Report on the Nuclear Powered

Thermo Electron Engine, pp

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AN EVALUATION OF THE FEASIBILITY OF THE USE OF A NUCLEAR REACTOR AS THE PRIMARY HEAT SOURCE FOR A THERMO-ELECTRON ENGINE

Introduction

The energy requirements of the world have been increasing by a factor of two[1] every decade during the past 100 years and the indications are that they will keep increasing at the same or a greater rate for several more decades. This increase is due first to the growth of the world population and second to the unpreceded rate at which our technologically-conscious civilization progresses.

A large percentage of this energy (15.%) is used in the form of electricity on account of the flexibility of electric energy as far as transportation, readiness in availability, and variety in applicability are concerned. The requirements for electric energy have been following the same growth pattern as all other energy needs (see Fig. 1).

Such a growth of energy consumption makes the efficacious use of the available sources as well as the development of new sources of energy more than imperative.

As far as the efficient use of the existing sources of energy are concerned, it can be said emphatically that modern technology has reached its upper limit or that it is very close to it.[2] Moreover the sources, which are being used now, are inadequate to meet the world energy requirements a few hundreds of years from now.

On the otherhand, as far as new sources of energy are concerned, the propositions which stand out quite distinctly are:

a) The use of solar energy. It is a well known fact that the sun showers the earth every day with a large amount of energy. The solar energy received by the earth in one year is greater than the energy of all coal, oil, and fissionable materials resources and it is delivered at the rate of 1 $\frac{kw}{M^2}$ a large percentage of which is in the form of heat. Practical devices which convert the solar energy into electricity or heat have already been constructed in various countries.

b) The use of the energy released from the fusion of light nuclei. When this proposal is technically solved, the energy demand of the world will be met for an indefinite time for all practical purposes. Furthermore, it might be worth mentioning at this point that if fusion becomes a reality, the chances are that the energy of fusion will be available directly in the form of electricity.(3)

c) The use of the energy released during the fission of heavy nuclei. This process is already well under development. The fission energy is produced in the form of kinetic energy of very short range, heavy fission fragments, hence in the form of heat. But heat is not one of the most desirable forms of energy, particularly when it is produced at very high rates (of the order of tens or hundreds of Mw). Thus, so far at least, the fission energy has been always transformed into electricity by means of conventional thermo-electric equipment, namely a turbo-generator set.

In the light of the previous short presentation it can be said that two of the three main sources of energy are heat sources. Hence any device which converts heat into electricity should be investigated as a possible converter for the solar or nuclear energy.

The scope of this report is to examine the feasibility of coupling a thermo-electron engine with a nuclear reactor. The thermo-electron engine is a device which accepts heat at the temperature level of around 1700°F and transforms it into electricity.

The question of primary interest at this point is whether there is actually any nuclear reactor design whose output temperature is higher than 1700°F, so that it can be used as the primary heat source for the thermo-electron engine. This is the topic of discussion of the following section.

I. Comparison of the Operational Parameters of Nuclear Reactors with the Operational Requirements of the Thermo-Electron Engine

There are three major requirements on the heat source, as far as the thermo-electron engine is concerned.

1) The temperature of the working fluid, which carries the heat from the source to the engine, must be above 1700°F in order for the process of thermionic emission to take place in the latter.

2) The working fluid must be non-radioactive so that it does not interfere with the physics of operation of the thermo-electron engine. This requirement is also highly desirable if health shielding around the engine is to be avoided.

3) Finally the working fluid should have very good non-corrosive properties and extremely low, if not entirely non-existent, permeability through solids. Both these specifications on the working fluid are very essential, since the first is already one of the main nuisances of any high temperature heat exchanger, and the second is an absolute "must" for the thermo-electron engine if it is to operate under high vacuum conditions in order to achieve high efficiencies.

The above requirements already restrict the types of reactors which can be used with a thermo-electron engine and several categories of nuclear reactor designs are entirely out of consideration.

In order to show this more rigorously, certain characteristic data of several nuclear reactors, which have already been constructed or whose completion is anticipated within the next two or three years, have been compiled in Table I. These data are selected from all nuclear reactor designs which have been suggested up to the present time and are available in the literature.

Consider for instance the first operational specification of the thermo-electron engine. A simple glance through the output temperatures of the reactors included in Table I shows that there is no coolant temperature anywhere near the level of 1700°F. From this point of view the problem of coupling a thermo-electron engine with a nuclear reactor might seem hopeless. However it is appropriate first to examine the reasons which have limited the output temperatures of nuclear reactors to low levels and thus determine what is to be expected in terms of higher temperatures and when. The main difficulties may be grouped as follows:

a) First, consider the group of reactors which use the fissionable fuel in the form of uranium alloys. The maximum temperature of this group is of the order of 400° - 1200°F and the main limitation is the fact that the different alloys used undergo a phase change at the same temperature levels. Such phase changes are entirely undesirable because they are deleterious to the mechanical and thermal properties of the alloys and hence they destroy the purposes for which the alloys were used in the first place.

One possible answer to this difficulty was the use of circulating liquid fuel metal reactors like the ones fueled with U-Bi. But even this answer did not turn out to be the most effective one. The main difficulty with this method is that the liquid fuel is highly corrosive and tends to transport masses of structural materials, like steel, from the hot spots of the reactor to the cold ones. As a matter of fact the higher the temperature of liquid metal fuel (around the level of 500°F) the higher the mass transfer rate(4) of the corroded structural materials. Consequently the people of the Brookhaven National Laboratory who are leading the research in the field of liquid metal fuels have limited themselves up to temperatures of 500°F.

Actually, it turns out that the mass transfer limitation might be overcome by using Niobium and Molybdenum in conjunction with Uranium. This idea has not been extensively used so far, and the chances are that it will not be widely used for quite a few more years, the principal objection being the high production cost of both Niobium and Molybdenum. It is very probable, however, that the greater demands for Niobium and Molybdenum will influence their production techniques and thus lower their costs.

b) Another factor, which hinders the increase of the temperature of nuclear reactors, is the problem of the behavior of different materials under heavy and long irradiations. More specifically, the nuclear reactor is a source of all types of radiation which cover a broad range of energies. This radiation is capable of not only affecting the electronic structure of different materials but also of disrupting the nuclear structure as well. Irradiation experiments are very time-consuming and nuclear reactor designers have been generally conservative as far as temperatures are concerned until many of the irradiation problems are solved. The general feeling has been that the different materials used in the nuclear reactor field, should not be thermally overstressed until the radiation effects are entirely known. However, there is a great number of materials testing reactors in different countries and data have been and are being accumulated at a rate which promises definite answers in the very near future. The indications are so far that irradiation is not a major problem.

c) Another general limitation of high temperatures in nuclear reactors is the overall problem of corrosion. The writer is not adequately prepared to go into all the details of the subject which certainly are of the uttermost importance in nuclear reactor design. It may be useful however to discuss very briefly some of the implications of the corrosion problem.

For one thing the nuclear reactor is a tremendous health hazard when not adequately controlled because every component of it is highly radioactive and 7.5 $^{mr}/hr$ of radiation to the personnel is enough to make the reactor environment unapproachable. What this means is that every simple component of the nuclear reactor must be entirely leak-proof under all possible operating conditions throughout the anticipated life. Consequently the corrosion problems must be minimized. Since the higher the temperature the higher the corrosion rates, the easy answer to this problem so far has been low temperatures. (The case of the N_aK cooled submarine reactor is a characteristic example of this difficulty. The whole design has been abandoned on account of corrosion problems[5] in the heat-exchangers, in spite of the excellent properties of the concept from every other point of view).

d) Finally, another problem which is not immediately related with the temperature of the reactor but which certainly limits the number of materials which can be used in the reactor, in spite of their temperature properties, is the neutron economy. In other words one cannot use any material as structural, moderating, or cooling material simply on account of its advantageous properties as far as temperature is concerned because these materials must also be judged from the nuclear physics point of view.

From the foregoing discussion one can see that materials have been the main problem of nuclear reactor designers and this is the area in which considerable research is taking place today in order to improve the status quo of nuclear reactors. The outcome of this effort is anybody's guess even though the results which are so far available are on the promising side as may be seen from the two nuclear reactor concepts referred to below:

The one, and most advanced nuclear reactor concept, is a design which has been proposed by a group of people of the Brookhaven National Laboratory.[6] It is the liquid fuel (standing) graphite-moderated, helium-cooled reactor which is planned to drive a helium gas turbine designed and developed primarily by Escher-Wyss in Switzerland.[7] The output coolant temperature of this reactor is 1500°F and the operating pressure 1200 psia. This reactor is actually under intense study by the Raytheon Company and its main parameters are summarized in Table II. (These data are not available in the literature and have been collected from the afore mentioned company and its technical staff.)

There are several outstanding properties of Helium as a coolant which are worth mentioning:

1. Helium is not naturally radioactive and it does not become artificially radioactive when it is submitted to the nuclear reactor radiations. Hence it is highly desirable from the health hazard point of view.

2. Its nuclear properties are very satisfactory.

3. It is an inert gas and non-corrosive even at high temperatures.

4. It does not diffuse through any solids[8] and thus it is highly desirable as a working fluid for the thermo-electron engine.

5. It is not burnable, hence there is no danger of explosion as with other gas coolants.

6. It is naturally available in the U.S.

7. It affords very high thermodynamic efficiencies as far as gas turbines are concerned due to its low atomic number. This aspect is not of course of primary interest to the thermo-electron engine but it is worth mentioning for economic comparisons and in view of the fact that the overall efficiency of the nuclear reactor-gas turbine plant has been estimated as 42%.

It is fair to say that the temperature of a helium cooled reactor may be increased to the point where it will match the requirement of the thermo-electron engine. This is due to the outstanding properties of helium listed above.

The other concept which sounds very promising is the use of ceramics in conjunction with liquid metal fissionable fuels and gases or liquid metals as coolants. The anticipated temperatures are 2000°F - 3000°F. However, the only information collected on this project is that the North American Aviation Company is working on it(9) and that recently the Argonne National Laboratory started a project in the same field.(10)

At the present state of development of high temperature reactors, it is the writer's belief that the Helium cooled concept is the most immediate and desirable solution to the thermo-electron engine problem and it is strongly recommended for further investigation.

Finally the writer wishes to mention another design which he has proposed to the Nuclear Engineering Department of MIT for intense study in the near future. It is the boiling metal reactor. What is meant by this is a nuclear reactor whose coolant is in the form of a liquid metal (like sodium for instance) which boils in the reactor. Thus the nuclear heat is carried away from the reactor by the metal vapors and used in the heat exchanger, which in this case might possibly be the thermo-electron engine. The implications of this design are hard to foresee, but the writer anticipates that if the reactor is feasible it would be useful to the T.E.E. Corporation because of the possibility of high temperatures.

It is hoped that the previous discussion gives a broad picture of the operational characteristics of nuclear reactors, their basic problems and the ways by which they are attacked.

In spite of the difficulties associated with high temperatures some possibilities have been outlined which are very promising as far as the thermo-electron engine is concerned. This conclusion, however, was reached only on the basis of operational specifications. In view of the fact that the discussion refers necessarily to large power installations, it is imperative to consider some economic facets of the subject. This is the topic of discussion of the next section.

II. Costs of Conventional and Nuclear Reactor Plants

The nuclear reactor is a source of energy produced at very high rates. As a matter of fact the heat transfer problems are the only ones that impose an upper limit to the specific power which is of the order of 20 - 500 kw per liter of volume of core material in all of the constructed reactors.(11) Moreover, the critical* sizes of nuclear reactors are of the order of several tons or hundreds of liters.(11) Consequently the nuclear reactor should be regarded always as a heavy power source rather than as a device whose output can meet any desirable small power requirement. Low power nuclear reactors are built only for special research purposes and they are very expensive.

Whenever a nuclear reactor is considered as a component of a power plant, it is of primary importance to examine also the economic aspects in comparison with other conventional means of production of power, like hydro- or thermo-electric installations. This is even more so in countries in which the natural resources of coal, oil, or natural gases are so rich that only competition on an economic basis would make the use of nuclear power possible.

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*Critical size of a nuclear reactor is the minimum volume that is necessary for a fissionable material assembly in order to maintain a stable chain reaction.

It would have been excellent if economic data on a large thermo-electron engine were available for a detailed comparison of a complete nuclear powered thermo-electron engine with conventional power plants. In spite of this lack, however, one can go through certain basic costs of nuclear reactor and conventional plants and thus determine some upper limits which the thermo-electron engine will have to meet eventually in order for its coupling with a nuclear reactor to be economically feasible.

A <u>Conventional Power Costs</u>

Conventional power generation costs vary widely for different locations and sizes of plants. A summary of average power plant and estimated power costs in the United States[12] is given in Table III.

In the case of coal fired plants, average costs are seen to range from 5.4 - 6.9 mills/kwh depending on the plant size and cost of coal. The cost of electricity from oil fired diesel plants, on the other hand, vary from 12 - 12.5 mills/kwh for 1 - 15 Mw plants. Hydro-electric costs are very sensitive to the cost of the dam and the site. On the average however, hydro-electric energy costs are in the same range as the costs of power from coal fired plants.

The main conclusions to be derived from the data of Table III are:

1. For small power plants, of installed capacity 1 - 15 Mw any new power producing installations must be able to deliver their energy at the bus bar at a cost of the order of 12 mills/kwh if they are to compete with diesel plants.

2. For large scale new power plants, the energy costs must be of the order of 5 - 7 mills/kwh. Certainly this figure of 5 - 7 mills/kwh

will vary slightly in the future on account of the increasing costs of coal. However, this is the cost figure that people in the nuclear reactor business are aiming for today.

3. For small or large power plants the cost of equipment which is used for the conversion of heat or hydraulic power into electricity usually amounts to half the capital cost of the total installation,(13) i.e. 100-170 $/kw. However it should also be kept in mind that the cost of steam or gas turbogenerator sets is reduced as the operational temperature is increased.(14) (See Fig. 2)

B. Costs of Nuclear Reactor Plants

From Table I it is seen that there is a great variety of nuclear reactor designs already operating or under construction. What this effectively means is that there is not "a reactor" which is better than any other type and which could be recommended for mass production. There is, however, one criterion which any reactor will have to meet eventually if it is to be economically accepted. This is the criterion of cost as determined by the conventional power plants. Hence an analysis of the costs of different nuclear reactor designs is justified at this point even though not of immediate interest to the T.E.E. Corporation.

Fortunately there are several reports on the costs of nuclear reactor plants and even though they are of different degree of optimism or pessimism, their scatter is quite acceptable from a technical point of view.

Figure 3 is a graphical representation(15) of the estimated costs of nuclear power plants which were presented to the Atomic Industrial

Forum conference in Chicago in September 1956 by the U. S. Atomic Energy commissioners W. K. Davis and L. H. Roddis, Jr. From this graph it is clearly seen that it is only a matter of time for the cost of nuclear reactor power to become competitive with the cost of conventional power. The curve for a plant X is also of particular value to this discussion because it shows how costly and time consuming development work is. This is a fact which should not be underestimated.

Another aspect of interest from the economics point of view is the variation of cost with the size of the plant. From the data of Table IV, the curve of Figure 4 has been plotted. The dotted line represents estimates of various authors of possible cost reductions due to improvement of present technology. From this figure it can be seen that by increasing the electric capacity of the power installation from 5 Mw to 100 Mw, the capital cost of the installation is reduced from 900 $/kw to roughly 200 $/kw. This is the reason why the general trend today in the nuclear reactor technology is toward higher and higher installed powers and particularly in view of the new developments in the construction of huge generators.(16)

A detailed analysis of the different factors which determine the cost of nuclear power have been compiled in Tables V, VI, VII, VIII, IX.

All costs have been evaluated on the basis of the following normalised costs:(17)

<u>Reactor Materials</u>

Natural uranium	$40 per kg
Thorium	$43 per kg

Reactor Materials (Continued)

Highly enriched uranium	\$15-20 per gram of U-235
D_2O	\$61 per kg (\$28 per lb.)

Fixed Charges

Reactor and turbine plant	15% per year
D O and other non-depreciating inventories	12% per year
Nuclear fuel	4% per year
Load factor	80%

It is not necessary to discuss all the cost data of Tables V through IX. However, it is useful to examine two cases of nuclear reactors whose ultimate energy cost falls between the limits set by the conventional plants.

1. Sodium Cooled Reactor built by North American Aviation Company

The electric power output is 125 Mw. The cost of the turbo-generator plant is 100 $/kw. The cost of the energy from this plant is between 6 - 8 mills/kwh and is made up of the following partial costs:

a) Capital Costs Reactor	2	mills/kwh	or	32 - 25%
Turbogenerator	2	"	"	32 - 25%
b) Fuel Inventory	0.3-0.6	"	"	3 - 9%
c) Fuel Cost	1 - 2	"	"	16 - 26%
d) Operating Cost	1	"	"	17 - 15%

2. Boiling Water Reactor by the Argonne National Laboratory

The electric power output is 250 Mw. The cost of the turbo-generator plant 100 $/kw. The cost of the energy produced is 7.7 mills/kwh and is made up of the following partial costs:

a) Capital Costs Reactor	2.5	mills/kwh	or	32%
Turbogenerator	1.7	"	"	22%
b) Fuel and D_2O Inventory	1	"	"	13%
c) Fuel Cost	1.6	"	"	20%
d) Operating Cost	1	"	"	13%

These two examples were selected from Tables VII and VIII. The analysis of the cost of the energy indicates that 20 - 35% of it is due to the turbogenerator. Assuming that the thermo-electron engine will not create any extra operational problems, it can be concluded that it has to deliver its energy at 2 mills/kwh.

The costs of small reactors are very high as compared with conventional plants. However, recent developments[18] indicate that there are many possibilities for cost reductions. Also there are cases where cost is not of primary importance when the reactor plant is designed for remote areas like Alaska where conventional power would have been just as costly. This is the case of the Army Package Reactor.

It is hoped that the data referred to above give a sound basis for comparison of the economic factors which are involved in the cost of electric energy with the thermo-electron engine. Some practical aspects of the coupling of the nuclear reactor with the thermo-electron engine which may require special attention are considered in the following section.

III. The Thermo-electron Engine - Nuclear Reactor as a Useful Power Source

Electric power, as it is being used today, is in the form of alternating current of 50 or 60 cps. This power is produced at the voltage level of 20 - 30 kv then transformed to 200 - 330 kv and transmitted to the load centers where it is used at the voltage levels of 110 to 22000 v. For various other special purposes power may be produced at other frequencies or voltages but these applications are rather the exception than the rule.

Since the thermo-electron engine is a device which converts heat into low voltage d.c. electricity, it is necessary to examine how it can be used by existing or potential electric power consumers.

As far as potential consumers of electric power delivered by a thermo-electron engine are concerned, they will be considered later in this report.

If the thermo-electron engine is to supply electric power to already existing consumers then there are two possible developments that the engine may follow:

1. The first is to develop a thermo-electron engine which will supply electric power to an electric network already in operation. This implies that not only a high power thermo-electron engine should be designed and constructed but also the problem of building the proper equipment for the transformation of the direct current of the thermo-electron engine into alternating current must be simultaneously solved.

Apart from the technical difficulties which may or may not be associated with the d.c. to a.c. conversion device, evidently the use of extra equipment restricts the range of capital cost of the thermo-electron engine. The writer is not prepared to discuss this subject in detail but he feels certain that it will require both time and money. Dr. Hatsopoulos has some ideas about possible solutions of the conversion problem. However, in case of high power the problem is rather involved. The efforts of some German and Swedish groups which have been attacking a similar problem have not so far been very successful. This of course is not an argument for not investigating any new possibilities or any old devices in the light of new ideas.

2. The other possible development for the thermo-electron engine is to design nuclear powered models for special customers. There are several industrial applications which require large power at low voltage d.c. For instance industries which produce metals electrolytically. It is suggested that a market study be made of such industrial applications for the thermo-electron engine.

Regardless of the path that the development of the high power thermo-electron engine takes, as far as consumption of its output is concerned, there are some other technical factors which have to be considered in case this engine is to be powered by a nuclear reactor.

Two of the most decisive factors of cost of nuclear power are:

(a) The anticipated long life time of the reactor.

(b) The long periods during which the reactor will be operating without refueling.

These imply that any other device which is associated with the nuclear reactor should either be long-lived or easily serviceable in order to achieve unobstructed operation of a specific power installation. It is recommended that this aspect be thoroughly investigated as far as the emissive elements of the thermo-electron engine are concerned. In case they are found to be short-lived, then the design of the high power engine should be such that replacement of the cathodes is achievable in the least time possible.

Another major problem is the vacuum, when the thermo-electron engine is visualized as a high power source. Consider a power installation of the order of 10,000 kw. Assume that the thermo-electron engine has a rating of 3 kw per ft^3. This implies a vacuum chamber of the order of 3300 ft^3. Certainly this will not be all vacuum but, still, evacuating a large space to high vacuum of the order of 10^{-5} - 10^{-6} mm Hg is a difficult thing to accomplish.

Evidently one possible answer to this problem is the use of multiple sealed-off units. This is also highly desirable in case the emissive elements are short lived because then the maintenance of the thermo-electron engine could be programmed in a way which does not obstruct the continuous operation of the power installation.

Sealing-off the thermo-electron engine units may or may not create any problems depending on the materials used for construction. However, barium or titanium getters will be very helpful in reaching ultimate vacuum.

Finally the volume of a high power thermo-electron engine may be an important factor to consider. Nuclear reactors are built to operate at a specific power greater than 100 kw per liter. If the specific power of the thermo-electron engine is orders of magnitude lower, then the installation might become uneconomical due to its size.

IV. Concluding Remarks

Three major aspects of the coupling of the thermo-electron engine with a nuclear reactor have been considered in this report.

1. The availability of heat from a nuclear reactor to meet the temperature requirement of the thermo-electron engine has been investigated. The detailed discussion of various reactors proved that on account of lack of appropriate materials the temperatures of the present-day reactors are 600 - 700°F lower than the operational temperature of the thermo-electron engine.

However three new possibilities were presented which promise higher reactor temperatures.

a. The helium cooled nuclear reactor. This is a design concept with excellent properties and possibilities of temperatures between 1500° - 2000°F. It is highly recommended for further investigation.

b. The use of liquid metal fuels in conjunction with ceramic structural materials. This design is under study now and the anticipated temperatures are between 2000° - 3000°F. Hence it might be used to power a thermo-electron engine.

c. The boiling metal reactor. This is a new concept of nuclear reactor design which has not yet been studied. If it is feasible, it may provide high temperatures at low pressures and thus be useful to the T.E.E. Corporation.

2. The economic factors which determine the cost of nuclear power have been analyzed. From the data collected it has been concluded that:

a. The nuclear reactor powered thermo-electron engine must necessarily be of high power rating.

b. The cost of the thermo-electron engine should be lower than 100 $/kw in order to be economically competitive with thermal power plants.

c. The contribution of the thermo-electron engine capital cost to the final cost of energy must be less than 2 mills/kwh unless the operational costs of the plant are reduced. The cost of special thermo-electron engines designed for remote areas and with ratings of the order of 1-2 Mw can be much higher than the figures quoted above.

Items b, c include necessarily the costs for maintenance of the cathodes during a period equal to the life-time of conventional equipment.

3. The usefulness of the coupling has also been discussed. The main conclusions and recommendations of this discussion are:

a. A high power thermo-electron engine might require d.c. to a.c. conversion equipment which necessarily will reduce the allowable cost of the thermo-electron engine. Furthermore, the conversion equipment may create some development problems.

b. A high power thermo-electron engine may create vacuum difficulties. It is suggested that the vacuum problem be given detailed and careful treatment.

c. A high power thermo-electron engine may have a large physical size compared to the nuclear reactor. Then the coupling may become uneconomical.

d. A high power thermo-electron engine may be useful in industrial applications which require large power low voltage d.c. It is recommended to make a market study of these applications.

The writer believes, however, that the T.E.E. Corporation should not seriously consider the development of a high power thermo-electron engine in the immediate future. It is easier and more advantageous to develop low power rating units for the following reasons:

a. The cost of low power devices is not as essential as in the case of high power installations.

b. The difficulties associated with a high power thermo-electron engine are not so important in the case of low power rating engines.

c. The low power models may create their own market without having to compete with existing conditions. This is a point which cannot be overemphasized. Consider for instance a thermo-electron engine for a small personal car, or for remotedly located households or for uses in aircraft (use the friction heat from the plane and transform it into electricity). These are examples which may or may not be practical. However, they imply applications which were not anticipated before and this is the field in which the thermo-electron engine will have a good start. It is a hard task to create new applications but it is a challenging one and that is what makes it more interesting.

d. The lack of moving parts in the case of the thermo-electron engine is more essential to small than to large units. Hence small units might compete with conventional power if they are installed right at the consumer's establishment. This is due to several factors, all of which converge to cost reduction.

1. Small units will be required in large quantities. Thus

they will be mass produced.

ii. Transmission and distribution of electric energy is very costly. Small thermo-electron engines by-pass this problem. Hence their cost could be 4-5 times higher than the figures quoted in section 3 and still produce energy cheaper than conventional plants.

iii. The heat rejected from the thermo-electron engine could be used for heating purposes thus resulting in tremendous savings.

Boston, Massachusetts
May 1957

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TABLE I - NUCLEAR REACTOR DATA

Reactor	Primary Coolant	Date First Critical	Power Mw Heat	Power Mw Elec.	Function	Designer
PRESSURIZED WATER (H_2O):						
1. APPR(Army Pkg. Power Reactor).	H_2O 4000gpm	Early 57	10	2	El.Power	Alco Products
2. PWR(Pressurized Wtr. Reactor).	H_2O 45000gpm	57	260	60	El.Power	Westing.Betti
3. Consolidated Edison Reactor (with Oil. . . . Superheat)	H_2O 120000gpm	1 Dec 59	500Reactor 177Superht.	140Reactor 96Superht.	El.Power	Babcock & Wil
4. Yankee Atomic Electric Co.	H_2O 56000gpm	60	480	134net	El.Power	Westing.CAPA
BOILING WATER (H_2O):						
5. BORAX III (Boiling Reactor Experiment) . . . ceased operations April 1956	H_2O	9 June55	12	2.3	Power Ex.	ANL
6. EBWR (Experimental Boiling Wtr. Reactor. . .	H_2O 7000-10000gpm	Early 57	20	5	Power Proto.	ANL
7. General Electric Boiling Water Reactor . . .	H_2O	57	12 initial value	3 initial value	Research Power	Gen. Elec. Co.
8. Dresden Nuclear Power Station.	H_2O 583000gpm	60	630	180 net	El.Power	Gen. Elec. Co.
9. Rural Cooperative Power Assn.(with separate Superheat)	H_2O 241000 lbs hr.steam	1 Jan 60	58	22	El.Power	AMF Atomics
10. Reactor for Amer. & For. Pr., Inc.	H_2O	--	40	10.6 net	Power Research	Gen.Elec.Co.
GRAPHITE:						
11. Hanford (8 Reactors).	H_2O	44 to 55	~1000 each	--	Pu Produc.	ANL
12. APS-1 (Soviet Atomic Power Sta.-1).	H_2O 1300gpm	May 54	30	5	El.Power	--
13. G-1 (French Production Reactor)	Air 33,000 lb min.	7 Jan 56	~40	5 gross	Pu Produc.	CEA
14. G-2 (French Power & Pu)G-3 to be similar. .	CO_2	57	150	~30 net	Power Prototype Pu Produc.	CEA et al
15. British Central Elec.Author.(2 stations,. . 2 reactors each)	CO_2	60 and61	--	~300 each	El.Power	--

Refuel Cycle (Full Power)	Plant Efficiency	Exit Primary Coolant °F	Exit Primary Coolant psia	Steam or Process Fluid °F	Steam or Process Fluid psia	Power Density KW/Liter	Reactor
~ 1.5 yr.	20	450	1200	407	200	~ 70	1.
--	23	542	2000	486	600	120-277 Max.	2.
1/3 in 4 mos.	33.5	510	1500	449 boiler 1000 superht.	420 boiler 370 turbine	100	3.
10,000 hrs.	27.8 net	~550	2000	485	~ 600	--	4.
--	19	419	315	430	315	20	5.
--	~ 25	488	615	488	615	15	6.
--	--	547	1000	547	1000	--	7.
--	~ 28.5 net	--	1000	--	970 475	~39	8.
--	29	533	915	497 boiler 825 superht.	650 boiler 615 turbine	21	9.
15mos.at 80% LF	26	489	615	489	615	--	10.
--	--	--	--	--	--	--	11.
~ 2.5 mos.	~ 17%	500-518	~ 1470	490-500	~184	~10	12.
--	--	428	~ Atmos.	312, 234, 158	80, 21 4.3		13.
--	--	572+	213	--	--	--	14.
--	--	--	--	--	--	--	15.

TABLE I (Continued) - NUCLEAR REACTOR DATA

Reactor	Primary Coolant	Date First Critical	Power Mw Heat	Power Mw Elec.	Function	Designer
SODIUM GRAPHITE:						
16. SRE(Sodium Reactor Experiment).	Na 1200gpm	57	21	6	Power Prototype	Atomics Internat
17. Consumers Public Power District, Nebraska . .	Na ~ 14,000gpm	60	245	75 net	El. Power	Atomics Internat
LIQUID FUEL:						
18. LMFRE(Liquid Metal Fuel Reactor Experiment. .	Fuel solution 396gpm	59	5.5	--	Experi-ment	BNL
19. City of Orlando Reactor	Fuel solution	60	--	25.40	El. Power	--
20. Design of LMFR by Brookhaven Guest Engineering Study Team (1955) . . .	Fuel solution 36,000gpm	Design only	550	193 net	El. Power	Brookhaven Guest Eng. Study Team 1955
ORGANIC MODERATED:						
21. OMRE(Organic Moderated Reactor Experi.) . . .	Polyphenyl 7200gpm	57	16	--	Experi-ment	Atomics Internat
22. City of Piqua Reactor	Terphenyl	61	~ 45.5	~ 12.5	El. Power	Atomics Internat
23. Reactor for Amer. & For. Power, Inc..	Terphenyl	--	--	~ 10	El. Power	Atomics Internat
INTERMEDIATE FAST AND FAST BREEDER:						
24. ZEUS.	--	Dec. 55	100w	--	Research	A.E.R E.
25. Dounreay Fast Power Breeder	--	57	60+	20	Power Experi-ment	Industrial Group U.K.A.E A.
26. EBR-2(Experimental Breeder Reactor-2)	Na 10,000gpm	59	60	20 gross	Power Proto-type	ANL
27. PRDC(Power Reactor Development Company) . . .	Na ~ 28,000gpm	60	300	100	El. Power	Atomic Power Development Associates

Refuel Cycle (Full Power)	Plant Efficiency	Exit Primary Coolant °F	Exit Primary Coolant psia	Steam or Process Fluid °F	Steam or Process Fluid psia	Power Density KW/Liter	Reactor
300 days	28.6	960	Atmos.	850	800	--	16.
--	30.6	925	Atmos.	825	800	--	17.
continuous	--	1022	~ Atmos.	Air 300	Air ~ Atm.	200	18.
--	--	--	--	900	1265	--	19.
continuous	35 net	1022	~ Atmos.	900	1265	~ 198	20.
--	--	530-710	300	--	--	--	21.
--	~ 28	<617	~ 440	450	425	--	22.
--	--	--	--	--	--	--	23.
--	--	--	--	--	--	--	24.
--	--	--	--	--	--	--	25.
3 mos.	~ 30	900	~ 25	850	1265	1000	26.
15 weeks	33	800	~ Atmos.	755	600	812 core	27.

TABLE II

LIQUID METAL - HELIUM COOLED REACTOR DATA

Coolant	Helium
Power - Mw	
Heat	150
Electric	63
Plant efficiency %	42
Exit primary coolant	
Temperature °F	1500°
Pressure psia	1200

TABLE III - CONVENTIONAL POWER COSTS

		$/kw	Mills/kwh
Coal-fired plant	400-600 Mw	$135	2.8
	100-200 Mw	$150	3.2
	10-50 Mw	$165	3.5
	Reserve Coal pile	$7	0.15
	Fuel cost: $6-$8 per ton		2.4-3.2
Diesel plant	1 Mw	$160	3.4
	10 Mw	$140	3.0
	15 Mw	$135	2.9
	Fuel cost: 14¢ per gallon	-	9.0
Hydroelectric	200 Mw turbogenerator	$115	2.5
	100 Mw turbogenerator	$120	2.6
	50 Mw turbogenerator	$125	2.7
	10 Mw turbogenerator	$170	3.6
	Dam + site, etc.	$100-$200	2.1-4.3

Assumptions: 15% fixed charges
80% load factor
34% thermal efficiency

TABLE IV - CAPITAL COSTS OF NUCLEAR POWER PLANTS

Reactor type	Electrical capacity, Mw	Cost $/kw	Reference Geneva paper No.
Experimental boiling water Reactor (EBWR)	4.5	890	497 (US)
D_2O-Boiling Water Reactor (BWR)	250	250	495 (US)
D_2O-Boiling Water Reactor (BWR)	62	450	495 (US)
90% D_2O-10% H_2O (BWR)	62	450	495 (US)
H_2O-BWR (natural circulation)	63	400	495 (US)
H_2O-BWR (forced circulation)	61	425	495 (US)
Fast Breeder Reactor (FBR)	150	300	501 (US)
EBR II	12.5	740	816 (US)
Aqueous Homogeneous (TBR)	100	200-250	496 (US)
HRE II	2	1050	816 (US)
Sodium-Graphite Reactor (SGR)	75	300	493 (US)
Sodium-Graphite Reactor (Thorium fuel)	100	265	493 (US)
SRE	7.5	630	816 (US)
Gas-Cooled-Graphite Moderated (GGR)	150	350	390 (US)
Water-Cooled-Graphite Moderated (PWGR)	223	290	492 (US)
PWR (D_2O Natural U)	20	375-550	11 (Canada)
Liquid Metal Fuel Reactor (LMFR)	210	240	494 (US)

TABLE V - ECONOMICS OF SMALL SCALE H_2O MODERATED REACTORS

Reactor Designation	Borax III		Army Package Power (APPR)	
Reactor Type	Boiling Water		Pressurized Water	
Source of Data	Geneva Paper 851		Nucleonics, May 1955, Jan. 1956	
Power Level, Mw Heat	10	15(2)	10	10(2)
Power Level, Mw Electricity	2	3.5	1.83	2
Cost, millions of dollars	0.55	0.55	2.1	0.8
Cost, $/kw	275	157	1150	400
Capital Costs, mills/kwh	5.9	3.4	24.5	5.8(3)
Reactor Inventory, kg U^{235}	11.8	--	≪25	--
Other Inventory, kg U^{235}	5.9	--	--	--
Number of Fuel Elements	87	--	--	--
Burn-up per Cycle, %	17	--	≫31	--
Fuel Cost, mills/kwh				
U^{235} inventory(1)	0.8-1.5	0.4-0.8	1.2-2.3	--
U^{235} burn-up(1)	3.9-7.7	3.9-7.7		3.6-7.2
Fabrication	4.7	4.7	25.9	2.3
Reprocessing	6.2	6.2		1.0
Operating Costs, mills/kwh	8.6	5.7		1.5
Total Power Costs, mills/kwh	30.1-34.6	24.3-28.5	~52	14.4-18.0

(1) for $15-30 per gram.

(2) for advanced designs.

(3) 10% fixed charges.

TABLE VI - PRESSURIZED H_2O ECONOMIC DATA

Company	Westinghouse, Duquesne	Yankee Atomic Electric	Consolidated Edison et al
Source of Data	Ref(1), Ref(2)	Ref(1)	Ref(1)
Total Heat Power, Mw	236	480	900
Electrical Power, Mw	100*	134	250+
Net Station Efficiency, %	23	28	28
Capital Cost, millions of dollars			
Reactor	27.7	17.4	—
Turbine Plant	10.0	16.0	55
Reactor Inventories, kg			
Uranium Fuel	52	28,800	275
Enrichment	~90	2.7%	~90
Fertile Material	10,800 nat.U.	—	8100 Th
Specific Power, kw heat/kg	22	17	60
Degree of Burn-up, MWD/T	6500	—	—
Cost, $ per kw	375-630	246	220

Ref.(1) Atomic Industrial Forum Reactor Data Tables, 1956

Ref.(2) RICKOVER, H.G., Nucleonics 14 (1), 14 (1956)

*Includes 40 Mw excess capacity for expansion

+Includes 110 Mw conventional superheating capacity

TABLE VII - ECONOMIC DATA FOR BOILING WATER REACTORS

Name of Reactor Type	Units	D_2O-BWR[1] forced circulation	D_2O-BWR forced circulation	90% D_2O + 10% H_2O forced circulation	H_2O natural circulation	H_2O forced circulation	H_2O forced circulation
Designer	---	ANL[2]	ANL	ANL	ANL	ANL	ANL
Source of data	---	P-495[3]	P-495	P-495	P-495	P-495	P-497
Total heat power	Mw	1000	250	250	250	250	40
Electrical Power	Mw	248	62	62	63	61	9.0
Net station efficiency	%	24.8	24.8	24.8	25	24.4	---
Capital Cost Data							
(a) Reactor	\$/kw						280
(b) Turbogenerator	\$/kw	] 250	] 450	] 450	] 400	] 425	180
(c) Reactor Materials	\$/kw	43	60-66	53-56	175-244	95-135	140-170
Fuel Inventory	kg	39,500	9800	9800	66,000	33,000	19
Fuel Enrichment	%	0.71	0.92	0.85	1.10	1.15	~90
Fertile Material Inventory	kg	---	---	---	---	---	4500
Special Material Inventory	kg	109,000	37,600	37,600	---	---	---
Fixed Charges (assumed)							
(a) Reactor	%	12	12	12	12	12	15
(b) Power Plant	%	12	12	12	12	12	15
(c) Fuel Inventories	%	12	12	12	12	12	[4 fuel
(d) D_2O Inventory and Losses	%	17	17	17	---	---	[15 fabrication
Fixed Costs							
(a) Reactor	mills/kwh	] 4.2	] 7.7	] 7.7	] 6.8	] 7.2	6.9
(b) Power Plant	mills/kwh						4.5
(c) Fuel Inventories	mills/kwh	0.3	0.4-0.5	0.3-0.4	3.1-4.2	1.6-2.3	0.3-0.5
(d) D_2O Inventory	mills/kwh	0.7	1.0	0.8	---	---	---

Table VII Continued

TABLE VII (Continued) - ECONOMIC DATA FOR BOILING WATER REACTORS

Name of Reactor Type	Units	D_2O-BWR(1) forced circulation	D_2O-BWR forced circulation	90% D_2O + 10% H_2O forced circulation	H_2O natural circulation	H_2O forced circulation	H_2O forced circulation
Fuel Cost Data							
Burn-up	MWD/T	10,000	10,000*	10,000*	10,000*	10,000*	10,000
Initial Conversion Ratio	---	0.90	0.87	0.77	0.84	0.82	0.70
Fabrication Cost	$/kg	65	66	66	66	66	45(nat.U) 6700
Reprocessing Cost	$/kg	---	---	---	---	---	4200(enriched U)
Uranium Cost	$/kg	40	75-110	64-86	103-170	112-185	40
Pu Credit	$/gram	---	---	---	---	---	---
Fuel Costs							
Total Fuel Costs	mills/kwh	1.6	2.5-3.1	3.3-4.1	3.2-4.4	3.6-5.0	4.5-5.7
Pu Credit	mills/kwh	---	---	---	---	---	---
Net Fuel Costs	mills/kwh	1.6	2.5-3.1	3.3-4.1	3.2-4.4	3.6-5.0	4.5-5.7
Total Power Cost	mills/kwh	7.7	13.9-14.6	14.4-15.3	15.4-17.7	14.7-16.8	20.4-21.8

*With addition of enriched U^{235}

(1) BWR = Boiling Water Reactor

(2) ANL = Argonne National Laboratory

(3) Geneva Conference (1955) Paper Number

TABLE VIII - ECONOMIC DATA FOR GRAPHITE REACTORS

Name of Reactor	Units	Calder Hall	Pressurised Water Graphite	SGR-Uranium	SGR-Thorium	SGR-Advanced	LMFR
Type	---	CO_2 cooled	H_2O cooled	Na cooled	Na cooled	Na cooled	Liq.Met.Fuel.
Designer	---	Risley	G.E.(Hanford)	NAA	NAA	NAA	BNL
Source of Data	---	Geneva Paper 390	Geneva Paper 492	Geneva Paper 493	Geneva Paper 493	Geneva Paper 493	Geneva Paper 494
Total Heat Power	Mw	200	800	243	250	400	550
Electrical Power	Mw	70(2reactors)	223	77	100	125	200-210
Net Station Efficiency	%	18	27.9	31.6	---	31.6	38.2
Capital Cost Data							
Reactor	$/kw	357	{290	180	145	100	{235
Turbogenerator Plant	$/kw	350		120	120	100	
Reactor Materials	$/kw	157	16-18	60-90*	54-108*	54-108*	23-45
Fuel Inventory	kg	100,000	41,000	24,600	360	360	90
Fuel Enrichment	%	nat. U	0.92	1.8	90	90	Highly enrich.
Thorium Inventory	kg	---	---	---	10,000	10,000	21,000 U^{233}
Special Material	kg	---	---	---	---	---	190,000(Bi)
Fixed Charges							
Reactor	%	9	15	15	15	15	16
Power Plant	%	6	15	15	15	15	16
Fuel Inventories	%	4	4	4	4	4	4
Fixed Costs							
Reactor	mills/kwh	4.6	{6.2	3.9	3.1	2.1	{5.5
Power Plant	mills/kwh	2.6		2.6	2.6	2.1	
Fuel Inventory	mills/kwh	0.9	0.1	0.3-0.5	0.3-0.6	0.3-0.6	0.2-0.3
Other	mills/kwh	---	---	---	---	---	---
Operating Costs	mills/kwh	1.5	---	2.0	1.5	1.0	0.7

TABLE VIII (Continued) - ECONOMIC DATA FOR GRAPHITE REACTORS

Name of Reactor	Units	Calder Hall	Pressurized Water Graphite	SGR-Uranium	SGR-Thorium	SGR-Advanced	IMFR
Fuel Cost Data Burn-up	MWD/T	not given because reactor is dual purpose	10,000	---	---	---	---
Initial Convers.ratio	---		---	0.72	0.9	1.0	1.0
Fabrication Cost	$/kg		---	---	---	---	---
Reprocessing Cost	$/kg		---	---	---	---	---
Uranium Cost	$/kg		---	---	---	---	---
Pu Credit	$/gram		---	---	---	---	---
Total Fuel Costs	mills/kwh		---	2.0-3.2	1.5-2.5	1.0-2.0	1.4
Pu Credit	mills/kwh		---	---	---	---	---
Net Fuel Costs	mills/kwh		---	---	---	---	---
Total Net Power Costs	mills/kwh	9.6	7.0	10.8-12.2	8.8-9.1	6.3-7.6	7.8

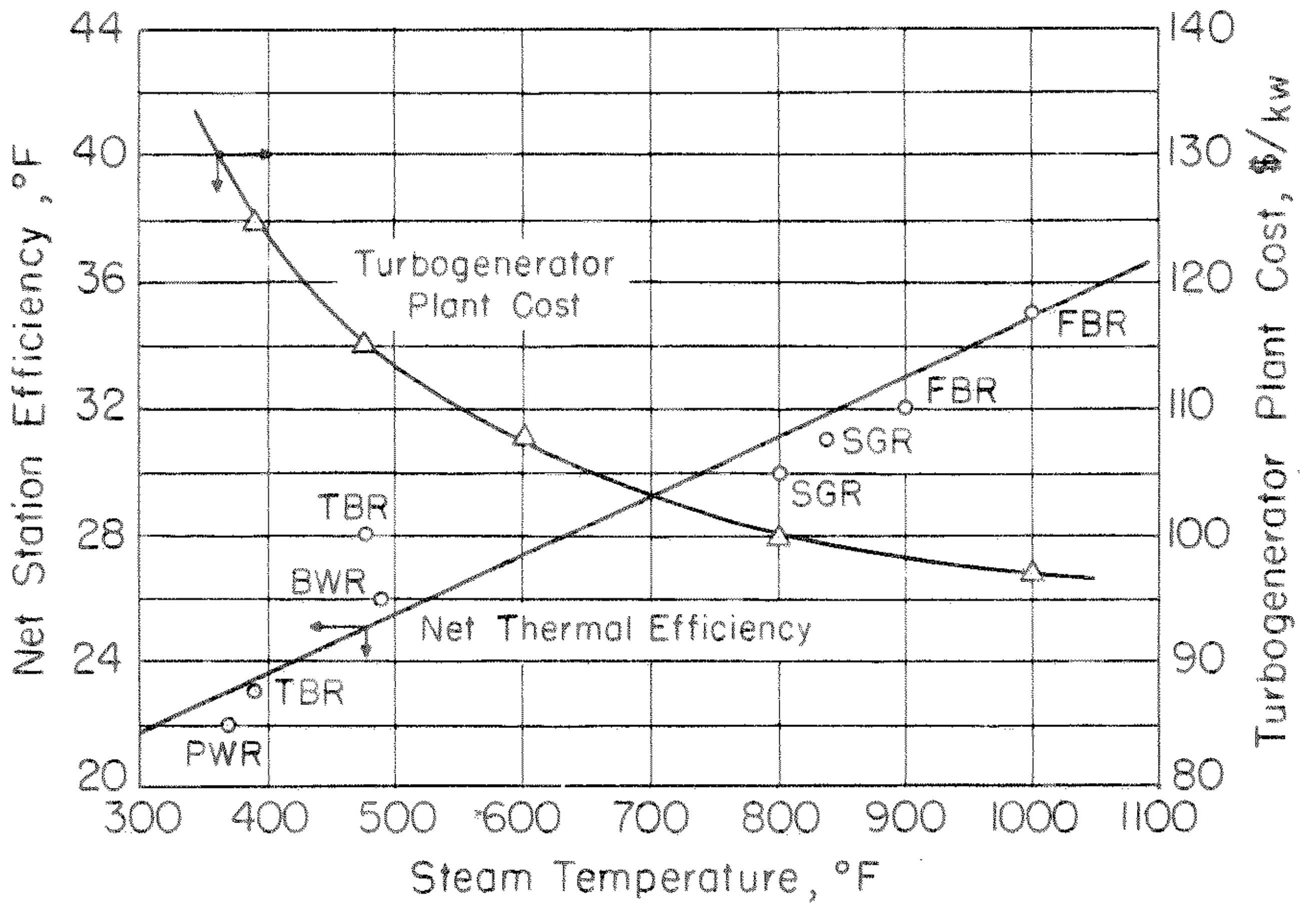
*These costs were not included in the reported capital costs.

TABLE IX - ECONOMIC DATA FOR AQUEOUS HOMOGENEOUS AND FAST BREEDERS

Type of Reactor	Units	Aq.Homo.U^{235} Burner	Aq.Homo.Two Region Breeder	Aq.Homo.Single Region Breeder	Fast Breeder	Fast Breeder
Designer		ORNL	ORNL	ORNL	ANL	Det.Edison
Source of Data		Private Communica.	Geneva Papers 476, 496	Private Communica.	Geneva Paper 501	AIF Reactor Data
Total Heat Power	Mw	480	440	480	500	300
Electrical Power	Mw	125	100	125	150	100
Net Station Efficiency	%	26	23	26	30	33
Capital Cost Data						
(a) Reactor	$\$ \times 10^6$	6-10	{20-25	6-10	{45	36
(b) Turbogenerator	$\$ \times 10^6$	15		15		9
(c) Reactor Materials	$\$ \times 10^6$	---	3.2-4.6	8.5-12	7.5-15	---
Fuel Inventory	kg	35-50	90	320	500	2100
Fuel Enrichment	%	90	90	90	Pu^{239}	20
Fertile Mat.Inventory	kg	---	15,000	14,000	---	---
D_2O	kg	50,000	26,000	50,000	---	---
Fixed Charges(Assumed)						
(a) Reactor	%	15	15	15	10	---
(b) Power Plant	%	15	15	15	10	---
(c) Fuel Inventories	%	4	4	4	5	---
(d) D_2O Inventories	%	9	9	9	---	---
Fixed Costs						
(a) Reactor	mills/kwh	1.0-1.7	{4.3-5.3	1.0-1.7	{4.3	---
(b) Power Plant	mills/kwh	2.6		2.6		---
(c) Fuel Inventories	mills/kwh	0.02-0.07	0.1-0.2	0.25-0.5	0.36-0.72	---
(d) D_2O Inventories	mills/kwh	0.3	0.2	0.3	---	---

TABLE IX (Continued) - ECONOMIC DATA FOR AQUEOUS HOMOGENEOUS AND FAST BREEDERS

Type of Reactor	Units	Aq.Homo.U^{235} Burner	Aq.Homo.Two Region Breeder	Aq.Homo.Single Region Breeder	Fast Breeder	Fast Breeder
Fuel Cost Data						
Burn-up per cycle	%	--	--	--	10	--
Breeding Gain	--	--	0.1	0.01	0.5	--
Fabrication + Reprocessing Cost	$ gram	--	--	--	3	--
Fissionable Mat.Credit	$ gram	--	15-30	15-30	15-30	--
Fuel Cost	mills/kwh	3.1-6.2	1.3	1.2	4.2	--
F.M.Credit	mills/kwh	--	0.37-0.75	0.04-0.08	1.1-2.1	--
Net Fuel Cost	mills/kwh	3.1-6.2	0.9-0.5	1.1-1.15	2.1-3.2	--
Operating Cost	mills/kwh	1.0	1.0	1.0	1.0	--
Net Total Power Cost	mills/kwh	8.0-11.9	6.5-7.3	6.3-7.2	8.1-8.8	--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40
36
32
28
24
20
140
130
120
110
100
90
80
300
400
500
600
700
800
900
1000
1100
Net Station Efficiency, °F
Turbogenerator Plant Cost, $/KW
Steam Temperature, °F
Turbogenerator Plant Cost
Net Thermal Efficiency
FBR
FBR
SGR
SGR
TBR
BWR
TBR
PWR

FIGURE 2