another subdivision, V_1, of the same size (same maximum consumption Q_M, same typical CPCU monotone); in addition, for the coldest days when the demand is over 80 percent of maximum consumption, V_1 will be backfed from V_2. The same applies to a period of scheduled shutdown: heat transport is shown on Figure 3.

(We shall show later on that it is altogether feasible to provide emergency supply to V_1 from V_2 under reasonable conditions, because this requires a Q_m flow which does not exceed by merely 40 percent the normal flow, Q_N.)

The maximum flow is 0.7 Q_M. We see that there is approximately $H_2 = 3700$, of which H_{2H} is roughly equivalent to 1100 and H_{2E} is equal to 2600. Summer consumption represents around 70 percent. In the hypothesis already contemplated in which $p_E = 0.5\ p_H$, we have: $p_m = 0.30\ p_H + 0.70\ p_E = 0.65\ p_H$

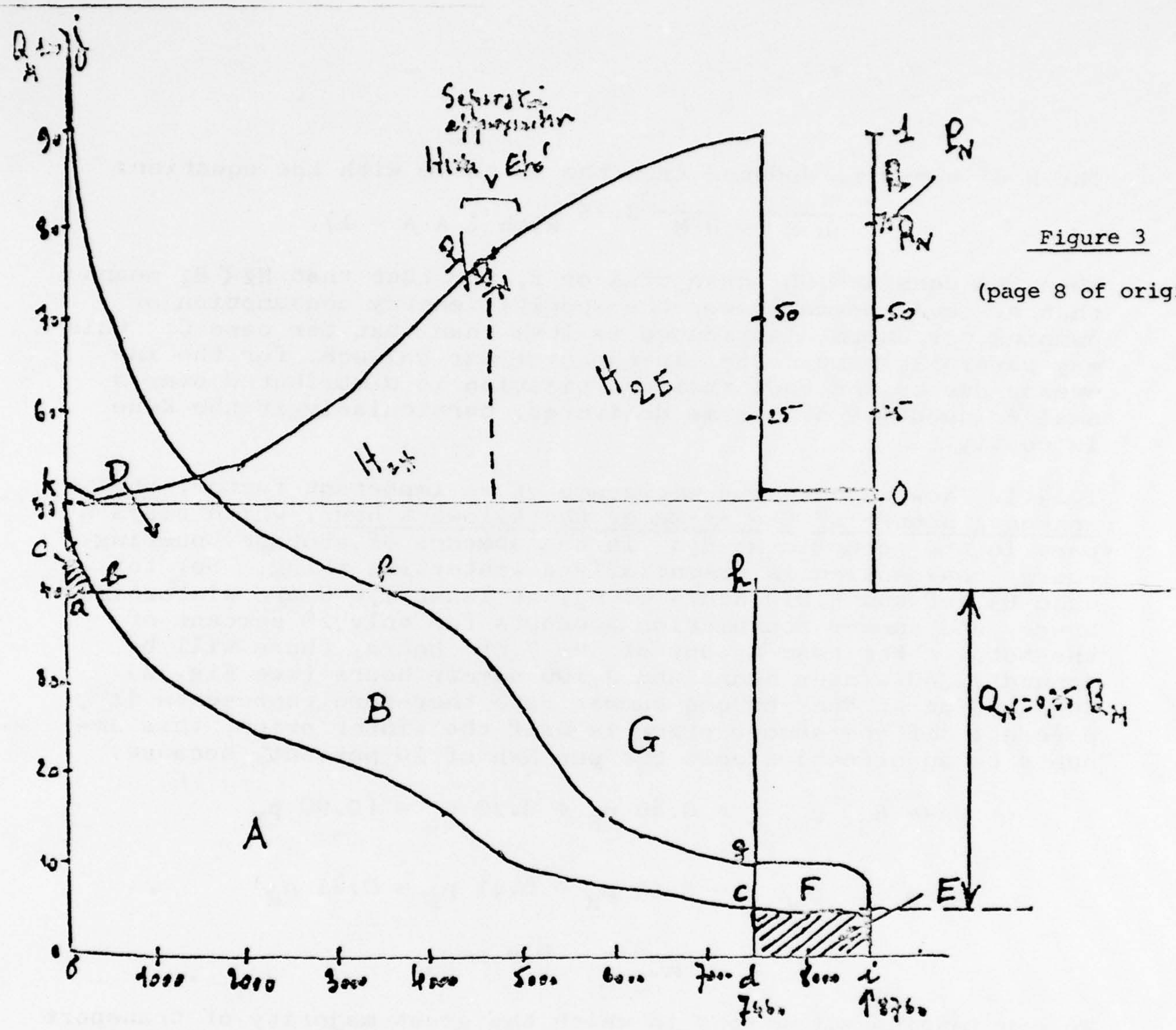


Figure 3

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Approximate separation

Winter Summer

A = town V_1, plant-supplied
B = town V_2, supplied from plant
C = town V_1, supplied from storage
D = town V_2, supplied from storage
E = town V_1, supplied from storage
F = town V_2, supplied from storage
G = storage at production site
//// = Return

You see the advantages of such a solution in which, in the last analysis, marginal therms are mainly transported by consuming kilowatt hours which are themselves marginal. In any case, the existence of summer rates for electricity is a factor which provides a strong incentive for storage.

Their existence, by its very nature, will influence the designer and hence the operation of the systems, as well as the characteristics of the systems themselves.

1.14. Losses

Transport losses are relatively insignificant, except over long distances. They are proportional to the diameter D of the pipeline, and the transition from one diameter to a larger one pushes them up only slightly, whereas it sharply cuts the power requirements and the cost of pumping, which vary as $D^{-4.75}$.

So the influence of losses plays only a very minor role in optimizing systems, and we shall disregard them from this point of view.

(The discontinuity of commercial diameters means that the losses dependent on diameters actually used have discontinuous values. We can derive the corresponding term in relation to a diameter assumed to be continuously varying.)

DETERMINING THE COST PER KILOMETER OF TRANSPORTING 1 THERM.

SEEKING TO OPTIMIZE PIPELINE DIAMETERS AND PUMPING POWER LEVELS.

2.1. The elements we have thus far enumerated enable us to fix the transport cost per kilometer, which is:

$$c = \frac{1}{10^3\, Q_N\, H_1} \left[A + \frac{1}{12.5}\, j_N Q_N\, (a + p\, H_2) \right] \qquad (1)$$

The normal pumping power P_N in Kw is in effect equal to $\frac{1}{12.5}\, j_N Q_N$ if j_N in mm and Q_N and Kth/h for an installation in which $\Delta T = 100°$ (difference between outgoing and incoming temperature)

$$c = \frac{10^{-3}}{H_1} \left[\frac{A}{Q_N} + \frac{1}{1.25}\, j_N\, \xi \right] \qquad (1\ \text{bis})$$

with:

$$\xi = p\, H_2 + a$$

ξ is a parameter characterizing the economic conditions for pumping operations in the system.

So as to make the considerations and calculation charts which follow independent of economic variations, we remind readers that an index, i, was defined earlier, so that:

$$A = A_o \frac{i}{io}$$

We set:

$$\xi_o = \xi \frac{i_o}{i} \quad \text{and} \quad c_o = c \frac{i_o}{i}$$

Equation (1) will then be written:

$$c_o = \frac{10^{-3}}{H_1} \left[\frac{Ao}{QN} + \frac{1}{12.5} j_N \xi_o \right] \qquad (1A)$$

which lets us study optimization under fixed conditions characterized by the equation $A_o = 51.0. D^{-1.435}$.

In the case of multiple electricity rates, we need only take the definition of ξ which is:

$$\xi = \Sigma p H_{2p} + a = p_m H_2 + a$$

with H_{2p} representing the schedule corresponding to rate p, or

with p_m being the weighted mean rate over the year per Kwh of electricity.

This same formula can also allow you to make accurate adjustments to a, insofar as this term would not have the constancy of cost per Kwh which the requirements of the method oblige us to assume for it.

2.2. Choosing the economic diameter

The givens are Q_{N1}, . H_1; H_2, and p, and hence ξ_o

To find the diameter D which would assure the lowest transport cost, we need only look for the point at which the c_o curve is nul $\frac{\partial co}{\partial D} = o$, at a constant flow Q_N:

$$\frac{1}{Q_N} A_o + \frac{1}{12.5} \xi_o \, dj = 0$$

With AQ constant we have $jD^{4.75}$ constant $\frac{dj}{j} = - 4.75 \frac{dD}{D}$

as $A_o = 5;.0 D^{1.436}$ and $\frac{dAo}{Ao} = 1.436 \frac{dD}{D}$

$$1.436 A_o - 4.75 \frac{Q j_N}{12.5} \xi_o = 0$$

$$1.436 A_o - 4.75 P_N \xi_o = 0$$

$$\boxed{P_N = \frac{1.436}{4.75} \frac{A_o}{\xi_o} = 0.305 \frac{A_o}{\xi_o}}$$

and the minimal value of c_o is:

$$c_o = \frac{10.^{-3}}{Q_N' H_1} \quad A + \underline{p} \ \xi_o \quad = \frac{10^{-3}}{Q_N H_1} \ \times 1.305 \ A_o$$

When the optimum is reached the transport cost is such that the cost of pumping (amortization of the pumps and power consumption) represents 30.5 percent of the annual amortization of the pipelines (pipelines thus represent 76 percent of the cost of transport, while pumping costs account for 24 percent).

In using these formulas one can make use of charts either with concurrent points or with straight-line points. This chart is attached to the present study.

To find c_o directly, we have constructed the straight line A_o/Q (which there is little practical point in graduating) which, with straight lines E1 and A_o, forms a second grouping representing the equation:

$$c_o = \frac{10^{-3}}{H_1} \times 1.305 \ \frac{A_o}{Q}$$

by alignment of points H_1, c_o, and $\frac{A_o}{Q}$.

Once you have this, you need merely join point H_1 to the intersection of the straight line already found and axis A_o/Q to read c_o on its graduation.

3. REMARKS AND CONSEQUENCES

3.1. Discontinuity of diameters. Choice of actual diameters.

The chart enables us to determine the optimum diameter, allowing for the operating level and for the cost per Kwhe. At optimum, the cost c_o of transport passes through a minimum.

As a result of this, we find that around the minimum of every curve this cost, c_o, presents a horizontal plateau in the $c_o D$ diagram; this means that if we take a different value for D, but one still close to the minimum, we get a compensation between the up or down variations in the annual payment corresponding to the investments and that of pumping costs which is inverse. So we have a certain freedom of choice insofar as effective diameter is concerned. We can take the next biggest commercial diameter just as well as the next smallest. However, if you contemplate any future increase in requirements, we shall obviously choose the larger diameter: by reason of its proximity to the minimum, this choice is not a penalizing one even in the immediate future.

(This choice therefore entails no perceptible change in transport costs so long as we stick close to the optimum calculated diameter. The chart does not allow us to calculate these rectifications because the formula $c_o = 1.305\ A_o/H_1Q$ applies only to the optimum diameter.)

We can, for that matter, quite easily pimpoint this detail by means of a quick calculation.

If you have an optimum diameter D_o for a flow Q, the choice of a diameter larger by n percent

$$D = (1 + \alpha)D_o \qquad \alpha = \frac{n}{100}$$

entails an increase in investment of:

$$(1 + \alpha)^{1.436}$$

Since at a constant flow we have:

$$P\ D^{4.75} = C^{te}$$

with the pumping cost varying as P, it varies as $(1 + \alpha)^{-4.75}$. Overall expenditures and the cost per therm (with the number of therms remaining constant) will finally vary as:

$$(1 + \alpha)^{1.436} + 0.305\ (1 + \alpha)^{-4.75}$$

for $\alpha = 0.10$ 1.147 + 0.305x0.9045 = 1.335 or + 0.03 or 4.3%

for $\alpha = 0.20$ 1.306 + 0.305x0.795 = 1.526 or +-.25 or 17.5%.

Insofar as you can adapt the diameter by around 10 percent either way, the incidence of diameter discontinuity on cost will not exceed 5 percent.

3.11. Flexibility of the solution

Even a quite perceptible increase will not necessarily, especially with large flows (in which c_o is slight)entail a prohibitive increase, but will allow broad expansion in the future, since an increase of 10 percent in diameter corresponde to an increase in optimal flow in the neighborhood of 22 percent. Thus, by taking a real diameter 10 percent greater than the optimal, it will become optimal with a 22-percent increase in flow, while paying only 4.3 percent more right now for transport. Another 22-percent increase bringing the total increase to 50 percent entails of itself only a 4.3 percent increase in the previous optimal price, which was itself slightly below the optimal price for the initial flow. In practice, we should still be below the initial price. So we see that by moving just above the optimum, we achieve very great flexibility insofar as the future potential of the system is concerned; there is a very broad area within which you will get a practically constant cost for therm transport by means of simple modifications of very low cost in the pumping plants: that range can run as high as 50 percent of the initial flow.

This is probably the main advantage of this economic study, because in choosing a pipeline diameter according to different criteria (for example on a load loss arbitrarily set a priori), you may well find yourself in a zone where an increase in the demand on the system could not be absorbed under reasonable conditions. This shows the advantage of choosing, for a constant-flow installation, pipeline diameters that are big enough, often with flow rates and load losses perceptibly below those commonly assumed.

The proximity of the ξ_o and the U flow-rates columns on the chart shows that there is an almost definite relation between U and ξ_o. For values of ξ_o close to 800 (for p = 10° and H_2 = 7460 hours, ξ = 822), the rate corresponding to the optimum stays close to 2.50 m/sec. For p = 6°, H_2 = 7460 h ξ = 460, it hovers around 3 m/sec.

> (On the contrary, for ξ = 1000, which corresponds to p = 13 centimes, you have to drop to flow rates of only 2.25 ± 0.25.)

A properly chosen flow rate criterion could, in the last analysis, yield conditions very close to optimum. It is in any case much better than a "load loss" croterion which can have some very unpleasant and costly surprises.

3.2. Variation in optimum diameter and transport cost as a function of an operating level.

3.2.1. Preliminary remarks

From the equations shown we can deduce that the optima D and A_o and the cost, c_o corresponding to them are linked to the nominal flow, Q_N and to the pair ξ_o - H_1 (1) defining the mode of operations by the three following explicit equations:

$$\xi Q_N^{2.75} \; D^{-6.185} = Cte$$

$$\xi Q_N^{2.75} \; A^{-4.317} = Cte$$

$$c_o \; H_1 \; \xi^{-4.317} \; Q_N^{6.765} = Cte$$

If you compare two solutions corresponding to the same demand, Q_M, but with flows of $Q_N = \alpha Q_M$ adapted to the operational level defined by ξ and H_1, we get:

1st level: $\xi_1 \, \alpha_1 \, H_1 \, D_{opt} = D_1$

2nd level: $\xi_2 \, \alpha_2 \, H_1 \, D_{opt} = D_2$

We have:

$$\xi_1 \, \alpha_1^{2.75} \, Q_M^{\;2.75} \, D_1^{-6.185} = \xi_2 \, \alpha_2^{\;2.75} \, Q_M^{\;2.75} \, D_2^{\;-6.185}$$

$$\left(\frac{D_1}{D_2}\right)^{6,185} = \frac{\xi_1}{\xi_2}\left(\frac{\alpha_1}{\alpha_2}\right)^{2.75}$$

The ratio D_1/D_2 does not depend on Q_M. The same goes for A_1/A_2.

Any reasoning about a particular case thus has a general impact, provided you express the results in percentages. On the diagram this can be seen by the equality of the segments (calculated on the logarythmic graduations).

3.22. <u>Comparison of severaltransport operating levels</u>

Consider the four following levels and a cost per Kwh of 10 centimes:

1. Flow Q_N = Q for 7,460 h - H_1 = H_2 = 7,560 h ξ_o = 822
2. Flow Q_N with H_1 = 5,700 h - H_2 = 5,010 h " = 577
3. Flow Q_N =1.25Q with H_1 = 5,070 h - H_2 = 3,400 h " = 416
4. Flow Q_N= 1.50Q with H_1 = 4,620 h - H_2 2,900 h " = 366
5. Flow Q_N=2.50Q with H_1 = 2840 h - H_2 = 1,120 h " = 188

This corresponds:

1. to the case of supply from a storage facility which may or may not satisfy the total demand of a town whose maximal thermal power is Q_M = 2.50 Q;
2. to supplying the same town with a supply ceiling equal to 40 percent of maximum need;
3. -d°- -d°- to satisfy 50 percent of those needs
4. -d°- -d°- to satisfy 60 percent of those needs
5. to total direct supply of that town.

Take for example: $Q_M = 1,250$ Kth/h

$Q = 500$ Kth

We arrive at the following results (Table II)

Case	Theoretical Diameter	Practical Optimum	Price of transport in centimes/100 K? (within 0.1)	OBS
1	820	800	2.6	0
2	770	700	3.25	+ 24 %
3	820	800	2.7	+ 40 %
4	860	800 or 900	3.1	+ 20 %
5	980	1000 or	3.5	+ 35 %
		900	3.6	+ 38 %

If you allow for a storage loss of 20 percent on stored therms, the cost per delivered therm in case 1 rises to 2.75 centimes.

We can make the following observations:

a. The same diameter is practically suitable for cases 1 and 3, with the cost per therm not very different.

b. It is suitable even for cases 1 to 4 and would not be too far off the mark even for case 5. Similarly, the 900 diameter would be good enough even for case 5 according to the foregoing remarks, and in cases 1 to 4 leads to increases of only 0.2 centimes, and it is therefore advisable if any increase in requirements is foreseen.

c. Absent storage at the point of consumption, solution 3 (supplying 50 percent of power) seems to give the lowest cost. This observation is interesting because it shows that if supply comes from storage at the production site, or from a heat-breeding reactor with a certain excess of power even independent of the savings resulting from the replacement of fuel oil by nuclear-origin therms from the angle of transport alone, you are quite normally led to provide a bigger share of the power that you would have expected a priori.

(This share is actually even larger.)

d. Finally, on short antennas, total supply without storage at the point of consumption or backup installation will not lead to any aberrances (except that in low flows there may be overly high fluid velocities), at least with the CPCU monotone.

At equal maximum power of 1.250 Kth, a monotone of the PARIS CLIMATE type (H_1 3,200 hours, ξ_o close to 100) yields an optimum of 4.1 centimes per 100 kilometers or 15 percent more than with the CPCU monotone, but along with it, it is true, there will be very high load losses and speeds (even technically too high).

> (ξ values below 200 [?] appear to be scarcely usable because of this fact. This means that there will be a peak problem for systems in which the Q_M/Q_{mean} ratio exceeds 2.5 or 3, which might justify local storage facilities.)

3.23. <u>Influence of electricity rates</u>

These come in via ξ. A drop in the power rate is reflected on the chart in a rotation around point Q in a counter-clockwise direction by the straight line $Q\xi$, and hence by a decline of optimum D.

3.231. One initial consequence is that the steady relative decline in power rates which has been going on for a long time and which nuclear power was to let resume after "digesting" the break due to the oil "crisis," will lead to a slight relative shrinkage of investment expenditures and of costs. On already existing systems, the rotation of the straight line around D corresponds to an increase in the optimal flow.

For example, if the price of a Kwh drops from 10 to 8 centimes, the ξ corresponding to case 1 drops from 822 to 672. This corresponds to an increase of about 6 percent in the cost of transport of a therm (A_o being the same, the price $c_o = 1.305\ A/Q$ will follow the variations of Q).

The consequence of this is that a system which was optimized at one time, is further optimized by a markedly increased demand; this observation is in addition to the considerations already developed earlier with reference to a zone of "flexibility"; that zone is broadened still further.

3.232. <u>Having different winter and summer rates</u> plays exactly the same role as a cut in rates when you are dealing with systems in which the summer expenditure quota is sizable.

3.2321. This is the case, for example, of the system we have already talked about, with 2 towns, each with a maximum demand of 1,250 Kth/h, with a mean demand of 500 Kth per hour over 7,460 hours, one of them close to a heat-breeding reactor, the other close to the storage facility. The maximum transit is 35 percent times 2,500 or 875 Kth:

$$H_2 = 3700, \quad p_m = 0.65 \quad p_h = .65¢, \ \xi = 316$$

The optimal diameter is 910, corresponding to $A_o = 855\ 10^3$ F/Kw.

There is no point in calculating H_1, since the total annual expenditure is 1.305 A_o = 1120 10^3 F/Kth or 11.200 10^6 c/100 Kth for an actual total delivery (minus 20-percent storage losses) which is well known to be 7,120 x 10^6 therms or 1.57 centimes per therm and per 100 kilometers of distance between the two towns,

$$(1) = p_h = \text{price for peak winter hours}$$

(not counting transport losses: these losses with a pipeline 900 mm in diameter are 3,600 th/km/yr or, in the case under consideration, 360,000,000 per 100 kilometers or 5 percent of the total distribution. With an 800-mm pipeline they are 3,200,000 Kth/km/yr. The incidence is fairly slight: 0.08 centimes /100 kilometers. Storage costs are not included either.) With such a design, it is no longer possible to dissociate production from consumption and storage because these three factors are part of a total, coherent whole which might be compared with another whole, such for example as that of two local storage facilities with the production plant located between the two towns. At that point we have an instant flow toward either town of 500 Kth/hr : H_1 = 7460 and H_2 = 7460 and p_{mh} = 9 centimes, ξ = 748.

The retail price is the one we have already calculated: 2.75 ¢ per 100 kilometers for each of the two transport components or 2.8 per 100 kilometers in all, allowing for storage losses, or 1.42 centimes per 100 kilometers of distance between the towns. The optimum diameter will be 800 or 900, and transport losses very close (320 x 10^6 therms instead of 360 x 10^6 with a differential incidence of less than 1 percent).

We find a difference of 1.57 - 1.40 centimes per 100 kilometers equal to 0.15 centimes per therm distributed (or around 0.60 centimes per stored therm).

It is this difference we must look at to see if it is or is not compensated for by the effect of scale economy on the storage plant facilities (in this case the comparison is between the solution of two storage facilities with a capacity of 800 x 10^6 therms each in each town, and the solution with a single storage plant with twice the capacity at one extremity).

By virtue of the preliminary observation made as to the proportionality of the findings 0.60 centimes per 100 kilometers for towns of 12500/500 Kth/hr would amount to:

$$0.60 \times \frac{3.5}{2.7} = 0.75¢ \text{ / 100km for 625/250 Kth}$$

$$0.60 \times \frac{4.4}{2.7} = 1¢\text{/100 km for towns of 250/100 Kth/h3.}$$

4. CONSEQUENCES INSOFAR AS CONCERNS DISTRIBUTION LINES

In a system there will thus generally be a central plant forming a coherent whole. For reasons made quite clear by the two-town example just cited, we shall have to supply, within this whole, certain sub-stations on a priority basis from the heat-generating plants, and certain others will be supplied in winter primarily from storage facilities. But in the last analysis we shall have a single price per distributed therm becaüse it is impossible to consider such a system other than as a whole. Let q equal the price which includes transport and storage costs and which may be subject to slight variations as a function of the total annual demand.

Onto this whole will be grafted distribution which we can assume are supplied at the single price, q, with this price also open to influence by the total flow from the antennae.

We shall now look at the problems posed by these distribution lines

4.1. Length of distribution lines

It cannot be such that at its end, the retail cost is greater than that of the fuel-generated therm, or 5.5 centimes /th in the first analysis

$$\frac{c_o l}{100} < 5.5 - q \qquad l < \frac{550-100\,q}{c_o}$$

c_o will depend on the mode of supply.

We have seen elsewhere that for supply with storage at the point of consumption and with the CPCU monotone c_o had a minimum which is the supply of 50 percent of power (see table in 3.22).

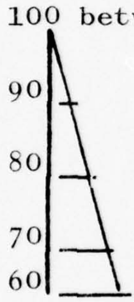
4.2. A question now arises: Is there any advantage in providing 100 percent of supply?

This leads to an increase of around 30 percent in the transport price per therm over the optimum 50 percent, but we must allow for savings in fuel and in amortization costs on the standby plant. It is certain a priori that there is always an advantage in supplying at least 60 percent of power because between 50 percent and 60 percent the drop in c_o is very slight. A quick look will show that between providing 60 percent and 100 percent of power, the increase in transport costs per therm is just about linear and increases by 22 percent (5.5 x 10 percent) going from:

$$c_{60}\frac{L}{100} \text{ to } 1.22\, c_{60}\frac{L}{100} \text{ (L = distribution length in kilometers).}$$

If we assume that for 60 percent the additional requirement will be 10 percent of the total and that the monotone between 100 percent and 60 percent is a straight line (the uppor portion of the monotones is of course the least clearly defined by reason of the random nature of extreme cold snaps. In fact, when you supply more than 80 percent of maximum power, the backup plant which provides the extra 20 percent will sometimes go for a year at a time without being used.),

we can calculate the marginal retail proce of transport per therm when we supply 90 percent, 80 percent, 70 percent, or only 60 percent (in relation, in other words, the cost of the total increase, to the additional amount distributed):



between 60 and 70% it is $d_{60} = 1.97\ c_{60} \frac{L}{100}$

" 70 and 80% " " $d_{70} = 2.76\ c_{60} \frac{L}{100}$

" 80 and 90% " " $d_{80} = 3.65\ c_{60} \frac{L}{100}$

" 90 and 100%" " $d_{90} = 9.17\ c_{60} \frac{L}{100}$

The sum of q + d must be compared with the price per fuel-generated therm provided under emergency conditions, which is to say with an operating time of:

for 60 percent of $\frac{1.10 \times 3000}{0.4} = 750$ hrs/yr (full power equivalent)

" 70 percent of $\frac{0.56 \times 3000}{0.3} = 560$ "

" 80 percent of $\frac{0.25 \times 3000}{0.2} = 375$ "

" 90 percent of $\frac{0.006 \times 3000}{0.1} = 180$ "

Assuming that in the cost of a fuel-generated therm from a plant operating for 3000 hours the production amortization amounts to 0.3 centimes of the 5.5 centimes if the usual cost per fuel therm. with the rest being proportional factors, the corresponding retail price per fuel-generated therm to be taken into account would be:

for 60% $f_{60} = 5.2 + 0.3 \times 3000/750 = 6.4$ centimes

for 70% $= 5.2 + 0.3 \times 3000/560 = 6.8$ centimes

for 80% $= 5.2 + 0.3 \times 3000/375 = 7.6$ centimes

for 90% $= 5.2 + 0.3 \times 3000/180 = 10.2$ centimes.

we find that installation of a backup fuel-fired plant is justified:

for 40% of power (only if the distribution lines exceeds 330 Km)
$60¢$

" 30% " " " " $\frac{240 \text{ Km}}{60¢}$

" 20% " " " " $\frac{205 \text{ Km}}{60¢}$

" 10% " " " " $\frac{111 \text{ Km}}{60¢}$

In addition, one must of course make sure that:

$$c_n \frac{1}{100} < 5.5¢ - q$$

as well as:

$$c_{60} \frac{L}{100} < 5.5¢ - q$$

$$L < \frac{550}{6C¢} - \frac{100q}{60¢}$$

For example, if you have consumption of 150Kth/hr at maximum power P_M, or:

$$0.60\ P_M = 90 \text{ Kth/hr}$$

$$\xi_{60} = 366 \text{ (CPCU monotone)}$$

$$c_{60} = 7 \text{ centimes (approx.)}$$

You have the following minimum distances to justify backup plants:

Power of the backup plant	10% P_M	20% P_M	30% P_M	40% P_M
Distance	16 Km	29 Km	35 Km	45 Km

These distances are inversely proportional to c_{60} and we see that they are quite considerable even for an antenna of modest proportions. It is most often advantageous to distribute 80 *percent*, very often to distribute 90 percent, and often to distribute 100 percent of power from the central plant. (1), (2)

1) (For example, for a city like Valenciennes which uses 500 Kth per hour at peak load, $c_{60} = 4.2$, a backup plant rated at 50 Kth per hour would be justified only for a feed distribution lines in excess of 26 kilometers, which is just about the distance between Douai and Valenciennes.

2) What we have here is in fact a fairly academic question when a system is nearing the construction stage. In practice, since you will always allow for some possibility of extension, it will always be a little oversized and therefore you will usually be better off supplying total requirements. The problem of optimization arises later in the form of a choice between building a backup plant and upping the rated power of the pumping stations, thus doing the same thing in two very different ways.

4.3. Storage at point of consumption

The relatively slight difference between the 100 percent transit price and continuous transit with storage leaves only a pretty slim slot for storage at point of consumption. If you allow for storage losses of 20 percent, the difference comes to only 28 percent, which means that storage will have to fit into the difference between:

$$0.28 \frac{c_s L}{100} \text{ per therm delivered}$$

c_s indicating continuous flow with storage of 1.12 $\frac{c_s L}{100}$ per stored therm, for an investment of 9.6 $\frac{c_s L}{100}$ centimes per storable therm per year.

Furthermore, $\frac{c_s L}{100}$ must be less than 5.5 ¢ - q (q is at least 2¢).

For q = 2¢, which is quite optimistic (3), that would lead to storage investments of less than:

0.35 Fr per storable therm for a 100-km distribution lines (c_s 3.5¢) (4)

0.28 Fr per storable therm for an 80-km distribution lines (c_s 4.5¢) (5)

0.25 Fr per storable therm for a 70-km distribution lines (c_s 5¢) (6)

---

(3) Not absurd, though, if the stored therms have been marginally produced, which is quite often the case.

(4) This refers to distribution lines of at least 300 Kth/hr, and hence to distribution lines with peak consumption of 750 Kth/hr.

(5) This may apply to distribution lines of around 150 Kth/hr.

(6) This may apply to distribution lines of around 100 Kth/hr.

You are at risk of very swiftly running headlong into the scale effect on storage facilities at the end of the distribution lines. (1)

(1) It is nevertheless possible to design local storage facilities tp provide backup for peak-hour standby plants. The sole consideration here is to cope with extreme demand peaks. A closer study of needs then becomes necessary, because at this point you have to consider variations over the day-span (particularly as between day and night) and over the week-span (particularly when you have plants or other activities which are shut down or slowed down over weekends). What you need now to cover these extreme peaks (above 80 or 90 percent) is no longer seasonal storage facilities, but daily, or at most weekly storage facilities. So you can consider several different solutions:

- you can consider storing in reservoirs (even low-temperature, unpressurized reservoirs) to supply certain localized sectors which warrant it,

- or storage in specially dug tunnels. It might be pointed out that even over the days or weeks when there is no need to draw upon them, these kinds of storage are still a paying proposition, because by using them you do, willy-nilly, subtract from transport at peak or full power hours and add to slack hours, and thus save peak-hour electric power.

4.4. Consequences as concerns storage facilities

We have already noted the difficulties which may arise for storage facilities at the ends of antennae. the advantage of using differential power rate structures in order to give preference to summertime therm transport, and the need for integrated design of production-transport-storage systems.

Furthermore, intensive design study of storage facilities should lead to providing them with a major scale effect. The relative building costs apparently should be strongly regressive, as should relative losses, once the scale of storage facilities is expanded. This consideration fits in quite nicely with the overall concept of a production-transport-storage design for systems, in which the generating plants are in the center of a sub-group of users, and storage facilities are in the center of other sub-groups with variable transfers and summer maxima.

This would lead us to establish very large storage facilities at a centralized point quite distant from the generating plants so that a major share (at least 20 percent) of consumers would be located within the zone comprised between the two; they would be supplied sometimes from the generating plant, sometimes from seasonal storage facilities using the connecting feeder to which the individual antennae would be attached. The boundaries of the zone supplied directly by the generating plant and from storage would shift over the year.

During the summer months, the feeder would feed into the storage facilities directly from the generating plant. A slightly over-powered pump installation would even allow of emergency fallback with total retro-supply from one or more storage facilities.

Such a design would lead to shifting most of the work of transport from generating plant to storage facilities to the summer months, and hence, in the final analysis, to transporting marginal therms using kilowatts themselves marginal: this is, of itself, optimization.

APPENDICES

We have seen that in judicious design of production and seasonal storage there was an advantage to be derived from distributing generating plants and storage facilities in such a way as to do most transport in summer, so as, in the final analysis, to transport marginal therms with marginal kilowatts during marginal hours.

In fact, this particular observation is even broader in scope, since even in winter or between seasons, the daily and weekly fluctuations in demand mean that trips from the generating plant to the storage facility (or even from the generating plant directly to users located close to storage facilities served by the plants on a priority basis) are maximal at night or on weekends when the decline in demand for heat is most marked. Closer analysis will show that even during these periods, the slack hours are the ones which match the peak transport hours, whereas transport is at its *minimum* during the peak demand hours.

On a very general level, the result of this is that the electricity required for transport is almost always marginal even in winter, and that the system-wide savings on the national scale must be calculated by taking a marginal cost for electricity, which is now, for example, 6 to 7¢, thereby reducing the ξ by a like amount.

On the practical level of system operation this means that the pumping stations will be using rates at which the obliteration of peak loads will make it possible on the one hand to determine a <u>fixed rate</u> on the basis of reduced power allowing for this obliteration of peaks and for the fact that full power is delivered only in summertime, and hence of achieving major economies on this fixed rate; on the other hand, it will make it possible to take full advantage of the slack-hour rates, even in wintertime and between seasons.

These observations show that with relatively low ξ levels which could be achieved through judicious use of rates (which might settle at around 300), you can get transport costs down to around 3 to 4¢ per 100 kilometers, even on feeders transporting averages of 500 Kth/hr, and that these costs are comparable with those of constant-flow transportof the same amount over a year, but not enjoying the same advantageous rates and far less well matched to actual production and consumption rates. This observation also leads to a reduction of economic diameters, and hence of investments.

Introducing set rates into the ξ formula

Electricity rates usually include a fixed annual rate per kilowatt for power contracted for, p_F, and a scale of prices per Kwh concumed, p_b, as a function of the utilization timetable (peak hours, winter full hours, summer full hours, winter slack hours, summer slack hours)

It is obvious that p_F plays the same part as amortization of the pumping station, and that we can therefore write:

$$\xi = a + p_F + \Sigma\, p_b H_{b2}$$

which gets around having to calculate the mean price per kwh including the fixed rate for each period, and lets you bring in only the sliding scale prices in calculating ξ.

HOW TO USE THE GRAPH

Knowing the nominal flow of heat, Q, and the value of ξ_o, which is a technico-economic given characterizing the operation of a specific feeder and condensing the weighted mean cost per Kwh of electricity, the per-kw amortization of the pumping installations and the weighted annual schedule H_2 of operation (equivalent hours of full power), by combining Q and ξ_o you get, on the D scale, the optimal economic diameter with its cost, A_o under the economic conditions of establishment given by the graph, and on scale P the pumping capacity to be installed per kilometer; and on scales j and U you can read the load losses and flow rates corresponding to them, in mm/m and m/sec).

Taking the point where this straight line intersects the peak, A_oQ, and joining the point thus obtained to the point on the H_1 scale corresponding to your operating conditions (H_1 is the weighted operating schedule for the system, with weighting for the flow (1), you get, on the c_o scale, the cost of transport per therm in centimes per 100 kilometers (not counting heat losses) under the economic conditions for which the graph was set up.

The value of ξ_o is given by the formula:

$$\xi_o = \frac{\xi i_o}{i}$$

(i = the cost index for pipelines, and is designed to offset economic variations. (When weighting of H_2 has an effect on the pumping power, this precautions makes it possible to make the chart independent of such economic variations.)

$$\xi = a + p_m H_2$$

a = amortization of pumping stations reduced to kilometers

pn = weighted annual price per Kwh of electricity.

the actual cost, c, is deduced from c_o by:

$$c = c_o \frac{i}{io}$$

HOW TO USE THE GRAPH FOR SUPPLY-RETURN TEMPERATURE DIFFERENCES OTHER THAN 100°

-:-

The Q and c_o columns (scale on the left) have been set for a ΔT on delivery of 100°.

For ΔTs other than 100°, you must either refer to the right-hand scale (in T/hours) and use hydraulic flows, or multiply the left-hand scale of thermal flows by $\Delta T/100$.

At the same time, multiply the values of the scale in the c_o column by $100/\Delta T$.

Example: for a flow of geothermic origin at 70°C with backflow at 55°C (ΔT = 25°C) you design a flow of 25 Kth/hr on a continuous basis (around ξ= 800).

Then connect ξ= 800 with the 100/1000 point on the Q column ($100 \times \frac{15}{100}$ = 25 Kth/hr); the optimal diameter is 400 mm.

Joining the intersection with A/Q to $H_1 = 8000^h$, you get 4.7 over c_o, which gives you:

$$4.7 \times \frac{100}{25} = 18.8 \simeq 19¢/100 \text{ km}$$

For a pipeline carrying 20 Kth/hr at 90/70 ΔT = 20°, you will also get D_{opt} = 400 mm and a retail price of 55¢ per 100 km, with a 2600-hour feed:

$$\xi = 76 + 125^{(1)} + 1000^h \times 0.07 \text{ fr} = 271$$

(1) Fixed rate)

D_{opt} theoretically will be 335 mm; practically, it will be 350 mm.

and you read 11¢ on the c_o column

$$11 \times \frac{100}{20} = 55 ¢/100 \text{ km} = 0.55¢/\text{th/km},$$

which would ban any such transport over more than a few kilometers.

2. USING THE GRAPH IN CASES WHERE THE ACTUAL DIAMETER IS FAR FROM OPTIMAL

-:-

The graph for the cost of transport is set up according to the formula:

$$c_o = \frac{10^{-3}}{QH_1} 1.305\ A_o$$

which corresponds solely to the optimal choice. If, for various reasons, there is variance from this choice, the graph can nevertheless enable you to calculate transport costs. The real cost at this point becomes:

$$c_o = \frac{10^{-3}}{QH_1} (A_o + P\ \xi_o)$$

Taking the straight line which connects Q with real D (or A_o), you get the required power, P, to install, but this straight line odes not pass through ξ_o. It cuts across the scale of ξ s at ξ'_o <u>which you read</u>. You then have:

$$P\ \xi'_o = 0.305\ A_o$$

because this straight line represents the optimal solution for the value ξ'_o, or:

c'_o is the cost corresponding to Q, ξ'_o as read on the chart via the classical method:

$$\frac{c_o}{c'_o} = \frac{A_o + P\xi_o}{A_o + P\xi'_o} = \frac{1 + 0.305\ \xi_o \xi'_o}{1.305}$$

and hence:

$$c_o = c'_o\ (0.774 + 0.226\ \frac{\xi_o}{\xi'_o}$$

This formula gives a relatively easy assessment of the real cost, once you know ξ_o.

SOME THOUGHT ON OPTIMIZING LONG-DISTANCE HEAT TRANSPORT SYSTEMS AND ON THE PLACE OF STORAGE IN SUCH SYSTEMS

Complement n° 1

1. <u>The incidence of certain aspects of electricity rates on the cost of heat transport in systems containing seasonal storage facilities and possible daily-weekly facilities.</u>

In transport installations containing storage facilities, it will in many cases be possible to make daily, weekly, or seasonal adjustments to the heat flow. This potential can result in:

a) storage at production points, be they seasonal or daily storage facilities, or daily/weekly facilities;

b) adjustments in production: this is the case particularly when production is accomplished by drawing off steam at some level in the power plant cycle. These steam drawoffs can be increased when power demand is low, either in slack hours or in summer, cut back or even cut out altogether at peak load hours, when power demand is maximum and where there is therefore an advantage to be derived from doiing away with all steam drawoffs so as to achieve peak electricity production.

The coincidence of slack hours for electric power with maximum heat production is a very favorable factor to the consideration of systems including storage facilities.

It is in fact possible to transport heat at instantaneous marginal transport cost. The instantaneous power is in fact proportional to jQ (j = load loss, Q = flow), and this instantaneous cost is proportional to $j\ p$ (p is the instantaneous rate per Kwh). All you need is to operate at constant jp, which is to say at constant $pQ^{1.75}$ for the electricity cost per transported therm to be constant. The fact that Q enters at its 1.75 power means that the reduction of Q is much slighter than the rate increase and that this result is obtained by a very slight reduction in the instantaneous flow.

An additional advantage of this option lies in the fact that the "fixed rates" in electrical supply contracts are set on the basis of a lower power level resulting from the power requirements contracted for during heavy hours, minus a fraction (usually 40 percent) of the difference between it and the maximum contracted power during heavy use hours which will be lower, and that furthermore power overruns in slack hours are practically never penalized.

A numerical example will make this mechanism clear:

Given a continuous transfer over 7416 hours (4368 hours of winter plus 3048 hours of summer) at a flow of Q_m.

These 7416 hours will break down into:

- 4,2 peak load hours
- 2084 heavy winter hours
- 1872 slack winter hours
- 1658 heavy summer hours
- 1380 slack summer hours

We shall assume the following rates:

* Peak hours	17 centimes
* Full winter hours	12 centimes
* Slack winter hours	5 centimes
* Full summer hours	7 centimes
* Slack summer hours	4.5 centimes

The $p\,Q^{1.75}$ constant, taking as a reference the value of Q_N corresponding to slack winter hours, yields the following flows:

* slack winter hours	$Q = 0.94\ Q_N$
* full summer hours	$Q = 0.86\ Q_N$
* full winter hours	$Q = 0.54\ Q_N$
* all peak hours	$Q = 0.44\ Q_N$

Over the same total schedule the mean flow is $0.77\ Q_N$.

This means that we have two equivalent solutions:

constant flow Q_M across 7416 hours and a weighted cost per Kwhe (outside the fixed rate) of 8.75¢ or a variable flow with a maximum equal to $Q_N = 1.30\ Q_M$ ($H_1 = 5870$).

In the first case the fixed rate is calculated on the power corresponding to the Q_M flow (or p_F times Kw of Q_M).

In the second case the fixed rate is calculated on the basis of the power corresponding to the $0.86\ Q_N$ flow (cost $0.77\ P_N$) with a discount allowing for peak hour flow $0.44\ Q_N$.

<u>First solution</u>

Let $Q_M = 250$ Kth/hr

$p_F = 100$ F/Kw

$p_m = 8.75¢ = 0.0875$ F

$\xi = 76 + 100 + 7486 \times 0.0875 =$

$176 + 657 = 833$

Optimal diameter of pipeline: 620 mm
Real " " " : 600 to 650 mm

Retail price $H_1 = 7486^h$

$c_o = 3.6¢$ per 100 Km per therm.

Second solution

$Q_N = 250 \times 1.30 = 325$ Kth $H_1 = 5870$

$p_F = 65$ F/Kw (since the taxable reduced power is $0.65P_N$)

There is no point in calculating p_n because we know that the expenditure is the same as if we were transporting the total Q_N flow in slack summer hours. So we have:

$$p_n H_2 = p_{HCe} \times 5870 = 262$$

$$\xi = 76 + 65 + 262 = 403.$$

Theoretical optimum diameter $D_{th} = 610$mm

Real diameter $D \approx 600$ or 650 mm.

$$c_o = 76 + 65 + 262 = 403.$$

The difference between the two solutions is less than the inevitable error in assessment.

First conclusion

This numerical example, fairly close to reality, has a general scope (1), and it shows that you can get just about (2) the same transport price for a therm in constant flow transport as in a judiciously adjusted flow and that the two systems have just about the same practical pipeline diameter.

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(1) Because the result is in fact independent of the chosen Q_M rating.

(2) In fact, the two representative straight lines shown on the graph intersect along the axis of c.

Impact of seasonal storage on production

It should be pointed out that if you have seasonal storage facilities on or near the production site which make it possible to transfer heat to distant storage facilities outside the production period, the result would be very favorable to storage.

This is easy to understand from a numerical example of transfer based this time on 8486 hours (so as not to take 8760 hours), or:

- peak = 412
- full winter hours = 2084
- slack winter hours = 1872
- full summer hours = 2348
- slack summer hours = 1770

Or in that case:

$$* Q_M = 0.81\ Q_N \text{ and } Q_N = 1.24\ Q_M \quad H_1 = 6820^H$$

and $* p_r = 0.5\ p_m$

$$* p_m H_2 = p_{h2c} H_1 = 0.045 \times \frac{8486}{1.24} = 304$$

$$* \xi = 76 + 50 + 304 = 430$$

$$* Q_N = 250 \times 1.25 = 312$$

Optimum diameter 590 : practical diameter, 600

Transport cost c_o = 3.1¢ per 100 km or a saving of around 18%.

Second conclusion

The existence of seasonal storage facilities close to the production site thus makes it possible to save around 18 percent of the cost of transfer to a distant seasonal storage facility. You will note once more that such installations differ only in the design of their pumping installations, since the same pipeline diameters are usable under several hypotheses. The transition from one operating system to the other therefore calls for only modest additional investments, and at no point moves out of the optimal domain.

If in addition the storage facility allows you to assure neighboring customers of winter peak supplies in excess of the capacity of the heat-breeding reactor, or a possibility of heat drawdown from a power reactor, allowing for the electrical power demand, such storage facilities may well be quite profitable.

II. Problems of temperatures. Losses
Basic differences between nuclear fuels and "fossil" fuels, and between the case of direct distribution and that of long-distance transport with storage. Advantage of high temperatures.

Heat losses during transport are a major item in plant budgets.

This importance is always much greater insofar as concerns direct distribution than it is in long-distance transport, particularly if the transport operations include seasonal storage facilities.

In direct distribution, the heat flow is tuned to the instantaneous demand and is highly seasonal in nature. Furthermore, losses are not dependent on flow, but solely on the temperature differential between the pipeline and the outside environment. If you are operating at fixed temperature, the relative importance of heat losses is inversely proportional to the flow. It is therefore logical to minimize losses by setting outgoing and incoming temperatures on the basis of thermal needs, keeping them as low as possible within the limits of those requirements and allowing for technical limitations (those resulting for example from a requirement to provide potable hot water).

This is most important when the heat is produced with costly fossil fuels. You can always assume, in fact, that the lost therms are produced by marginal operation, since their abolition would produce only a marginal gain. In the case of N°2 fuel oil, the marginal cost per them is now 4.8¢ before taxes (on the basis of 380 francs per ton with a boiler yield of 0.80). In a distribution system in which losses at full power are 2 percent, in summer operating conditions, if demand is 20 percent less, if the distribution temperatures and hence the losses are unchanged, they will reach 20 percent with an annual mean of 8 percent for a monotone type of housing supply (2000 hours). If, in summertime, instead of distributing at 180°C with return at 80°C (a mean of 130° or 90°C above the temperature of the pipelines), you distribute at 90°-40° (mean 55 or 30°C above the conduit temperature), the losses are divided by 3 in summer. They drop from 20 percent to 6.5 percent, for a gain of 13.5 percent; with a retail price of 4.8¢ per therm, the summer gain is 0.75¢ per distributed therm (4.8¢ (1 - 1/0.865).

In exchange, you will have to allow an increase in flow and hence in pumping costs, but this flow, even so, is only 30 percent of the maximum and the specific consumption per therm proportional to the load loss is only $(o.3)^{1.75}$, or around 12 percent of the maximum specific consumption, instead of $(0.1)^{1.75}$ or around 2 percent, or a difference of 10 percent more. It should also be added that in summer you take advantage of the minimum rate, and this minimizes this difference when you look at costs. Well, to compete with individual household heat production, an urban distribution system can accept total transport costs no greater than 3¢, a fraction of the difference between the retail cost of the heat in the plant at FO2 around 5.5 ¢ and its domestic retail price at FOD around 9¢. If the system is optimal, the cost of pumping will represent on the average only 24 percent of those 3 centimes (we know that in an optimalized system this is the proportional share of pumping in fixed costs in the total cost of transport), or 0.72¢ in mean annual value. Allowing for the existence of the summer rate and for the fact that 0.72¢ is not the maximum cost, the transport surcharge may come to 10 to 20 percent of 0.72¢ or 0.1 to 0.2¢, and is considerably less than the 0.75 centimes saved.

The "distribution temperature drop" system is thus clearly profitable.

It is no longer so, however, when you are talking about heat produced from nuclear fuel. in this case, in fact, the marginal cost per therm is 1 centime in the CAS-type heat breeders, markedly less (0.5 centimes in production from live steam, 0.2 to 0.3 centimes in marginal production by steam drawdown), when the heat comes from a nuclear power plant.

The loss reduction saving then is only 0.15 centimes or less (0.07 and even 0.03 or 0.04 centimes) per distributed therm, owing to the very low marginal cost. The saving falls to around the same order or less than that of pumping surcosts, since the latter are in fact the same as for fuel-produced therms at equal distribution costs.But since when you talk about heat cheaper to produce, you can accept higher costs of transport or distribution, the extra costs remaining the same, but in relative value they are increased. The "lower outgoing temperature" operation is not profitable. Only a lowering of the return temperature which enables you to save at once on transport (by increasing ΔT and hence loweringflow) and on losses (by lowering the mean round-trip temperature), or again the simultaneous lowering of both without diminishing their difference, are acceptable.

The conclusion is even clearer when you talk about long-distance transport, particularly to storage points far from the production site. Maximum flows in such cases take place in summer and, despite the summer rates, the instantaneous marginal specific costs are then maximal; at best, they are just about constant over the year. Given this, there can be no question of cutting down the ΔTs, because a cutback in ΔT of 30 percent (from 1 to 0.7) would have to be offset by an increase in flow of 40 percent, entailing specific expenditures $(1.4)^{1.75}$ times as great, or an increase of 80 percent on an optimalized system. With a transport cost of 3 centimes of which 24 percent or 0.72 centimes goes for pumping and 80 percent of that 0.72 centimes are proportional costs. This would therefore correspond to an increase in distribution cost of around 0.48 centimes per therm. (1)

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(1) 0.72 x 80 percent = 0.48 centimes, from which you should deduct the 0.03 to 0.04 centimes corresponding to the loss reduction, or 0.33 to 0.45 centimes)

Quite the other way around, it is a good idea to take advantage of drops in return temperatures during the summer insofar as you can design systems to exploit them, so as to increase your ΔTs and either increase the heat flow without increasing the hydraulic flow, or cut back the hydraulic flow while retaining the heat flow, which wouldgive you sizable savings on marginal transport cost (by increasing the ΔT from 100 to 140^o you reduce, at constant heat flow, the instantaneous marginal specific cost of transport per therm by 45 percent or, under the present hypothesis about 0.30 centimes, which is a long way from negligible, since it would bear on every therm transported in summertime).

The approach of transporting heat over long distances once there are massif shifts in summer, which is to say when you have storage facilities, is radically different from the direct distribution approach, and even the distribution approach is quite different according to whether you are dealing with nuclear-produced therms (at low marginal cost) or fossile-produced therms (at high marginal cost).One of the consequences is that nuclear plants on the one hand (save in the special cases where their heat production is surrounded by technological limitations of temperature), and the season technicque of storage on the other, should logically lead us to look for the highest possible differential in outgoing-incoming temperatures, and that the quest for low-temperature trans port techniques which a lot of people are interested in now certainly does not have the economic future people somewhat rashly and deceptively attribute to it on the basis of views which in fact correspond only to local distribution of heat athigh marginal cost. There is no reason to make nuclear power bear the burden of a haunting fear born of the increase in crude oil prices.

The loss problem is more complex. It is best to distinguish between "outgoing" losses which entail an increase in flow and therefore do have a transport cost, and "return" losses, which must simply be replaced by an equivalent input but have no transport cost of their own.

In variable operation it is better to break the "outgoing" losses down into two parts:

a. a part proportional to the flow which has an identical cost of transport with that of heat actually delivered;

b. the rest which has no effect on the dimensions of pipelines, pumps, or anything else, and the cost of which consists solely of the specific instantaneous power consumption for pumping, which is very low, because it is transported when the Q_H flow is low, and hence the pumping power is too (it varies as $Q_H^{2.75}$) The cost of transport is ....

Finally, it would be well to note that in a variable operation the average outgoing cost of the heat lost is not the average cost of heat, because most of the lost heat is produced in summer or during slack hours.

Then there is the pretty considerable factor of heat from the pumping power, 80 percent of which is recovered by the water.

We might, just by way of a finishing touch, devise a system for calculating transport costs recurrently. These are initially calculated disregarding losses, then, once the losses are known, they are factored into consumer billing as we said earlier. In this case, it would suffice to recalculate the transport costs al lowing for these losses. Since we know that their existence does not affect the diameters, one recurrence would be enough. But actually, this little touch does not seem very necessary.