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REACTOR WASTE HEAT UTILIZATION AND DISTRICT HEATING REACTORS

Nuclear District Heating in Sweden - Regional reject heat utilization schemes and small heat-only reactors

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Most papers at this conference treat nuclear plants as electricity producers which will supply a growing part of the electricity demand whilst electricity increases its share of the overall energy demand. However, nuclear energy could increase its share of the energy market even further and improve fuel conversion efficiencies if, in addition, more serious attention were given to the use of the reject heat from nuclear power production at temperatures appropriate for district heating and to the production of heat only in small and simple low temperature reactors. The possible role of these two forms of nuclear energy in district heating schemes is the subject of the present paper.

1. THE HEATING MARKET IN SWEDEN

Traditionally three heating forms have competed for the heating market in Sweden since about 1950:

a) Oil fired boilers, dominant everywhere at the outset

b) District heating, which gradually penetrated the new suburbs with multiflat buildings, and thereafter also the down-town areas of most cities in Sweden

c) Electric heating, which gradually began to take over in new one-family houses, especially after the oil crisis.

By now some fifty cities have district heating schemes, in all cases using hot water at 120°C delivery and about 60°C return on the coldest winter day for the primary network. At other times lower temperatures are used, see Fig 1. Most of these schemes were started by small stationary or movable heat only boilers supplying favourable district heating islands. Gradually these were interconnected to create larger systems. For the ten largest cities district heating loads were eventually reached justifying the construction of combined heat electric plants with back pressure (or in a few cases pass-out) turbines for the base heat load. The saving in fuel consumption and fuel costs which combined plants achieved compared to separate power stations and heat-only boiler plants outweighed the penalties of smaller outputs (and therefore higher specific investments) of the combined plants compared to the large central power plants.

The oil crisis disturbed this economic balance in so far as it improved the economics of nuclear power plants compared to oil burning plants, thus restricting the economic field of application of oil fired heat/electric stations to relatively large plants. The higher oil prices have also made it worth while to study seriously the alternative of nuclear heat/electric and even nuclear heat-only plants.

As yet there is a large growth potential for district heating in the dense areas of many cities and with improved distribution technology it would also be an economic challenge to electric space heating in one-family house districts.

The strong commitment to reducing gross fuel consumption growth rates and concern for environment are further factors favouring district heating schemes. However, a cautious approach to nuclear energy in the current government policy may balance this trend where nuclear energy sources are concerned.

2. THE USE OF NUCLEAR PLANT REJECT HEAT

2.1 Swedish projects and studies

Sweden was early in demonstrating nuclear district heating by the Ågesta heavy water reactor commissioned 1964. For ten years this pilot scheme delivered 10 MW electricity to the grid and 70 MW of heat to the suburb "Farsta" of Stockholm, with a very good reliability record. As yet it has had no successors anywhere in the world. Ågesta was too small to give good economics, but it gave valuable experience. As the citizens of Farsta had become accustomed to the smokeless nuclear heat, there were many protests from the public when Ågesta was shut down to allow the nuclear effort in Sweden to be concentrated on bigger units.

Also proposals for large regional schemes came early - already during the late 1960's for the Greater Stockholm region. But large schemes require many decisions at national and local government level - for instance how far from the major population centres the plant should be located. So, there is even now no definite decision on this project. However, extensive studies are going on. Fig 2 shows a map of Sweden with the regions of main interest.

The existing nuclear plant at Barsebäck in the south of Sweden already has two nuclear units. If a third unit is added the reject heat could supply the base heat load for four cities from Malmö to Helsingborg with transport distances of 20 to 40 km. A preliminary study has been made and is now being worked out in detail.

For the Greater Stockholm area discussions on siting are still in progress. A site south of the city has run into heavy local opposition. Another alternative is the existing station at Forsmark, with two units under construction. However, the transport distance to the centre of gravity of the load is very great - 130 km. One scheme for transport by conventional steel pipes was costed, but has shown to be marginally more expensive than local generation from oil plants in the Stockholm area. As we shall see later, new technology could change this.

The third project of interest is Greater Gothenburg. It is at a distance of 60 km from the existing station at Ringhals, which has four large units under operation and construction. Plans have however not been made in as great detail as for the other two regions mentioned.

2.2 General considerations

As illustrated by the turbine schematics in Fig 3, the rejection of one kWh of heat at temperatures suitable for district heating involves a sacrifice of only about 1/6th to 1/10th of a kWh of electricity, depending on the water temperatures selected and the number of steam extraction points used to heat the water. 1/6th of a kWh applies with high water temperatures, e.g. about 165°C delivery, 1/10th of a kWh at low temperatures - about 95°C delivery. If the production of electricity in new power plants costs, say, 25 mills/kWh, the above electricity sacrifices involve a loss of revenue (and corresponding extra costs in compensating nuclear capacity elsewhere) of 25 mills x 1/6 to 1/10 = 4.2 to 2.5 mills per kWh of heat delivered to the district heating network. As the reactor and fuel requirements are identical to those for a pure electricity producing station and the turbine costs are increased only to a minor extent, these figures represent approximately the total cost of a reject heat supply for district heating at the power station site. The heat is thus extremely cheap at source, but must also be transmitted cheaply if the product is to be competitive at the receiving end. As nuclear power plants are generally required to be located at some distance from large urban population centres, the transport problem is important.

It is not economic to transport the entire peak heat demand, Fig 1, as this would make necessary the construction of very large transport lines. Generally the transport lines should be dimensioned to transport not more than 50 % of the maximum demand (corresponding to about 85 % of the heat energy), allowing the remainder to be generated by local oil fired peaking plants. The longer the transport distance, the smaller is the fraction of the maximum demand which one can afford to transport from the nuclear site.

Whilst the heat at source is cheapest when low water temperatures are used, heat transport lines (using conventional steel pipe technology) are cheaper with higher temperature differences between delivery and return (and therefore higher delivery temperatures) as this allows the use of smaller pipe diameters. Hence an optimization problem arises which results in short range transports being effected more economically at lower temperatures, long range transports at high temperatures.

Fig 4 gives examples of the combined cost of reject heat production and transport for systems of various maximum heat demands - 1 000, 2 000 and 4 000 MW as a function of transport distances. Roughly, 50 % of these outputs would be transported for small distances, less than 50 % for large ones. The figure is drawn for the calculated optimum temperatures, though in practice only a few standard temperatures would be used. In practice some additional cost allowance has to be made for cost of spur lines to interconnect a large regional system.

The curves show that for big systems relatively great transport distances are economically justified without exceeding the cost of heat from local oil fired heat-only boilers at world market oil prices.

2.3 Influence of new technology

At the Swedish R & D Centre at Studsvik, new types of corrosion resistant pipes are being tested. These avoid the need for surrounding the pipes with concrete protection ducts against ground water and thereby reduce costs. Pipes under test include prestressed concrete pipes with internal protective coats or liners and various types of glass fibre reinforced pipes. The first goal of the tests is to show that these pipes are acceptable up to about 100°C, and to this end tests at higher temperatures and pressures than working conditions are being conducted. They have been in progress since 1975 and the results are promising.

Because of their corrosion resistance, such pipes can also use untreated sea or river water and thus open the way to one-way pipe runs without return pipes when large distances are involved and conditions are favourable. Fig 5, which includes some cost comparisons with conventional pipes, suggests that considerable savings are attainable compared to steel pipes, despite the lower temperature limits which have to be imposed. Economic gains would improve further in future, if improved temperature regulation and other measures on local district heating systems gradually resulted in reduced return water temperatures.

Development work is also proceeding on small pipes of plastic which can carry both heating water and hot tap water in the same systems for the last stage of the distribution from sub-stations to individual houses. Each heat exchanger substation would supply 100 to 300 one-family houses. These systems which have already been demonstrated for office building heating in Studsvik since 1973 and for some small houses promise to make district heating economic even for the one-family housing districts thereby increasing the total demands which can be connected to the nuclear and other district heating networks.

3. HEAT-ONLY REACTORS

3.1 Background

As indicated in section 2, reject heat use from large nuclear power plants is confined to a restricted number of areas in Sweden with large population concentrations. If the use of fossil fuel is to be avoided in remaining urban centres spread over the country small cheap reactors with properties which allow near urban locations are required. The purpose of the reactor described in this section is to achieve these aims by using low temperatures, low pressures, a simple design and inherent safety properties to make near urban location and low costs possible.

3.2 Project SECURE

In the budget for energy R & D decided by Swedish Parliament in 1975, funds were made available for initial development of a low temperature, heat-only reactor for urban district heating. In 1976, the Finnish Government allocated money for the same purpose. A joint Finnish-Swedish design effort was started early in 1976. The organizations responsible for the work are AB ASEA-ATOM and AB Atomenergi (Sweden) and Finnatom Oy and Technical Research Centre (Finland).

Project SECURE (Safe Environmentally Clear Urban Reactor) encompasses the preliminary design and safety analysis of a 200 MWth reactor for the municipal space heating system of a city of 50 - 70 000 inhabitants. This power level represents a compromise between the improved economics for a larger output and the increased potential market for a smaller unit. Present work does not refer to any specific site.

Study of the duration curves for outgoing temperature and thermal load, Fig 1, show that it is sufficient to design the reactor for 95^{o}C outgoing temperature on the heat distribution water and for about half the maximum load. Under these conditions one can expect an annual heat generation corresponding to 4 - 5 000 h effective full power hours. The peak load is covered with fossil fuelled topping heaters. Only about 10 % of the total annual energy need has to be met with fossil fuel.

For economic reasons, the reactor should be located close to the load centre of the district heating grid being served; in fact the purpose of the design being developed is to eliminate any requirements of geographic separation between urban high-density habitation and the reactor site.

Clearly the relatively low output and the use of low temperatures and pressures give a safety advantage. Nevertheless, placing an energy producing reactor "downtown" or nearby runs counter to most current thinking and requires an extraordinary emphasis on safety in addition to this natural advantage. Not only must all safety requirements of the authorities be met, the basic safety of the system must also be understood and appreciated by the general public.

Current light water power reactors achieve the required high degree of safety by the use of engineered safety systems containing active components such as pumps and valves. By rigid quality assurance, redundancy, diversity, physical separation and in-service functional testing the probability of an accident with major impact on the environment is made vanishingly small. However, this leads to high investment and maintenance costs and the resulting plant design complexity virtually prevents comprehension of the safety problems by the concerned layman. Thus, both economics and public acceptance dictate another approach.

This requirement has led to a novel design. Although space does not permit a detailed discussion of the criteria employed, some of the basic philosophy should be evident from the following brief description, for which reference is made to Fig 6.

The reactor is located inside a large, slightly pressurized cold water pool containing about 1 000 ppm boron as boric acid. The main coolant circuits with pumps and heat exchangers are located outside this pool. The whole reactor installation is located in an underground cavity.

Reactivity control is by means of boric acid concentration adjustment only and there are no mechanical control rods. However, for long term shut-down boron steel spheres can be dropped by means of gravity to a position inside the core, e.g. if the reactor has to be temporarily abandoned in case of some kind of natural disaster. The reactor is cooled by an intermediate circuit, which in turn is cooled by the district heating grid water.

The core is simultaneously and permanently connected to three different coolant circuits, namely the two primary circuits where the heat is extracted during normal operation and a natural circulation circuit connecting it to the pool of borated cold water. There are no valves or other mechanical obstructions in any of the circuits.

However, during normal operation the natural circulation circuit is blocked by a gas bubble above the core. This gas bubble is kept in place by the pressure drop across the core existing as a result of the coolant circulation as can be seen from Fig 6. The height of the bubble equals the pressure drop through the core.

This pressure drop is constant during normal operation since the flow from the constant rpm circulation pumps is constant. The reactor outlet temperature is kept constant whereas the inlet temperature is varied with the reactor power.

If there is a decrease in circulation ratc, e.g. due to run down of the pumps upon loss of power supply, the core pressure drop will decrease as will the height of the gas bubble. The corresponding displaced gas volume is replaced with cold highly borated water from the pool and the reactor is shut down. If the pumps stop, the gas bubble disappears altogheter and the core remains shut down and cooled indefinitely via the borated pool and natural circulation circuits that dissipate decay heat to ambient air.

Depressurization, loss of heat sink or excess reactor power may also endanger the adequate cooling of the core. These conditions will give rise to reactor shut down in the same way as pump run down by inclusion of an "hydraulic brake" in the primary circuit. This consists of a set of parallel venturi tubes where steam formation accompanied by increased pressure drop and decreased flow occur before steam formation starts in the core. Thus there is a built in safety against the main risk contributing incidents that could potentially endanger core cooling, in contrast to the use of engineered safety systems in a conventional power reactor.

For protection against combinations of malfunctions, such as increase in operating pressure beyond prescribed limits followed by uncontrolled reactivity addition, conventional redundants safety circuits are provided. However, their function is only to trip the main circulation pumps, whereupon shut down and safe cooling are guaranteed.

Loss of cooling water is impossible because the reactor pool is situated in the lowest section of a leak tight rock chamber. Leakage from the bottom of the pressure vessel will lower the level somewhat, eventually resulting in depressurization and shut down as shown below by the opening of a gravity controlled puncturing device. The core remains submerged.

In good Scandinavian rock a blasted chamber subsequently injected with cement is considered sufficiently leak tight to serve as the reactor building without further sealing arrangement. The ventilation system contains no filters. In an emergency it is simply shut down and the system is closed by means of automatic valves in in- and outlet lines.

The secondary heat exchangers and the fossil topping and stand by heater can be placed in a surface building.

Some principal data are given in the following table.

Reactor power	200 MWth
Outgoing grid water temperature	95°C
Outgoing temperature, intermediate circuit	105°C
Reactor water temp, inlet/outlet	90/115°C
Pressure at core outlet	0.6 MPa
Total fuel charge	13.1 ton U
Max fuel rod linear heat rating	27 kW/m
Equilibrium ingoing fuel enrichment	2.65 %
Burn-up, equilibrium fuel cycle	22000 MWd/t U

Summarizing, it is felt that the present design should be so safe as to make possible urban underground location without restriction according to any criteria based on actual risk evaluation. Safety assessment by an independent group is currently in progress, using event tree analysis.

With regard to environmental impact, this is the first pollution free municipal heat supply plant conceived. Waste heat is negligible (less than one percent of power), there is no smoke, gaseous radioactivity release is nil, and there is no liquid radwaste release (ion exchangers etc are taken to a central plant at a nuclear power facility).

3.3 Future prospects

At the time of writing, no results of economic calculations of plant investment costs are available. It is therefore too early to predict the potential market penetration of the concept. In particular, the minimum output the plant can be built for while still remaining economic on the basis of any set of financial conditions and fossil fuel prices is unclear at present. The incremental cost for an increase in power output is, however, much lower than the average cost, i.e. economics improve markedly with increased plant output.

This fact, plus the highly desirable environmental properties may make the heating reactor an interesting proposition in much larger unit sizes than that which has been studied up till now. In particular, where a nearby power reactor either cannot be licensed for safety reasons or lacks a waste heat recipient for power generation during periods of low heating demand, the heat-only reactor should be an interesting proposition. The move away from fossil fuel may in this case be motivated as much by environmental as by supply security considerations. There seems to be no problems to expand output of the plant design described here to the 5 - 600 MWth range, and a detailed study of such a larger plant is planned.

4. CONCLUDING REMARKS

The duplicate approach of reject heat utilization for the large population centres and small low temperature heat-only reactors for the small and medium size towns promises to provide Sweden with an option to replace much of the oil now used for heating by nuclear fuel - and to do so in a very efficient way. If the endeavours succeed in establishing projects of this type in Sweden and elsewhere, nuclear energy should be able to increase its share of the energy market and improve the efficiency of utilization of nuclear fuel.

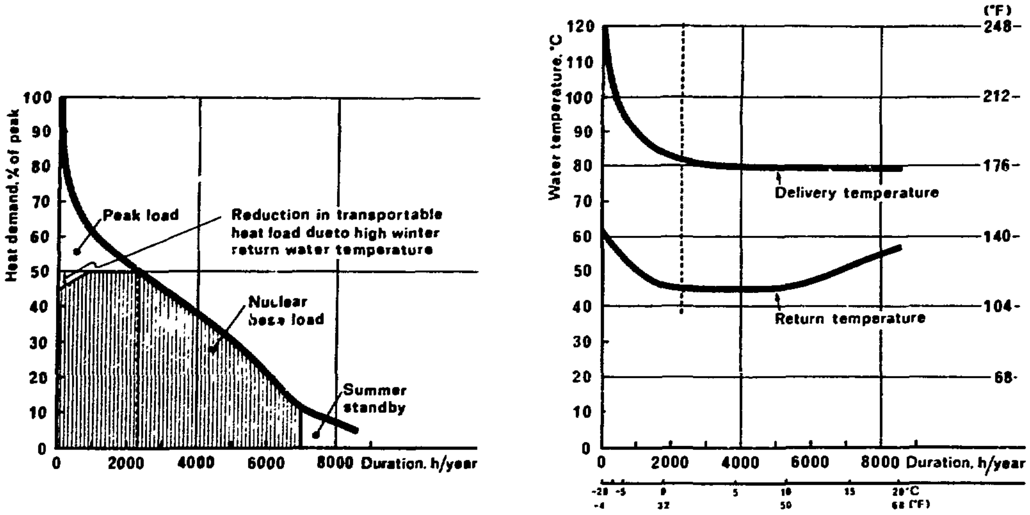


Fig 1. Heat load duration, load allocation and water temperatures under typical conditions in Sweden (Stockholm).

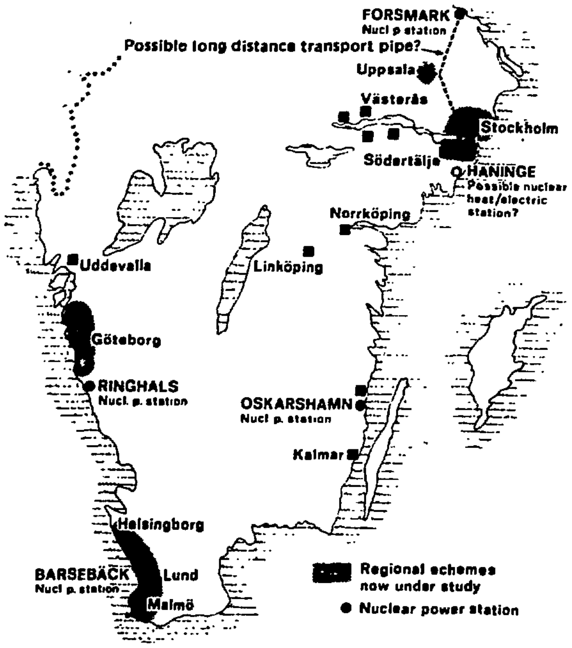


Fig 2. Map of Sweden showing location of regional district schemes under investigation.

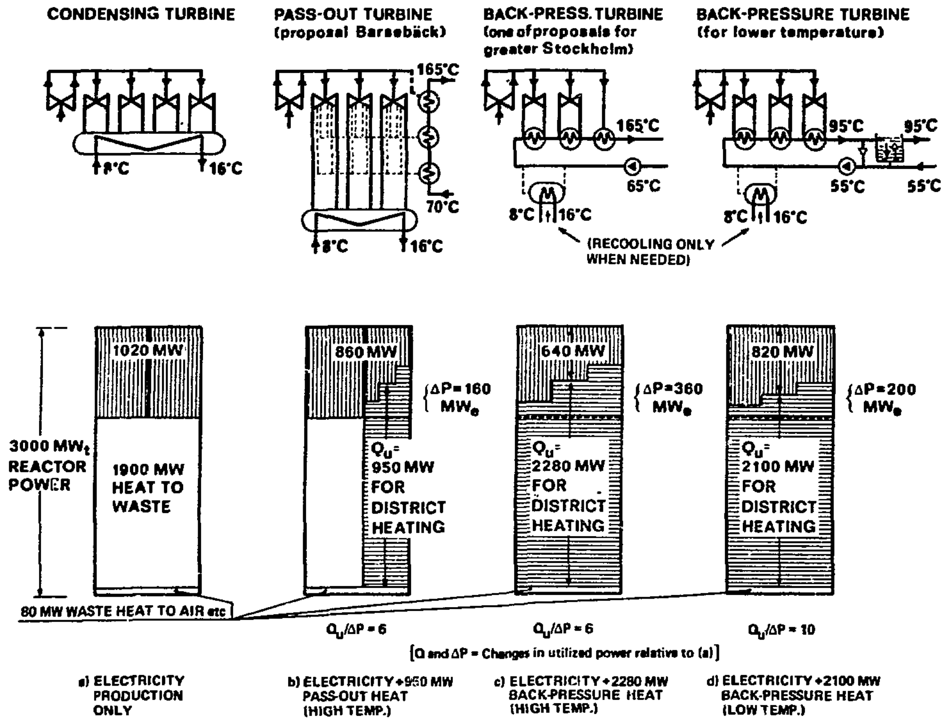


Fig 3. Turbo-generators for large nuclear station (with and without district heating).

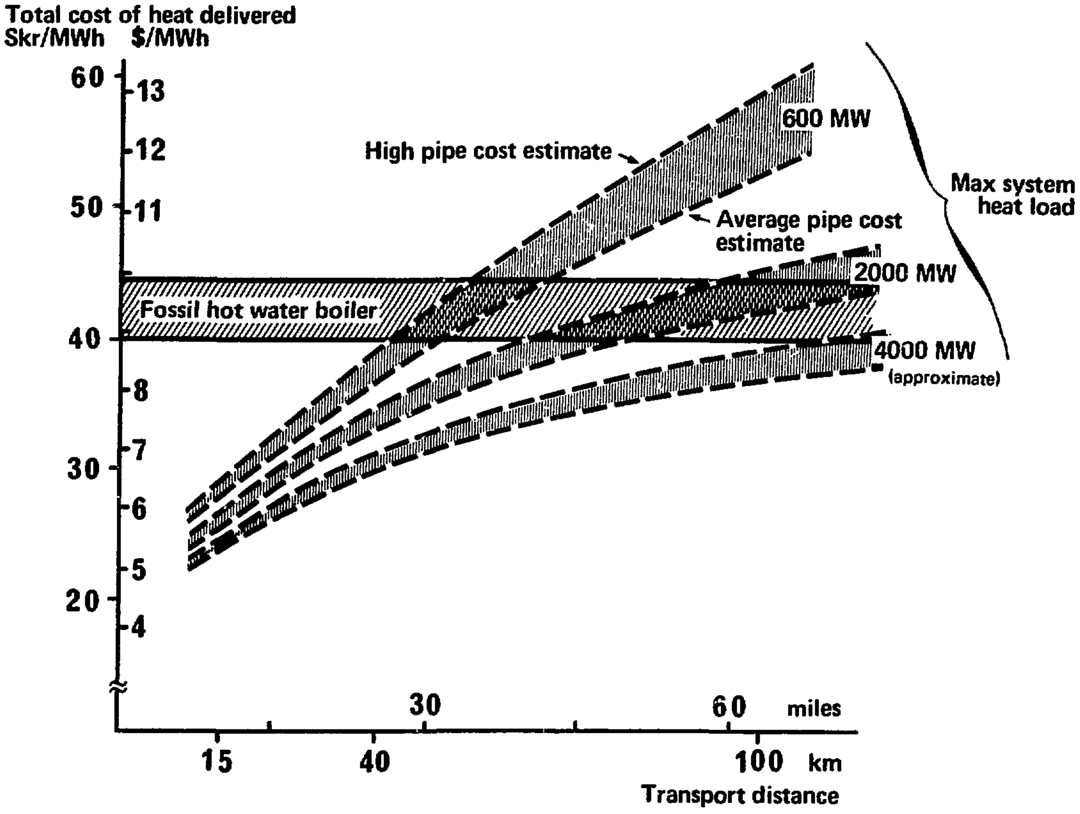


Fig 4. Total cost of heat delivered for different max system heat loads. Conventional pipe line technology.

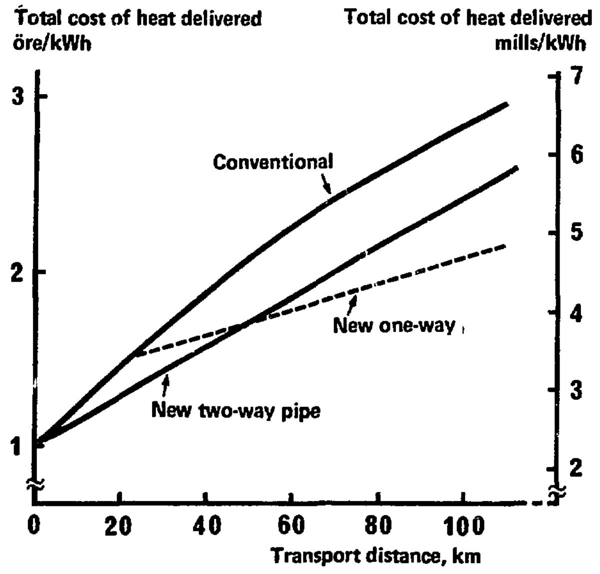
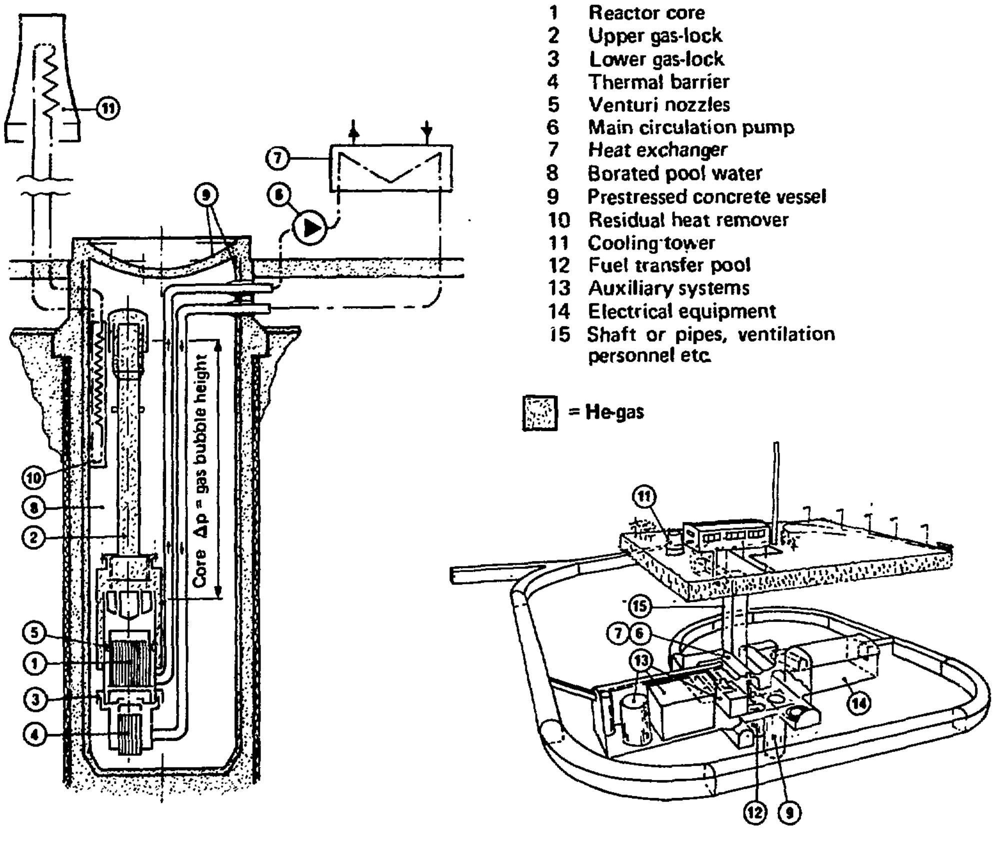


Fig 5. Potential for cost reduction with newer pipe techniques under development (2 300 MW, 4 500 h/year).



1 Reactor core
2 Upper gas-lock
3 Lower gas-lock
4 Thermal barrier
5 Venturi nozzles
6 Main circulation pump
7 Heat exchanger
8 Borated pool water
9 Prestressed concrete vessel
10 Residual heat remover
11 Cooling tower
12 Fuel transfer pool
13 Auxiliary systems
14 Electrical equipment
15 Shaft or pipes, ventilation personnel etc.

▨ = He-gas

Fig 6. Low Temperature Heat Reactor Concept, "SECURE".