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MOBILE FUEL PLUTONIUM BREEDERS

A STUDY OF ECONOMIC POTENTIAL

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MOBILE FUEL PLUTONIUM BREEDERS

A STUDY OF ECONOMIC POTENTIAL

by

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ABSTRACT

In the Direct Contact Reactor concept, molten plutonium fuel is circulated and cooled by contact with an immiscible coolant. As an example of a mobile fuel system with a closed fuel-blanket processing loop, the DCR is compared in its economic potential with an advanced solid fuel breeder. The study shows a saving in fueling cost using mobile fuel which is substantially greater than the added investment and operating cost.

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1. SUMMARY

It has been generally assumed that the use of a mobile fuel offers potentially important gains in the reduction of reactor fuel cycling costs. Used as an unclad, unfabricated bulk material, such a fuel may be cycled through the reactor while at power, and processed continuously in a system which is integral with the reactor. The Los Alamos Scientific Laboratory has undertaken the development of mobile fuel fast breeder concepts and is currently pursuing the technical aspects of this approach. This report examines the extent to which the assumed economic advantages of mobile fuel are likely to be realized in a large scale plant based on current development results.

To reduce the uncertainties of estimating advanced systems, a comparative study was made in which two 300 Mwe fast breeder plant designs were contrasted, one using mobile fuel and one using an advanced solid fuel. Estimates of construction and operating costs were worked out from the designs, using the ground rules of the AEC "Nuclear Power Plant Cost Evaluation Handbook." Since neither concept has been proved experimentally so far, the estimates obtained are not necessarily indicative of absolute power costs. However, the mobile and solid fuel plants exhibited distinct differences in their economic characteristics, and conclusions based on these differences are expected to be valid because of the comparative nature of the study.

In comparing the cost of power from the two stations the most significant difference was due to the elimination of off-site fabrication and recovery of fuel elements through the use of mobile fuel. This was the result intuitively expected, but it was surprising to find that this difference was more than 3 times as large as the extra investment charges and operating costs required for the mobile system. The net advantage in power cost was about 1.3 mills/kwh. It is clear

that there is an economic incentive for the development of mobile fuel fast breeder reactors.

A negative fuel cost is another characteristic of the mobile fuel plant. This result is produced by the on-site closed cycle reprocessing system, whose capital cost appears as a part of fixed charges for the whole plant, and does not vary with the fuel throughput. Since the plutonium credit greatly exceeds the incremental operating costs of the fuel process, the net operating expense is lower the higher the plant output. Such a station would be operated at a high plant factor throughout its lifetime.

The mobile fuel concept studied uses a molten plutonium fuel alloy which is circulated and cooled by direct contact with a jet of liquid sodium. The reactor has 3 cores surrounded by a single paste blanket of UO_2 in sodium. The solid fuel plant is based on advanced concepts developed by Atomic Power Development Associates, Inc., Power Reactor Development Company, Inc., and the Detroit Edison Company.

The following table summarizes briefly the data for the two stations:

TABLE 1.1

COMPARISON OF PLANT CHARACTERISTICS

	Mobile Fuel (DCR Plant)	Solid Fuel (SFR Plant)
Total construction cost	\$64,071,000	\$56,170,000
Cost per kwe	\$214	\$187
Projected power cost @ 80% plant factor (mills per kwhr)	5.1	6.4
Incremental power cost (fuel cost) (mills per kwhr)	-0.3	+1.6
Plutonium inventory (total cycle) (kg)	1200	1200
Plutonium production ratio (breeding ratio)	1.3	1.3
Number of cores per reactor	3	1
Core volume, liters	3 x 227	2000
Specific power (kw per g of Pu)	0.57	0.58
Doubling time (years)	15.7	16.5

Fuel material and container	Pu-Co-Ce (molten alloy in Ta)	$PuO_2 \cdot UO_2$ clad in ss.
Blanket material and container	UO_2-Na paste in ss.	UO_2 clad in ss.
Core burnup per pass	>50%	5%
Steam temperature (°F)	975	870
Steam pressure (psig)	1450	1450

2. INTRODUCTION AND OBJECTIVES

In forecasting the application of nuclear energy to power generation it has been generally expected that reactors burning U^{235}, because of a higher state of development, would be first to attain a position competitive with conventional power plants. Breeder reactors, taking longer to develop, were expected to become competitive at a later time, possibly through exhaustion of fossil and U^{235} energy sources. The utilization of U^{238} and thorium energy resources through breeders has been recognized as a long term necessity.

The major area of effort for both burner and breeder reactors has been in reducing fuel cycle costs. If both can eventually achieve drastically simplified fuel systems with minimum cycling costs, the remaining fuel cost lies in the basic energy cost, or burnup fuel cost. Here the advantage lies strongly with the plutonium breeder, which consumes only U^{238} costing a few cents per gram, compared to the burner fuel costing nearly a thousandfold as much. In addition the breeder produces a salable excess of plutonium, which further reduces costs.

A study of development trends shows that the fast plutonium breeder reactor may achieve a competitive position much sooner than was first assumed. There are two main reasons for such a possibility. One is that fast reactor concepts have been found which are well suited to the attainment of reduced cycling cost. The other reason is that the economics of a breeder reactor is more strongly affected by fuel cost improvements than is the case for a burner.

One way to approach the objective of minimum fuel cycling costs is the use of mobile fuel. This concept involves a form of fuel which is not fabricated into individual assemblies, but which can be made to flow into and out of the reactor in bulk form. Also involved is the notion of an attached continuous processing unit, so that reactor and fuel processing form a closed, integrated system.

This type of fuel cycle has economic merit for any reactor, but is nowhere more rewarding than in the breeder reactor, because of the low ultimate fuel cost. The combination of an integrated mobile fuel system with a fast breeder reactor has received very little study from the economic standpoint. Several reactor concepts of this general type have been proposed in recent years, and received varying degrees of study or development. All of these have been based upon an intuitive feeling that the mobile fuel approach should offer economic benefits, but it was a feeling without much quantitative basis.

It is the authors' belief that enough information is now available to permit a more concrete evaluation of the economic climate which awaits the successful development of mobile fuel fast reactors. This report presents the economic conclusions which were obtained from study of such a system. Even though the results must be considered preliminary in nature, any quantitative comparison is useful in assessing the incentive for effort in this technically difficult field. The authors found that the areas of uncertainty in design and operation were of a nature which resulted in a much smaller uncertainty in costs than expected. The conclusions obtained may therefore contribute to a transition from a plausibly attractive concept to a definite economic goal.

In order to reduce the uncertainty introduced by the estimating process, and to allow more reliable conclusions to be drawn as to the economic consequences of using mobile fuel, two plants were estimated. One is the mobile fuel plant; the other is an advanced fast breeder of the clad solid fuel type. These plants were matched in many characteristics, which made it easier to pinpoint their differences.

The particular mobile fuel concept selected for study is presently under development by the Los Alamos Scientific Laboratory. It is an advanced concept, called the Direct Contact Reactor, which makes the fullest utilization of the unique chemical, nuclear, and metallurgical properties of plutonium. Although promising, the concept is still in the laboratory stage, and must undergo further development before being considered for plant use. In spite of this present unproved condition, the technical difficulties to be resolved are not of a type which prevent a fairly close estimation of cost in a scaled-up system. The direct contact concept is believed to be sufficiently representative of other possible mobile fuel concepts to give useful light on the economic potential of them all.

The objectives of this report may be summarized as follows:

1. To combine current reactor concepts, fuel processing information, and materials technology into an overall plant design concept.

2. To estimate the construction cost of such a plant and that of an equally advanced solid fuel plant on a fairly realistic basis, using the rules of the recently published AEC Cost Evaluation Handbook, and using standard components for the conventional portion of both plants.

3. To estimate and compare the resulting operational power cost for the two plants.

4. To observe how the economics of a low fuel cost plant differs from that of conventional plants, and how the choice of optimum plant components and turbine cycle would be affected by these differences.

5. To examine the safety characteristics of the mobile fuel reactor concept to see whether its economic potential might be augmented or offset by safety considerations.

In addition to the objectives itemized above, there are other less specific objectives to be realized. The most important of these are concerned with guiding the development of the reactor concept itself. For example, the cost studies reported in Chapter 3 lead to the conclusion that mobile plutonium breeder plants may produce cheaper power than fossil fuel plants in the near future. If this should prove true, a demand for such plants would soon create a shortage of plutonium, with the result that the actual value of plutonium in the market would tend to rise substantially. This would result in emphasis on reactors optimized for short doubling time. Such information is valuable in planning the development of the concept. Another result of importance is the realization that such plants would be base-loaded throughout their life, and therefore the reactor design should emphasize high reliability and availability, equal, if possible, to that of the turbine itself.

It must be understood that the reactor concept described has not yet been tested experimentally. The study and its conclusions must not be construed as a proposal to construct such a plant, but used rather to guide and encourage the development work on mobile plutonium concepts. The first molten plutonium reactor, LAMPRE I, began operation in April, 1961.[1] A small, direct contact core is under construction and will be operated before the end of 1962. Larger versions of this and other promising mobile systems can be tested upon completion of the Fast Reactor Core Test Facility at Los Alamos in 1964.[2] Under the most favorable circumstances it is expected that four or five years will be required to test the technical feasibility of the scheme, and an equal period to construct and operate a larger scale prototype. Even if fifteen years should be required before commercial application would be feasible, the breeder reactor would assume an important position in the national energy picture long before originally expected. Perhaps the most important objective of this report may be the correction of that earlier expectation, and a demonstration that lower power costs, rather than depletion of other energy sources, will bring the fast breeder reactor into use.

3. ECONOMIC CONCLUSIONS

3.1 Introduction

The mobile fuel reactor plant described in this report is not one which can be built today. It is based on technology which is currently considered feasible but which is still in the research stage. This general area of reactor technology is leading to the development of fast breeder reactors with a unified mobile fuel cycle. The particular concept described herein is considered to have certain unique characteristics which promise to have a decided economic advantage over conventional solid fuel fast reactors. These characteristics are believed by the authors to be an inherent feature of mobile fuel reactors as a class, and not an accident of the particular design chosen.

In the complicated interplay of factors determining the cost of nuclear power, it is often difficult to assess the merit of various advantages claimed for a particular reactor type. An economic study serves to show the true effect of the supposed advantages in a numerical perspective. A comparative study of competing proposals is even more definitive, since the effect of uncertainties in the estimating procedure is thus minimized.

Through the courtesy of the Detroit Edison Company and, through them, Atomic Power Development Associates, Inc., and Power Reactor Development Company, Inc., cost experience on the Enrico Fermi Atomic Power Plant was made available to the authors, together with pertinent features of their advanced design concepts with related cost estimates. Thus was made possible the close juxtaposition of advanced versions of both the mobile fuel and clad solid fuel reactor concepts under the same set of ground rules and cost estimating procedures. The estimates for both plants are subject to the uncertainties of estimating unproved, undeveloped systems, but it is believed that the technical uncertainties are unlikely to reverse the general conclusions of the comparison, while the construction cost estimates, if in error, will affect both plants similarly.

The two plants studied are a molten plutonium core reactor concept originated at Los Alamos, and an advanced plutonium-uranium oxide fueled reactor under consideration at Detroit. The first is designated the Direct Contact Reactor (DCR) since heat transfer from the molten fuel alloy is by direct contact with the sodium coolant, while the second type is called the Solid Fuel Fast Breeder Reactor (SFR). The direct contact core concept is not described because of its similarity to the recently published PFFBR design.[3] Both plants are rated at 300 Mwe net, and construction and operating cost estimates were prepared using a system of accounts and ground rules which agreed essentially with those proposed by the AEC in its "Nuclear Power Plant Cost Evaluation Handbook," including revisions dated May 15, 1961. The system was extended and modified as necessary to accommodate the DCR plant, for whose on-site processing system the Handbook did not provide.

3.2 Construction Cost Estimates

A brief summary of the construction cost estimates for the two plants is given in Table 3.1. The estimates are compared in the sections below, and a fuller breakdown of the DCR estimate is given in Appendix A. The estimate for the DCR reactor and its associated special equipment was based primarily on recent LASL procurement experience on small scale equipment, while the SFR estimate was based on the experience and advanced reactor design studies of the Detroit Edison Company, APDA, and PRDC. These sources of information made possible a considerably more detailed cost estimate than would have been possible using the general estimating guides of the AEC Handbook. A comparison shows that the resulting figures are slightly higher than those which would have been obtained using the guides.

TABLE 3.1

DIRECT CONTACT VS. SOLID FUEL FBR COST COMPARISON

Acc.	Item	No.	Item	(Dollars in thousands) DCR	SFR
21			Structures & Improvements		
	211		Ground Improvements	800	800
	212		Buildings		
		A	Turbine Building	1,200	1,200
		B	Office & Service Buildings	350	130
		C	Fuel Rec., Stor., Decay	---	---
		D	Active Waste Disposal	60	40
		E	Steam Gen. & Feed Water	865	370
		F	Control Room	110	110
		G	Health Physics	25	25
		H	Miscellaneous Bldgs.	45	200
			TOTAL ITEM 212	2,655	2,075
	218		Stack	20	20
	219		Reactor Building	1,080	1,080
			TOTAL - ACC. 21	4,555	3,975
22			Reactor Plant Equipment		
	221	.1	Reactor Vessels & Supports	610	860
		.2	Reactor Controls	240	650
		.3	Reactor Shielding	1,890	1,770
		.4	Aux. Heating & Cooling	145	145
		.7	Cranes & Hoists	185	160
			TOTAL ITEM 221	3,070	3,585
	222		Heat Transfer Systems		
		.1	Primary Coolant System	1,905	2,180
		.2	Secondary Coolant System	5,705	2,460
		.3	Steam Generation	2,150	1,950
		.4	Coolant Rec., Supply & Treat.	340	445
		.6	Coolant, Initial Charge	170	130
			TOTAL ITEM 222	10,270	7,165
	223		Fuel Handling & Storage	15	1,500
	224		Processing Equipment	1,610	---
	225		Waste Disposal	1,525	80
	226		Instrumentation & Control	1,640	1,250
	227		Feed Water Supply & Treat.	960	960
	228		Steam, Cond. & F. W. Piping	1,950	1,950
	229		Other Reactor Plant Equip.	810	370
			TOTAL - ACC. 22	21,850	16,860

Table 3. 1 (continued)

Acc.	Item No.	Item	(Dollars in thousands) DCR	SFR
23	231	Turbine Generators	8, 110	8, 110
	232	Circulating Water Systems	975	975
	233	Condensers	1, 125	1, 125
	235	Turbine Plant Boards, Inst., Etc.	290	290
		TOTAL - ACC. 23	10, 500	10, 500
24		Aux. & Acc. Elec. Equipment		
		Aux. Power - Reactor Plant	925	860
		Acc. Elec. - Turbine Plant	1, 220	1, 220
		TOTAL - ACC. 24	2, 145	2, 080
25		Misc. Power Plant Equip.	480	445
	TOTAL DIRECT CONSTRUCTION COSTS		39, 530	33, 860

SUMMARY

Acc.	Item	DCR	SFR
21	Structures and Improvements	4, 555	3, 975
22	Reactor Plant Equipment	21, 850	16, 860
23	Turbine-Generator Equipment	10, 500	10, 500
24	Aux. and Acces. Electrical Equipment	2, 145	2, 080
25	Misc. Power Plant Equipment	480	445
	TOTAL DIRECT CONSTRUCTION COST	39, 530	33, 860
982	General and Administrative (8. 5%, 9. 0%)	3, 360	3, 047
		42, 890	36, 907
99	Miscellaneous Construction Cost (1%)	429	369
		43, 319	37, 276
981. 1	Engineering Design & Inspection (12.7%, 13.5%)	5, 502	5, 032
		48, 821	42, 308
981. 2	Nuclear Engineering (9. 0%, 10. 2%)	4, 394	4, 315
		53, 215	46, 623
984. 11	Startup Cost (35% of Annual O and M)	357	298
		53, 572	46, 921
20	Land and Land Rights	360	360
		53, 932	47, 281
	Contingency (10%)	5, 393	4, 728
		59, 325	52, 009
	Interest During Construction (36 mo., 8%)	4, 746	4, 161
	TOTAL CAPITAL COST	64, 071	56, 170
	Cost per kwe	$214	$187

An inherent feature of the DCR concept is its integrated processing system. This system, in common with some other mobile fuel reactor concepts, is constructed as an integral part of the plant, whereas solid fuel reactors (with the exception of EBR II) generally contract for their fuel cycle services off-site. In the latter case, a proportionate share of the capital investment required for such off-site facilities is reflected in the fuel cycle cost, and thus appears as an operating charge. In the DCR, the corresponding equipment is part of overall plant investment, and therefore appears as fixed charges. Because of shared services, space, and shielding, it is not feasible to segregate rigorously this portion of the investment, nor is it appropriate to do so, since the DCR could not operate without its integrated fuel system.

3.2.1 Structure and Improvements (Account 21)

The difference of $580,000 for the two plants is the net result of shielding required in the DCR steam generator bay, plus additional allowance for office and service facilities for the processing personnel, partially offset by the much more complex fuel decay storage and shipping facilities required for the SFR. There is a possibility that the intermediate heat exchanger for a DC core could be shielded from neutron activation, but the evidence is not yet clear enough to justify omitting the secondary sodium system and steam generator shielding at this time.

3.2.2 Reactor Plant Equipment (Account 22)

In the primary coolant systems, the cost of using tantalum in the DCR is partially offset by its smaller size compared to the SFR system. The major cost difference appears in the secondary system--$5,705,000 for the DCR vs $2,460,000 for the SFR. This is mostly due to the use of tantalum for the primary side of the intermediate heat exchanger. Future development work will show whether a much cheaper material would be suitable at this point.

Entirely similar steam generators were provided for the two plants. Those for the DCR are slightly smaller but are estimated to cost 10% more due to the need for remote access to instrumentation and controls.

The DCR primary coolant is automatically purified by contact with the fuel. This results in simplified and cheaper coolant receiving, purification, and storage facilities.

Fuel handling equipment is a major item in the SFR. The processing equipment in the DCR is about comparable cost-wise, although the equipment itself is entirely different.

Because of on-site processing, the preparation of high level radioactive wastes for ultimate disposal represents a major cost item in the DCR. The SFR has only relatively low level wastes to treat.

Although the DCR is inherently self-regulating from the nuclear and power output standpoints, the close integration of fuel and primary coolant processing with the core requires considerable process instrumentation not found in the SFR. This is estimated to represent an additional $390, 000 for the DCR.

The DCR concept provides for considerably more elaborate remote maintenance facilities than those thought necessary for the SFR. The difference, including the cell structure, is nearly $500, 000.

3.2.3 Turbine-Generators and Heat Dump (Account 23)

Although independently calculated, the steam conditions, flow rates, etc. for the DCR and SFR plants were nearly the same. For this reason no significant differences were found in the costs of the turbine-generators and associated equipment, the main steam piping, feedwater supply, and condenser systems.

3.2.4 Auxiliary and Accessory Electrical Equipment (Account 24)

The separate blanket cooling system of the DCR, plus its reprocessing facilities, is estimated to require more power supply equipment than the SFR. This cost is partially offset by the elimination of fuel handling equipment. The net difference is estimated to be about $65, 000.

3.2.5 Miscellaneous Power Plant Equipment (Account 25)

The DCR requires a somewhat larger staff and better laboratory support than the SFR. Equipment-wise this represents a difference of $35, 000 in the two estimates.

3.3 Operating Expense

Table 3.2 gives the estimated annual operating expense for the two plants. The calculations were based on the standardized 80% plant factor assumed in the AEC Handbook, but were also extended to 95% plant factor to show the importance of this variable in the two systems.

Nuclear calculations gave plutonium inventory and breeding ratio estimates for the two reactors which were so close that the values for both were arbitrarily fixed at 1200 kg Pu inventory and 1.3 breeding ratio. In the case of the DCR more than 98% of the inventory is continuously in the core, while in the SFR the fraction in the core is 70%. In both systems the plutonium is required in the form of nitrate or oxide, rather than metal, so that a price for plutonium of \$10.50 per gram was used, representing a price of \$12 per gram for metal less \$1.50 per gram conversion charge. This price was used for both credits and use charges.

In accordance with the instructions of the Handbook, the allowance for working capital at 12.5% consists of two figures--2.7% of estimated annual operating expenses, plus 60% of the fabricating cost for the first charge for the core and blanket. The initial charge of the DCR core and blanket is estimated to cost \$2,500,000. If fully capitalized it would represent an additional \$125,000 over the \$187,000 per year allowed.

The \$2,500,000 figure represents \$500,000 for cerium and cobalt alloying agents for the initial fuel charge, and \$2,000,000 for the 200,000 kg of depleted U as UO_2 needed for the inner and outer blanket systems. This is based on the current UF_6 price of \$2.50/kg plus an allowance of \$7.50 per kg for its conversion to oxide, for a total of \$10/kg. A better price for the conversion could perhaps be negotiated commercially for an order of this size, while the amount of UO_2 required could probably be significantly reduced by optimization of the design.

In Appendix B are summarized the fabrication and fueling costs for the SFR.

TABLE 3.2

ANNUAL EXPENSES

(Dollars in thousands)

Fixed Charges	DCR		SFR	
Construction Capital @ 14.3%	9,162		8,032	
Working Capital @ 12.5%	197		232	
Land @ 12.5%	45		45	
Nuclear Liability Insurance	284		284	
TOTAL FIXED CHARGES	9,688		8,593	
Operating Expense				
Regular Oper. and Maint. Personnel	700		700	
Special Operators and Maint. (Sodium)	70		70	
(Fuel Proc.)	70			
Regular Materials and Supplies	80		80	
Special Materials and Supplies (Fuel Proc.)	100		—	
TOTAL OPERATION & MAINTENANCE	1,020		850	
Fuel Cycle Cost — Plant Factor	80%	95%	80%	95%
Off Site Cost	100	119	4,036	4,793
Pu Use Charge (1200 kg @ $10.50/g)	598	598	598	598
Less Pu Credit (@ $10.50/g)	-675	-802	-675	-802
NET FUEL COST	23	-85	3,959	4,589

SUMMARY

	DCR 80%	DCR 95%	SFR 80%	SFR 95%
Fixed Charges	9,688	9,688	8,593	8,593
Operation and Maintenance	1,020	1,020	850	850
Fuel Cycle	23	-85	3,959	4,589
NET ANNUAL COST	10,731	10,623	13,402	14,032
Power Produced (x 10^9 kwh)	2.1	2.5	2.1	2.5
BUS-BAR COST (mills/kwh)	5.1	4.2	6.4	5.6

The nuclear liability insurance figure of $284,000 per year is that recommended by the AEC Handbook and is based on the Dresden plant. It could be argued that the inherent safety features of the DCR plus its considerably lower inventory of fission products within the reactor should entitle it to a much lower insurance rate. This is partially offset by the presence of reprocessing facilities which could be given a rating based on a higher probability of accidents but which were orders of magnitude less serious than a reactor accident.

Operation and maintenance expenses are based on the AEC guide, using 8 extra operators for the SFR and 16 extra for the DCR, with corresponding increases in maintenance materials and supplies. An additional allowance of $100,000 per year was made for DCR fuel processing supplies and chemicals.

The $100,000 shown as an off-site fuel cycle expense for DCR represents an allowance for ultimate disposal of high level radioactive wastes. Low level wastes would be disposed of on site.

3.4 Discussion and Conclusions

The power cost estimates derived in this report must not be construed as claims or predictions. However, the general trend of the results and the relationships between the figures are believed to be useful indicators of the economic potential of mobile fuel plants.

3.4.1 Power Cost

A comparison of the costs shown in Table 3.2 can be summarized by saying that the DCR plant suffers a disadvantage from fixed charges of about 0.5 mill per kilowatt hour (at 80% plant factor) compared to the SFR, and a 0.1 mill disadvantage in operation and maintenance cost. The total of 0.6 mill is offset, however, by a fuel cost difference of 1.9 mills in favor of the DCR, a net advantage for mobile fuel of 1.3 mills per kilowatt hour. Moreover, at higher plant factors the advantage is increased. The conclusions of this report are based primarily on the noted differences in the power costs for the two plants. The absolute level of costs is subject to more uncertainty, and must be taken only as a guide to projected costs.

3.4.2 Effect on Plant Factor

A mobile fuel reactor with integrated fuel system is unique among heat power stations in having a lower net expense at higher plant factor. This characteristic is a result of credit from excess plutonium and of built-in processing capacity. At first sight it would seem to be a disadvantage to have to pay the same for fuel processing whether one used it to capacity or not, but as Table 3.2 shows, the investment is returned three-fold by the savings in fuel cycle expenses. The operations of fuel storage, packaging, shipping, decladding, and fabricating are completely eliminated. In addition to a lower net cost, the built-in processing capability gives the mobile fuel system the unique characteristic of a negative fuel cost. This characteristic in turn will have an effect on the plant factor at which the system will be operated, as follows.

In Fig. 1 the estimated annual expense for the two plants is shown as a function of plant factor. The solid fuel station has an incremental power cost of 1.6 mills per kwh, derived from 1.9 mills for the additional fuel which must be cycled at increased load, and a plutonium credit of 0.3 mill. In the mobile station the incremental cost is negative, since the additional plutonium credit of 0.3 mill per kwh is virtually the only change. If a mobile fuel station were situated in a utility system having mostly conventional stations (either fossil or nuclear fueled), the base load would be placed upon the mobile fuel station, since there would be a substantial financial penalty for not doing so. In general utility practise the cheapest producer unit is base loaded, but the mobile fuel plant, having negative fuel cost, would be base loaded whether or not it is the cheapest producer. A high plant operating factor would thus be a characteristic of any mobile fuel plant, once built.

3.4.3 Effect of Plutonium Price Changes

The power cost estimated above for a mobile fuel fast breeder is in the neighborhood of 4 mills per kilowatt hour at high plant factor, under the assumption that plutonium metal is priced at $ 12 per gram. It is important to examine how changes in the price would influence the conclusions of this report. At the

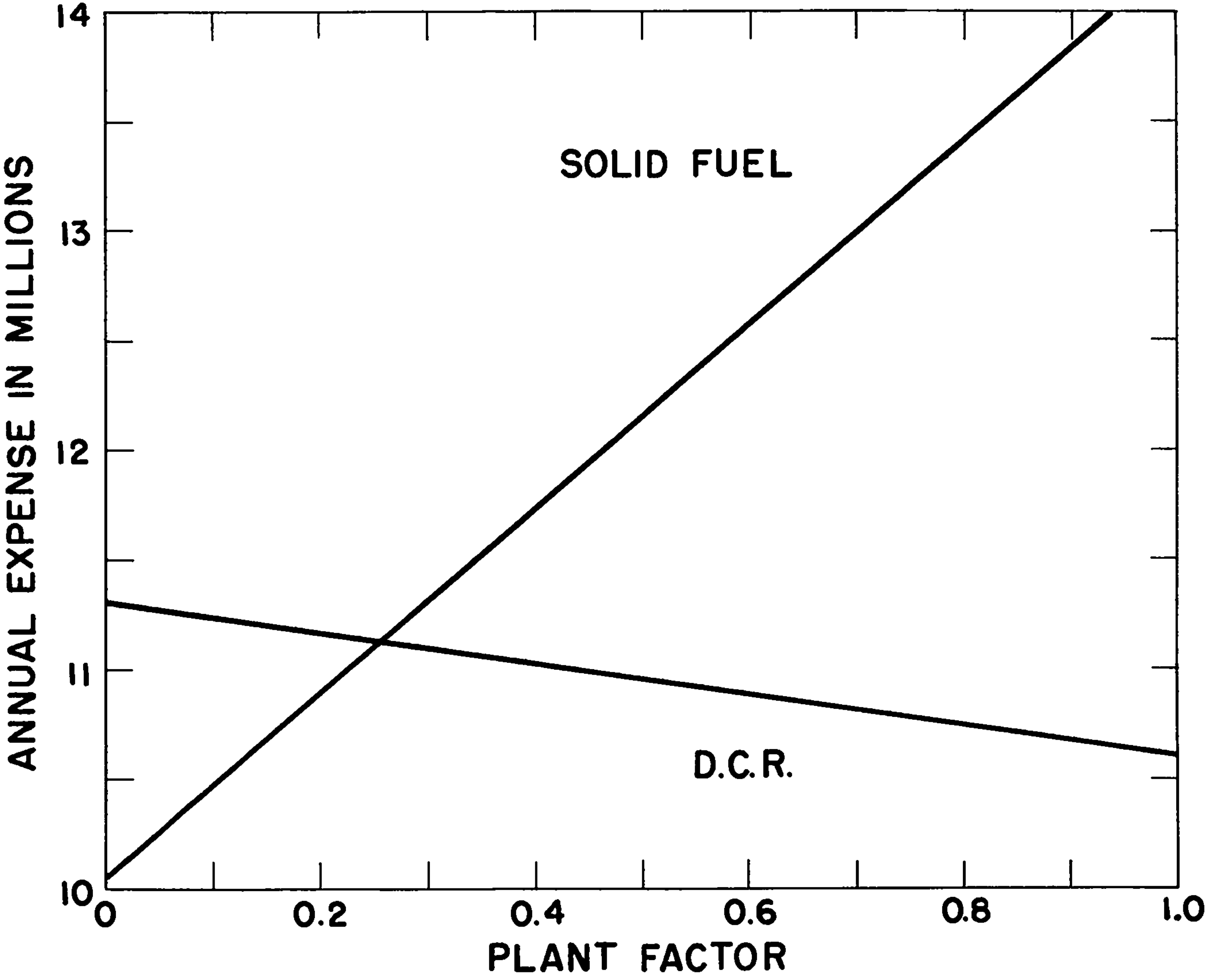

Fig. 1 Effect of Plant Factor on Annual Plant Expense

present time there are some indications that the government-established price for plutonium may be lowered as was that of U^{235}. Such a price change would be intended to reflect the value of plutonium as a burner fuel in terms of the value of U^{235} in thermal reactors.

However, if a fast breeder reactor could be built which proved to yield definitely cheaper power than a coal-fired plant in any location, the demand for plutonium to start such reactors would soon exceed the supply. In addition to forcing the value of plutonium upward, this would also influence reactor design in the direction of short doubling times for plutonium.

The reactor parameters which determine the doubling time (T_d) are the breeding gain (G), the specific power (S), and the plant factor (F). Defining the breeding gain as net plutonium increase per plutonium fission in the overall reactor, measuring specific power in kilowatts of plutonium fission power per gram of total fuel cycle inventory, and defining plant factor in the usual way, one finds the doubling time in years is given by: $T_d = \frac{2.55}{G \cdot S \cdot F}$. (In this expression the energy yield from plutonium is taken as 0.933 Mw days per gram.)

Figure 2 shows the effect of a change of breeding gain alone on power cost, other factors being constant. An increase in the price of plutonium is readily seen to increase the incentive to improve breeding gain. Similar effects are operative on specific power and the plant factor when the price of plutonium increases.

3.4.4 Effect of Private Ownership of Plutonium

It may be expected that government control of fissile material will continue as long as strategic and security reasons dictate, but private ownership may not be inconsistent with government control. If at some time a free market in plutonium is established and private ownership is required, then the lease rates on plutonium will become the same as for any non-depreciating capital investment. Figure 3 shows the variation of nuclear power cost from the reactors in this report if the specific power is varied, and other factors held constant. (It is usually impossible to change one such parameter independently in an actual

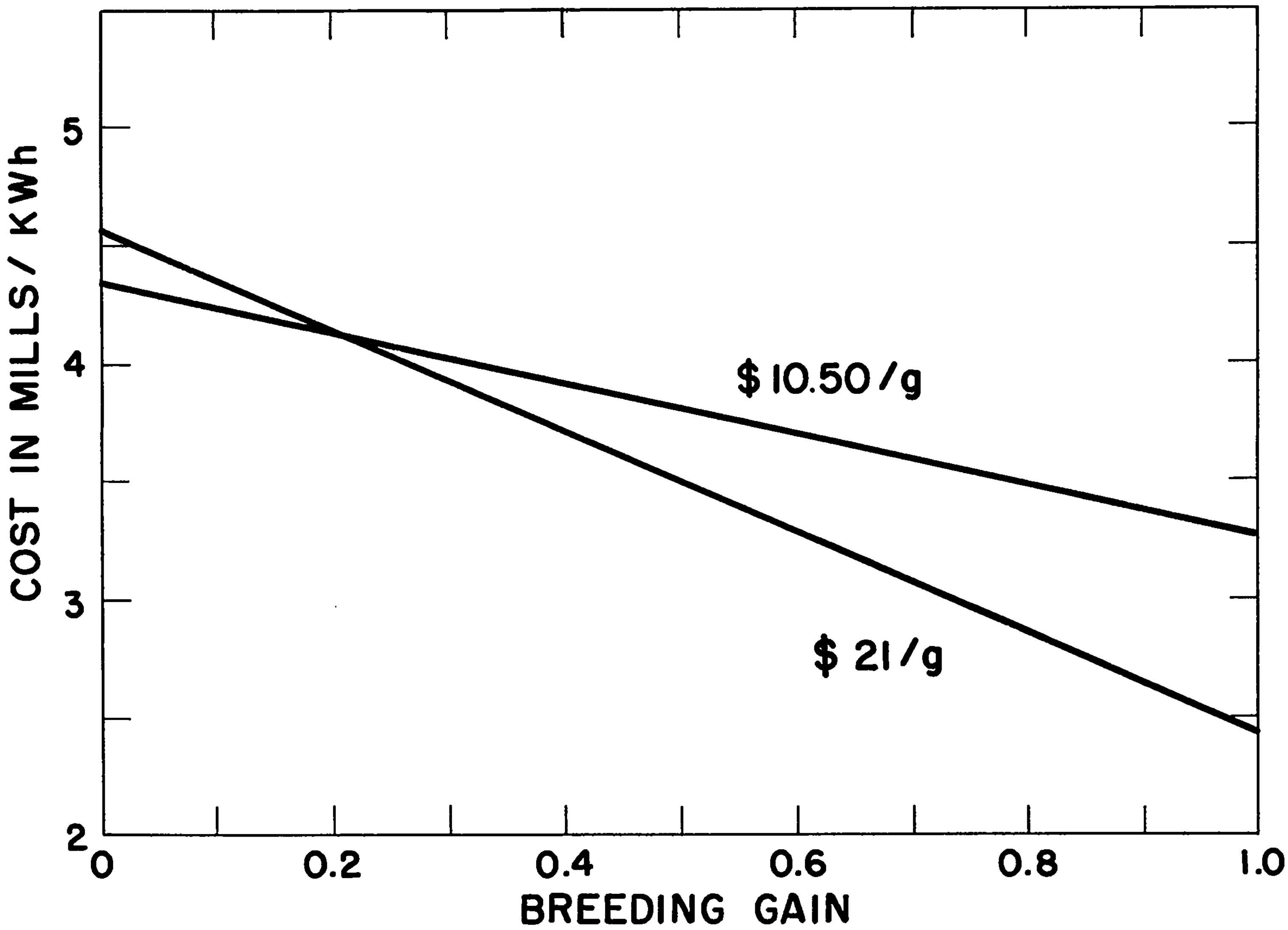

Fig. 2 Effect of Plutonium Value on Breeding Incentive

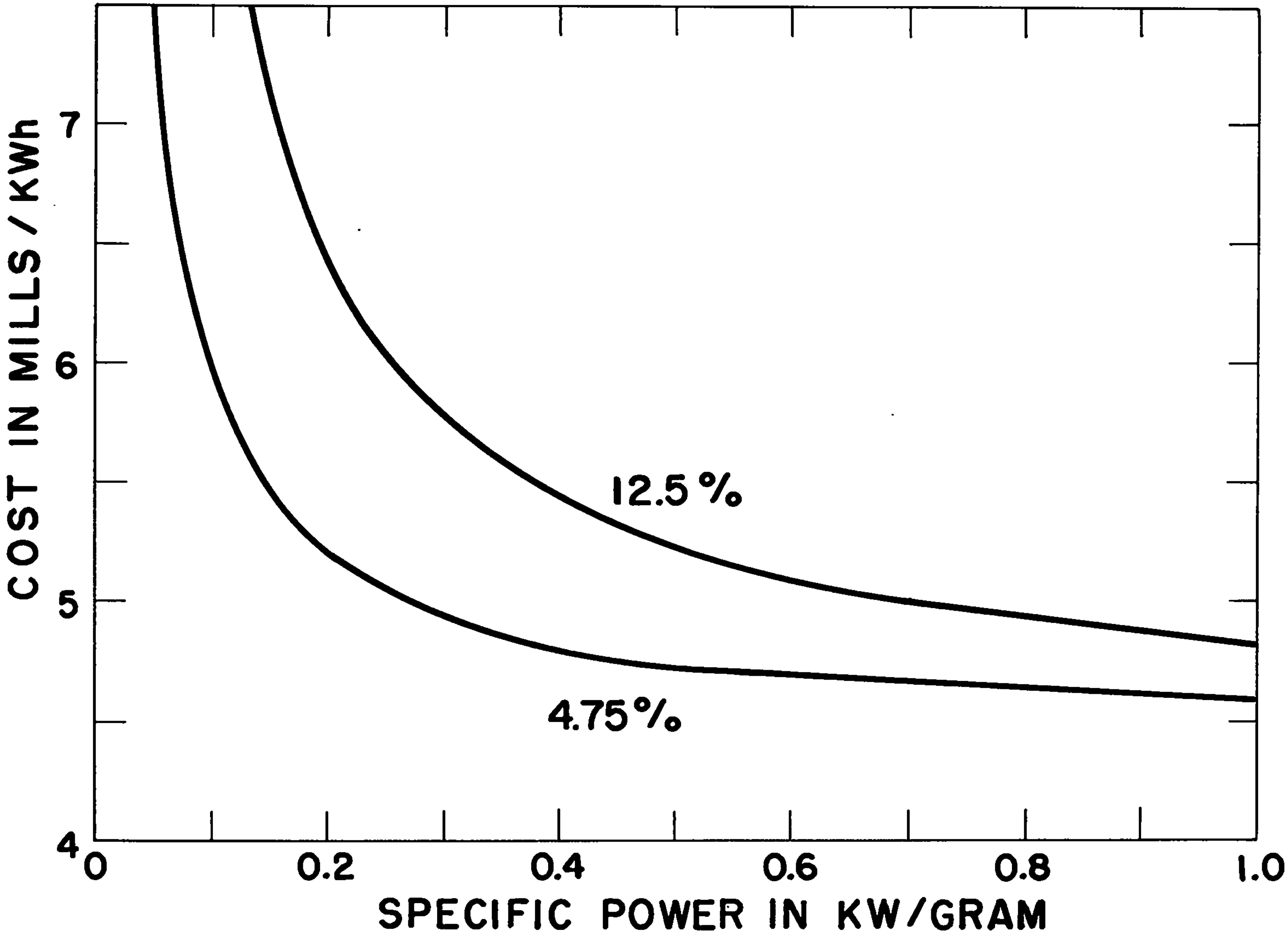

Fig. 3 Effect of Plutonium Lease Rate on Specific Power Incentive

reactor design.) The lower curve shows that under the 4.75% lease rate (use charge) now granted by the AEC, there is little incentive to improve specific power above 0.5 kw per g. Under private ownership, the lease rate would be 12.5% at present, and as the upper curve shows, there is a continuing incentive toward improvement. As mentioned above, this effect would be accentuated if the price of plutonium increased also.

3.4.5 Effect of Negative Fuel Cost on Plant Design

Table 3.2 shows that at high plant factor the net fuel cost of a mobile fuel plutonium breeder may become negative. That is, the value of the plutonium by-product may exceed the total of all other costs of fueling the reactor. Negative fuel cost removes the principal parameter which has governed the improvement and optimization of power plants for many years--fuel economy. It is quite certain that a power station optimized for low or negative cost fuel would be differently designed than present day stations. The study made in this report used conventional steam plant design practise, but the authors have found it interesting to speculate how the steam cycle and other parts of the design will change, when such low cost breeder plants can be built.

The old question was: How much increased capital investment can be justified to obtain a given increase in fuel economy? The new question would be: How can a plant of a given electrical capacity be constructed for the minimum total investment? This does not mean that plant efficiency is completely ignored, since a sacrifice in efficiency in any plant component, such as the steam turbine, would require more reactor, fuel processing, steam generation, etc., i.e.-- more capacity in every component up to the one in question. The answer to this question is surprisingly difficult to obtain, and far from obvious. Much detailed calculation would be required. One effect on turbine design can be readily foreseen, however, In conventional plants which run mostly at less than full load the turbine design is a compromise between part load efficiency and full load capability. It is clear that with negative fuel cost and with the expected high load factors for mobile fuel plants, only the full load efficiency of the turbine is important. Thus the turbine would be designed to perform best at peak output, with minimum cost.

4. THE DIRECT CONTACT CORE

4.1 Introduction

The utilization of plutonium as a power reactor fuel presents major differences from the use of uranium. The toxicity of plutonium prevents the use of direct handling and fabricating procedures, and the low melting point, complex metallurgy of its alloys, and strong fluxing tendencies of the metal make the thermal performance of metallic fuel elements very poor. For a solid fuel the most feasible form would be a ceramic, but the remote handling procedures required make such materials relatively expensive to fabricate.

An alternative promising approach is to use plutonium in the form of a liquid metallic alloy, taking advantage of plutonium's tendency to form low-melting alloys. This molten plutonium reactor fuel approach (LAMPRE) has been under development at Los Alamos since 1956. The direct contact core is a version of this concept which takes advantage of the immiscibility of sodium with molten plutonium alloys to provide both heat removal and partial fission product extraction from the core by direct mixing of the liquid fuel with the coolant. In the following sections, the operation and properties of such cores are discussed, together with their expected potential usefulness in the achievement of high-performance breeder reactors. This description is intended as an illustration of one promising arrangement for the utilization of molten plutonium--other core arrangements and concepts are being considered and may prove superior upon further investigation.

4.2 Schematic Diagram and Operation of a Direct Contact Core

The core and heat removal system are represented schematically in Fig. 4. The core is a vessel completely filled with liquid fuel at all times. The fuel is circulated rapidly through the core by means of an external jet of liquid sodium, which extracts heat from the fuel in addition to supplying the pumping impulse. A contact time of a few milliseconds permits complete temperature equilibration of the mixed stream; the immiscible fluids are then separated centrifugally by utilizing their large difference in density. The fuel returns to the core, while the hot sodium is cooled in a heat exchanger and pumped back to the jet nozzle.

In an actual core the arrangement and shape of the components is chosen to permit a small inventory of fuel outside the reactor, to achieve the maximum thermal output, and to facilitate the placement of the breeding blanket as close as possible to the core. Illustrative preliminary arrangements are described. These may be modified as the result of further experimentation.

4.3 Fuel and Container Materials

4.3.1 Fuel Alloy

The fuel proposed for direct contact cores is an alloy of plutonium, cerium, and cobalt. As shown in Fig. 5, the ternary composition diagram of the system exhibits a low temperature eutectic valley with a melting point near 420°C and a more or less constant cobalt content of about 25 a/o.[4] This means that Pu and Ce may be used in varied ratios over a wide range, with little change in melting point. This characteristic permits the plutonium enrichment of the fuel to be chosen to suit the reactor design, a degree of freedom which is most important in obtaining high performance core designs.

Other fuel systems are also possible, but have not yet been studied as fully. The system Pu-Ce-Cu, though limited to Pu concentrations over a narrower range, includes those of interest for large scale application. There are

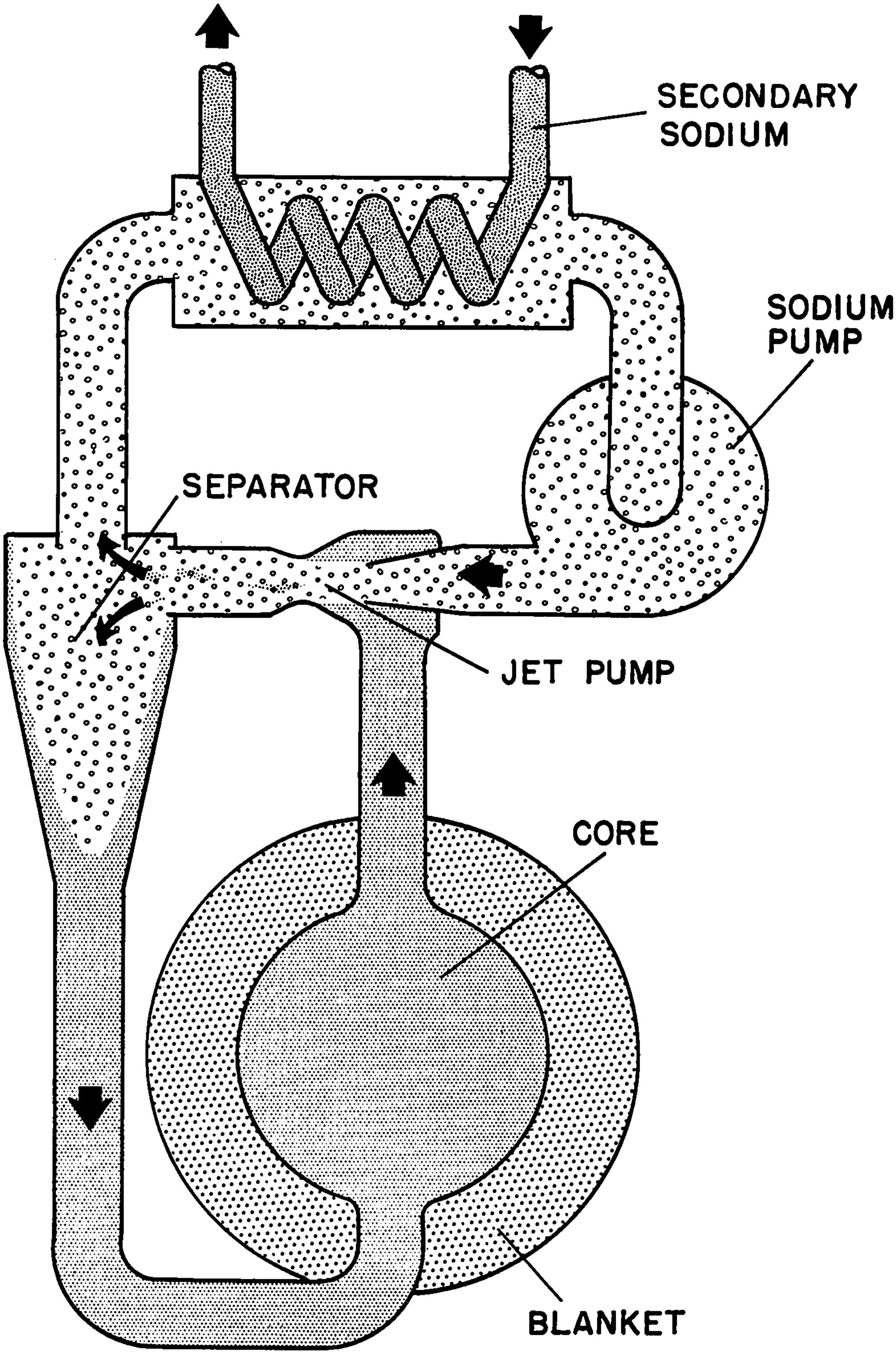

Fig. 4 Schematic Drawing of a Direct Contact Core

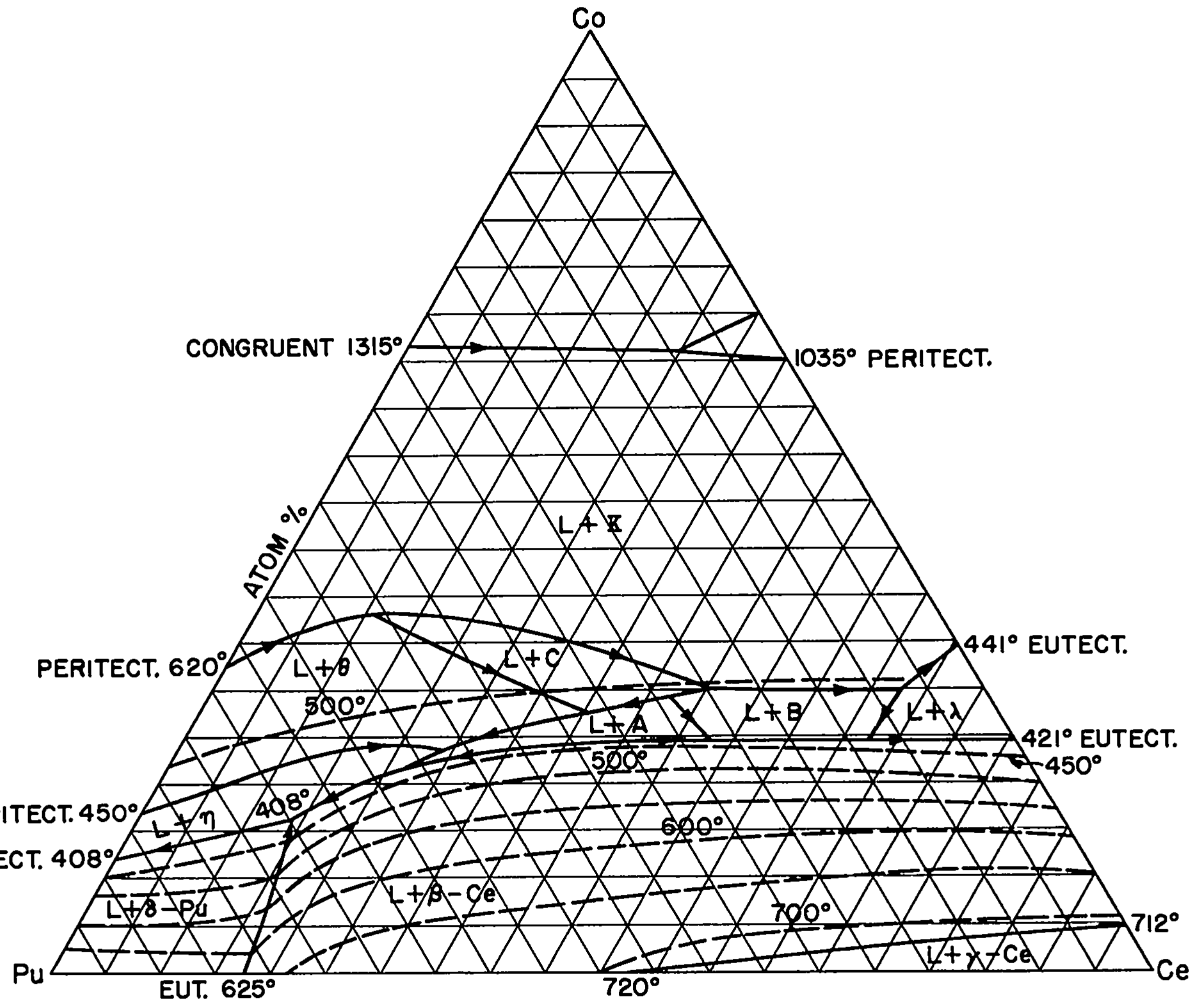

Fig. 5 Ternary Composition Diagram for Pu-Co-Ce
(Courtesy of Ellinger, Land, and Johnson, Los Alamos Scientific Lab.)

indications that this system may prove less corrosive than the Co system, though tests of this point are just beginning.

4.3.2 Container and Structural Materials

The requirements for a direct contact core are significantly different from those for a core embodying an internal heat exchanger:

1. The core consists principally of a container shell; there is very little internal structure, which need not be leaktight since it functions only as a flow guide.

2. There is no heat transfer across container walls, so they can be made as thick as desired within neutron loss limitations. Pressure stresses can be kept fairly low, and thermal stresses will exist only during temperature transients.

3. Fairly high corrosion rates can be tolerated because of the thick walls and low surface to volume ratio. There are no small fuel or coolant passages to become clogged.

4. High temperature gradients and high velocities in the fuel mean that mass transfer and erosion must be successfully resisted.

5. For lack of more definite knowledge it must be assumed that small droplets of fuel will remain entrained in the sodium stream after the phase separation step. Such droplets would alloy with stainless steel components, so that the core sodium system, pump, and intermediate heat exchanger must be constructed or clad with a refractory metal such as tantalum on the primary coolant side.

Materials effort to date has been primarily concerned with the highly concentrated (15 g/cc) plutonium fuel used in LAMPRE I. The few tests so far with dilute fuel indicate that it is easier to contain than the LAMPRE I fuel. High purity tantalum, yttrium, and niobium all show good promise in these static tests and all are resistant to sodium. The effects of velocity and high temperature gradients are unknown so far. For non-structural portions of the core, as in liners, nozzles, and flow baffles, a ceramic body would be feasible. In preliminary tests, a few ceramic materials have shown good resistance to the dilute fuel.

The successful fulfillment of the container requirements is essential to the direct contact core concept. Present efforts should provide definite information on this problem by the summer of 1962.

4.4 Operating Characteristics

4.4.1 Heat Removal

As in any circulating fuel reactor, heat removal is determined by the flow rate and temperature rise. The volumetric heat capacity of the fuel is estimated at about 0.47 cal/cc °C, which means that at 250°C temperature rise, about 32 gallons per minute must be circulated per megawatt of power. The most appropriate sodium flow for a given fuel flow is subject to several factors, a volume ratio near 3:1 being selected as optimum for the present study. A sodium flow of 100 gpm per megawatt gives a temperature rise of about 150°C.

The temperature rise of the fuel is superimposed upon that of the sodium, since the heat transfer is concurrent. The lowest temperature in the sodium system must be above the melting point of the fuel, so that any entrained droplets will drain back to the core, rather than freeze to the heat exchanger or other surface.

The contaminated sodium which pumps the fuel gives up its heat in an exchanger, located just above the core, to a secondary sodium circuit which is used to generate steam. The proposed arrangement of these components is given below. (See 4.5.)

4.4.2 Fission Product Extraction

The continuous contact of the fuel and sodium streams in the jet pump will extract fission products of the alkali, alkaline earth, tellurium, and halogen groups into the sodium, along with the gaseous elements. The sodium-soluble products could be left in the sodium, since they are negligible in quantity, amounting to about 1 part per thousand after a full year. The accumulation of these radioactive species, however, can be avoided by reprocessing the sodium, and equipment for this is included in the plant design.

The other fission products are expected to remain in the fuel phase, which consists of 67.5 a/o cerium, 25 a/o cobalt, and 7.5 a/o plutonium. Estimates[5] of the solubility and rate of build-up of such products in the fuel show that only minor perturbations of the composition and melting point would be expected even if all the original plutonium were fissioned, with new plutonium added to maintain reactivity. This 100% burnup level would be reached in 6 or 7 years at the specific power expected in such cores. At some point the solubility limit of zirconium and molybdenum would be reached, and these elements would deposit as a solid phase. It is not yet known just where deposits would form, but the small amount of material involved is not expected to cause any problems.

A large, dilute, direct contact core is not expected to require any fission product removal for long periods of time except the collection of gaseous elements, unless it is desirable to decontaminate the sodium. The only core processing necessary would be the addition of plutonium to replace that consumed.

A convenient mechanism does exist, however, for additional fuel processing should it become necessary. A small amount (0.1%) of sodium chloride added to the sodium phase will produce an appreciable solubility of many additional fission products in the sodium phase, which could then be processed in well-known ways on a continuous basis.

The processing of the fertile blanket is discussed in a later chapter.

4.4.3 Temperature Coefficient and Control

Since the direct contact core contains essentially only liquid fuel, and is always full, a temperature rise produces both lowering of fuel density and removal of fuel from the core. The net effect is a prompt temperature coefficient of reactivity of about -5×10^{-5} per °C. This large coefficient produces a high degree of stability and self-regulation, as has been well demonstrated with other liquid fuel reactors, such as Los Alamos' water boiler, LAPRE II, and LAMPRE I, and the Oak Ridge HRE and HRT. When operating at power, such reactors respond to the insertion or withdrawal of reactivity primarily by a change in operating temperature, the power remaining the same until the demand of the heat extraction system is changed.

Operating control of such a reactor is thus conveniently achieved by heat demand, and the reactivity is adjusted only to obtain the desired operating temperature. With this mode of control there is no excess reactivity held in control mechanisms, eliminating a major source of danger. In the direct contact core, temperature adjustment could best be made by means of the plutonium concentration of the fuel. With fuel at the proper concentration, the core would be hot and critical whenever filled, so that accidental freeze-up of the fuel would be impossible. To shut down the core, the fuel would be pumped to a storage reservoir by a small sodium jet pump. The core arrangement shown in Fig. 6 includes a fuel displacement plunger, which would be used only if an emergency occurred in which freeze-up of the fuel would be desired or unimportant.

4.5 Arrangements of Components, Maintenance and Replacement

The components of a direct contact core which come in contact with fuel and fission products are the core vessel, the jet pump and phase separator, the core sodium heat exchanger (tube side only), the core sodium pump, and the surge volume. As shown in Fig. 6, these elements may be arranged one above the other within a cylindrical envelope. The resulting assembly is called a core capsule. It is highly compact, uses the minimum of connective piping, and provides its own structural support. The position of the core at the bottom helps alleviate shielding problems, since the heat exchanger and pump interpose mass and distance. The arrangement has the advantage that any droplets of fuel carried up by the core sodium tend to be returned by gravity to the core again, so that inventory is maintained. The capsule is placed in a stainless steel thimble around which is the blanket material. Annular ducts in the thimble lead the secondary sodium to and from the shell side of the core heat exchanger. The entire assembly is contained within the secondary sodium system, so that double containment is achieved without complexity. A third layer of containment is provided by the piping and reactor vaults.

Maintenance or replacement of a core capsule is complicated by the fact of its great length (50 feet or more), which requires a high crane bay. Any work

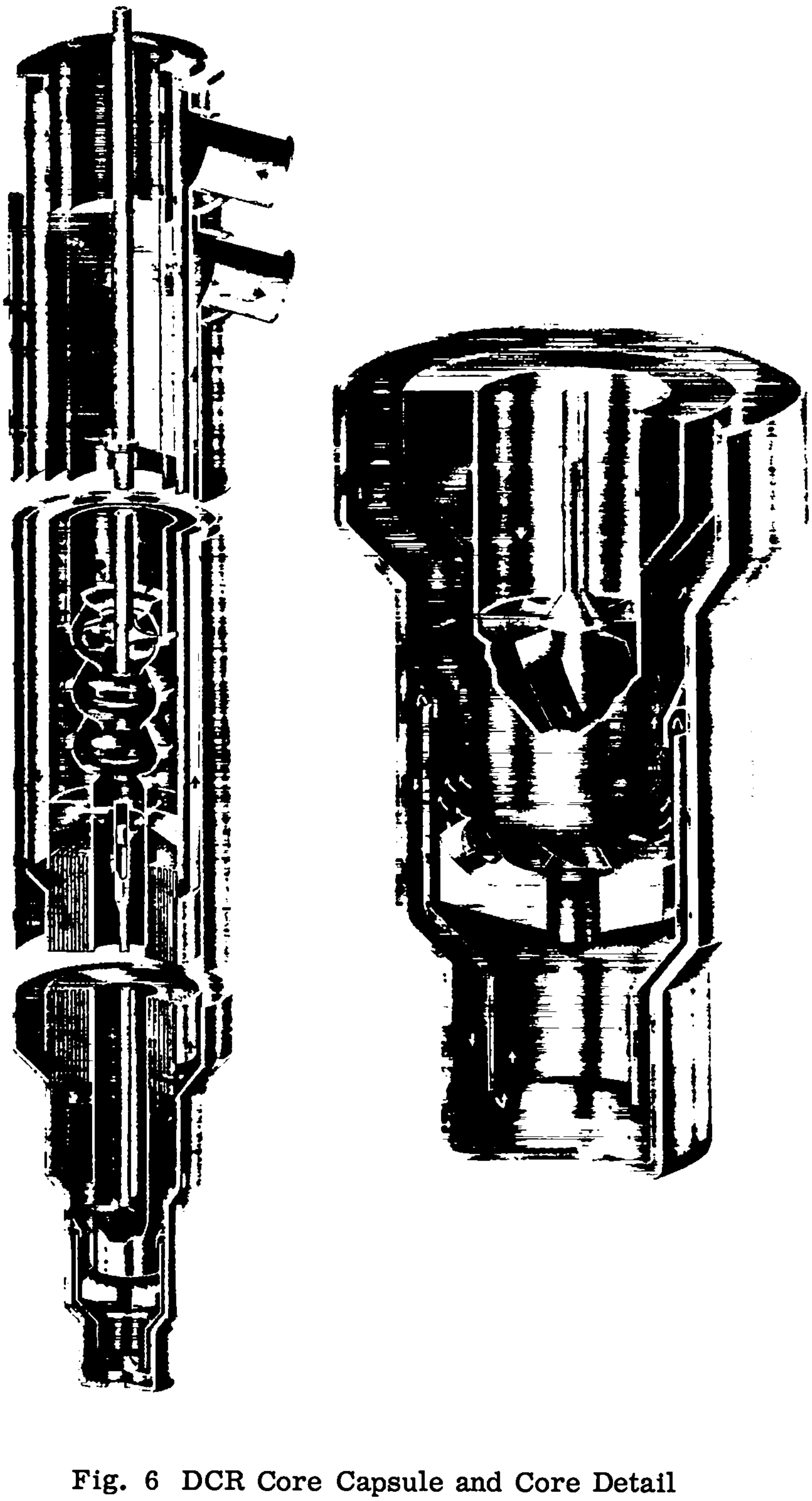

Fig. 6 DCR Core Capsule and Core Detail

on the core system would be preceded by jet pumping of the fuel out the top of the capsule through a small, shielded line to a storage tank equipped to keep it molten, followed by a similar removal of the core sodium. Removal and replacement of the pump could be accomplished in place by opening the secondary and primary seals. Experience at Los Alamos in operating molten plutonium-sodium loops has shown that such operations are feasible and that plutonium contamination can be controlled. More extensive repairs would require removal of the entire capsule to a maintenance cell equipped with manipulators. It is fortunate that the most expensive components, the pump and heat exchanger, are considered least likely to require maintenance, while the relatively simple core container and jets can be replaced on the assembly with a few connections.

After replacement of a core capsule, it would be purged by pumping gettered sodium through it at high temperature for some hours, before restoring the core sodium and fuel from the storage tanks. Slow, metered addition of fuel from the tank would provide a safe, reversible approach to criticality, similar to that used successfully on the LAPRE II reactor.[6]

4.6 Safety Characteristics of a Direct Contact Core

The inherent safety characteristics of a reactor concept may turn out to be even more important than the cost of power it produces. The stability properties of a direct contact core are completely unknown in an experimental sense, although this situation is to be remedied in the near future by tests at Los Alamos. In the meantime some tentative conclusions can be drawn from the geometry of the system and from calculations.

The core of a DC reactor is essentially structureless. It consists of a closed container completely full of fuel. Inlet and outlet pipes connect the core with the jet pump and separator, which are isolated neutronically from the core to some extent. Closely fitting around the core is a secondary container, and the wall of the blanket region. Should rupture or leakage of the core occur, it would be nearly impossible for the liquid fuel to assume a configuration of higher criticality (greater buckling) than it had in the core. The fuel system contains no voids which could fill with fuel, no fuel elements which could melt down or move together, and no coolant to be displaced. The neutron shield which separates core and pump would have to be rigidly prevented from movement in either direction.

The large prompt negative temperature coefficient of a liquid fuel reactor is well known. It provides a built-in shutdown mechanism which has the capability of absorbing relatively large and rapid insertions of reactivity with no after effect except a rise in temperature. The calculated temperature coefficient of the DC core is -5×10^{-5} per °C, which is the same as that measured for LAMPRE I. For the latter reactor, R. M. Kiehn has calculated that a ramp insertion at the rate of $5000 per second would not result in mechanical damage to the core, provided the total temperature rise were not too high. (See Appendix of Ref. 2.)

The amount of temperature rise which can be safely tolerated by a direct contact core is unknown, but laboratory experiments indicate that while corrosion becomes more rapid at higher temperatures, no sudden containment failure would be expected for short exposures of even 2800°C. Such a fuel temperature rise of 2000°C over the normal operating temperature would be destructive for most reactors. The direct contact reactor may thus be unique in having a high tolerance for rapid reactivity insertions, which produce only temperature excursions, and an unusual capability of withstanding temperature excursions without a phase change in fuel or container.

The contact of sodium with the fuel provides the possibility of continuous removal of fission products if desired, so that a smaller inventory is stored in the core system in the event of release to the surroundings. Among the fission products removed from the core are some of the delayed neutron precursors. The magnitude and results of this effect are under study. While a low core β is potentially a detriment to safety, the presence of delayed neutrons from the blanket is expected to offset the loss from the core. The wash-out of neutron precursors from a small fluid core is to be studied experimentally in the near future.

The experimental studies will provide better grounds for assessing the inherent stability of D. C. cores, but the geometrical considerations and the nature of fluid fuels provide some assurance that inherent safety characteristics superior to most solid fuel cores can be obtained.

4.7 Other Core Concepts

The direct contact core described in this chapter has not been tested experimentally. The hydraulic characteristics of such cores are currently being studied experimentally, and the nuclear characteristics are receiving analytical attention. Fuel and container materials are being tested in an extensive program. The concept must remain in the unproved classification until these programs have shown sufficient promise to lead to operating tests of pumped cores. Such tests are being planned for operation in 3-4 years' time. As mentioned above, low power critical and stability tests will be done in the near future.

The question may fairly be asked as to whether the future of unified plutonium reactor plants, as discussed in this report, depends upon the success of the direct contact core concept. Two alternative approaches are described briefly in the paragraphs below. Both are untried but promising concepts which if proved technically would offer the same economic promise as the plant hypothesized in this report.

4.7.1 Spiral Core

This name is given to a core in which liquid plutonium fuel is contained relatively statically in tubes or passages, and transfers its heat by conduction through the container walls to sodium flowing through the core. The tubing or fuel containers would probably have a spiral configuration, hence the name. This concept would be a direct descendant of the LAMPRE I fuel capsules, but modified for continuous processing and degassing of fuel. The concept is described in more detail in LA-2332.[2] This core would have few nuclear uncertainties, and the only apparent barriers to its success are control of the corrosion of the thin-walled container, gas purging problems, and the question of solids deposition in the core passages.

4.7.2 Paste Core

The use of plutonium fuel in the form of a paste of UO_2-PuO_2 particles in liquid sodium would retain most of the advantages of a liquid fuel which are obtained from its mobility, and would drastically reduce the uncertainty due to corrosion or materials problems. Such pastes could be contained in stainless steel at any temperature from 200°C to 800°C. In exchange for the corrosion problem, however, are the problems of transport, gas purging, density control, and reprocessing. Reactor concepts utilizing large particle uranium metal paste have received considerable attention by Atomic Power Development Associates, Inc., including support of experimental studies. Some preliminary experiments have been done at Los Alamos on paste properties and transport methods using UO_2 particles of small size, and further work is underway. Reprocessing of paste can be done readily by adapting existing methods.

5. DESCRIPTION OF PLANT

5.1 Introduction

The reactor plant described in this report departs in several ways from the approach used in most existing reactor stations and design studies. First, it is a unified plant, meaning that essentially all the operations involved in the production of power are included in the plant in a close-coupled, integral unit. The basic fuel material, U^{238}, as either natural or depleted uranium, is brought into the plant in bulk form, and is converted within the reactor first into plutonium and then into heat in a continuous series of linked operations. Where it is necessary to isolate one operation from another, this is done by interposing heavy concrete shielding, which also forms part of the reactor shielding. The authors believe that isolation in this way can be just as effective as locating the various operations in separate installations, and permits major savings in loading, shipping, and unloading facilities, housekeeping facilities and personnel.

Second, the plant is designed as though it were based on experience. It is not a reactor experiment, nor even a prototype plant, which properly is constructed with a cautious approach, provision for major change and modification, segregation of all components, and deliberate overdesign. Rather, the system described is assumed to be the second or third of its type, with tested processes and operating experience available. This does not mean that no provision for breakdown is made; on the contrary, the processing equipment, for example, is provided in duplicate or is readily replaceable. The principal value of experience lies in reducing the overdesign margin required. The shielding, structural components, and operating space are adequate but not wasteful; the correct amount of insulation, standby power, and spare parts is provided, etc. Exact information was not, of course, available for this design, and might have a noticeable effect on the estimated costs. The available information was used realistically, without adding the ignorance factor which would be provided for a prototype plant.

Third, the plant is based upon a direct contact molten plutonium reactor with multiple cores and a uranium oxide paste blanket. Unique as this combination of choices may be, it is believed that the economic conclusions of this report are not limited by this particular example. The possible approaches to a mobile fuel fast reactor are fairly numerous. A study has been made of the cost factors in several of these approaches, and the conclusion formed that the one chosen herein was probably the most expensive, but that the reactor portion of the plant would not be changed in cost by more than 20%, regardless of which core concept was chosen. This would mean less than 7% change in overall plant cost.

5.2 General

The plant consists of one large three-core reactor having 800 Mw thermal output, three sodium-heated steam generators, and one 320 Mw cross-compound turbo-generator. The net output of the plant is 300 Mw electrical. The reactor installation includes all processing necessary for the complete fuel cycle, means for repairing contaminated equipment, and facilities for packaging waste products and by-product plutonium for shipment. The above systems are all housed in one large mill-type building, with most of the radioactive equipment underground in heavily shielded pits. The main building also houses the necessary offices, personnel and storage rooms, and the single control room for the plant. Another building on the site houses the equipment for batching and treating low level wastes. Apart from these differences, the plant characteristics are those specified in the AEC Cost Evaluation Handbook. As directed in the Ground Rules, the plant cost estimates include bus-bar power components only, with no provision except space for the transformer and switchyard portion of the system.

The reactor portion of the plant is described from its external characteristics only. The principle of its operation is discussed in Chapter 4. The nuclear design of the reactor is based upon practises of the reactor development division of the Los Alamos Scientific Laboratory, and upon machine calculations of the DSN type, using Kiehn ten-group cross sections. This work is not discussed in the present report.

5.3 Main Building

As shown in Fig. 7, the main building consists of a mill-type structure about 86 feet high, 110 feet wide, and 370 feet long. The building is not pressure tight and has only ordinary heating and ventilating supplies. Against one side a small two-story wing of masonry construction houses the plant offices and personnel rooms. The wing extends somewhat into the main bay of the building, so that the plant control room overlooks the entire operating floor. A 150/30 ton bridge crane travels the length of the main room. Storage, supply, and ventilating equipment rooms are located as interior structures in the corners of the main room. They do not extend up to the crane rail.

5.4 Reactor and Process Area--General

Horizontal and vertical sections of the reactor and process area are shown in Figs. 8 and 9, respectively. The arrangement has the purpose of providing adequate isolation of separate operations but close spacial contiguity for the easy flow of process materials. The system may be visualized as a series of concentric shells, with the reactor cores at the center surrounded by the inner and outer blankets, the reactor inner shielding, and the reactor containment vault. The heavy concrete walls of the vault provide part of the biological shielding of the reactor, as well as the back wall shielding of the process cells. The process cells enclose the reactor on the sides. Both the reactor and the cells are serviced by an upper pipe gallery for the transfer of process materials. The outer shell of containment and biological shield is provided by the main operating floor slab and the outer shield walls of the process cells.

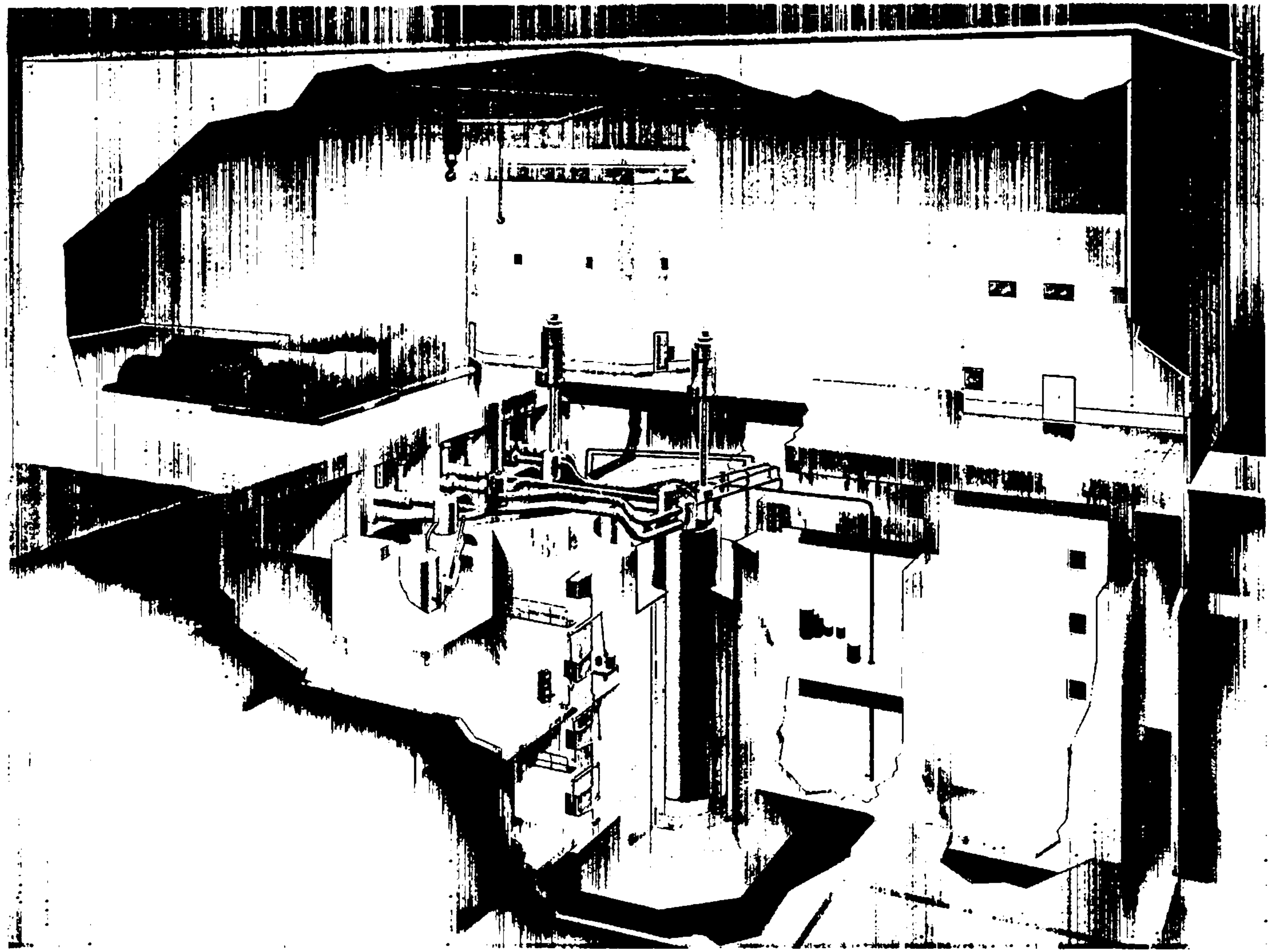

Fig. 7 Cutaway View of DCR Plant

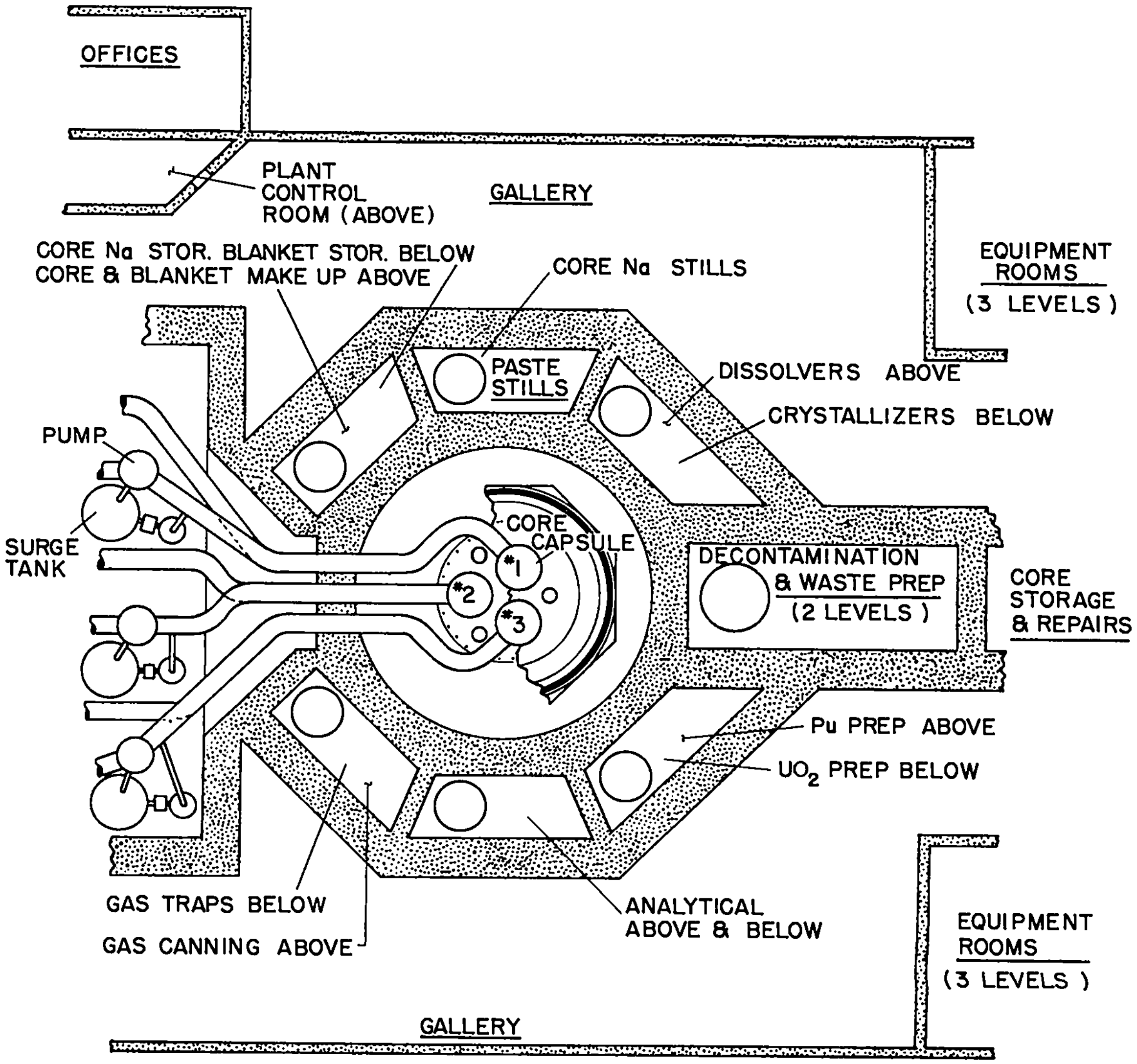

Fig. 8 Horizontal Section of Reactor and Processing Cells

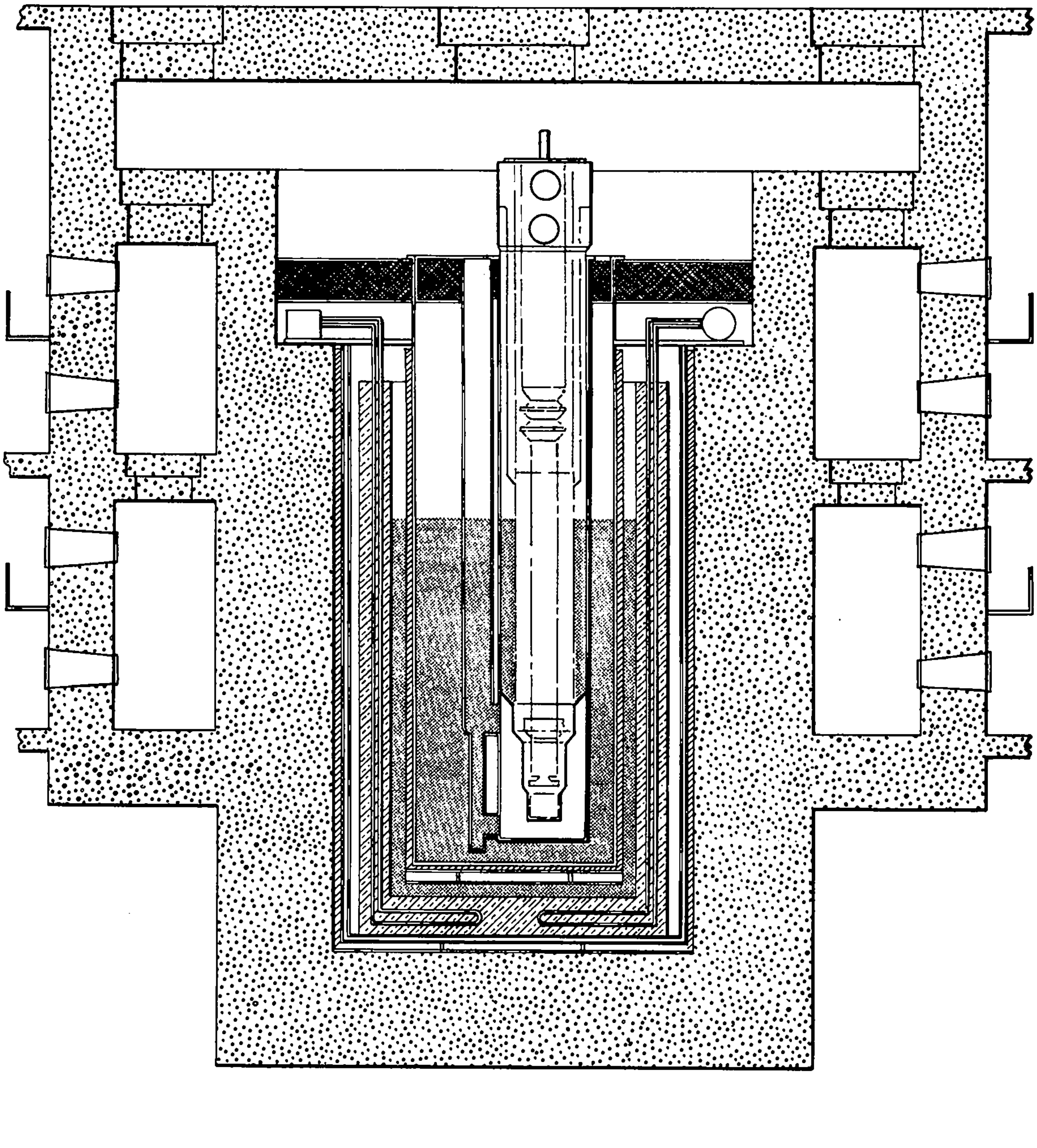

Fig. 9 Vertical Section of Reactor and Processing Cells

5.5 Core Insert System

Three core insert capsules, each supplying a little less than one-third of the full plant capacity, are located in a single vertical cylindrical tank, the reactor vessel, and comprise the plant reactor system. Each core insert (Fig. 6) is a complete assembly and includes a reactor core container, fuel flow baffles, heat exchanger tube bundle, core sodium pump, and motor, all sized for a thermal capacity of 227 megawatts. Each capsule is 4 feet in diameter and extends 60 feet below the main floor level. The regions contacting the liquid plutonium fuel alloy are fabricated of niobium or tantalum.

The heat exchanger tube bundle in each capsule is fabricated of niobium or tantalum or clad on the tube side, and consists of 2,320 tubes 1/2 inch in diameter by 16 feet in length. The unit is built with a central downcomer but no shell.

The pump is a vertical sump type, 2-stage diffuser pump, discharging downward, with a capacity of 22,200 gpm at 45 psig, equipped with vertical shield plug, magnetic variable speed coupling, and drive motor. The pump housing and impeller are niobium or tantalum clad. The rotating parts of the pump can be removed vertically for servicing. The shaft seal is located in the helium-filled surge volume above the sodium.

A stainless steel capsule encloses each core assembly and directs the flow of secondary sodium through the shell side of the heat exchanger. The complete capsule is designed to be readily removable and replaceable.

5.6 Blanket Systems

5.6.1 Inner Blanket

There are three inner blanket systems (Fig. 9), one associated with each core capsule. The inner blanket system acts as the container for the core insert and consists of a stainless steel tank, a pump, and associated piping for circulating the uranium oxide paste. The paste is pumped as a dilute slurry but settles through the main region surrounding the core as a dense paste. A stainless steel heat exchanger receives a portion of the secondary sodium flow and removes approximately 40 megawatts of heat generated in each inner blanket after it has reached equilibrium plutonium content. A stainless steel pump of 10, 000 gpm capacity is used to circulate the blanket paste.

5.6.2 Outer Blanket System

The outer blanket system surrounds the three core units and is contained in the lower portion of the main reactor vessel, a cylindrical tank 13-1/2 feet in diameter and 41 feet high. This tank is clad with stainless steel and fitted with a top plug containing the nozzles for the three inner blanket tanks and pump sumps. It also carries a paste circulating pump of 10, 000 gpm capacity for jet pump circulation of the outer blanket paste. Thermal conduction through the walls to the inner blanket systems removes the small amount of heat developed in the outer blanket.

5.7 Reactor Pit Tank and Support System

The main reactor tank is backed up by a carbon steel secondary container. The space between this container and the cell liner tank is filled with steel and unclad graphite shielding. The cell liner is approximately 24 feet in diameter by 42 feet deep. The reactor vault is capped by a structural circular beam designed to support the main reactor tank. The beam is enclosed and filled with steel shot or similar material, forming a portion of the shield. The plug for the main reactor tank also contains shielding. It supports the three inner blanket sleeves which penetrate it. These in turn support the core inserts.

5.8 Process and Service Cells

The process and service cell design philosophy is based on a combination of remote and direct maintenance. Experience at Los Alamos indicates that this approach provides a desirable compromise between the simplest, most reliable process equipment and provision for unforeseen breakdowns. Each cell contains the required equipment for one major step in the processing of the fuel, blanket, coolant and cover gas systems, and is isolated from the other cells both by containment seals and shielding. (See Fig. 8.) Duplicate equipment is provided for critical operations in the same cell. The equipment is operated by sealed Model A manipulators for the most part, although through-the-wall sealed handles, electric switches, and other means might be used for certain equipment. Much of the equipment is of such small size that the entire apparatus can be handled by the manipulator. In other cases the apparatus is mounted on racks which are hung from the back wall of the cell. The racks can be removed or replaced using a small winch aided by the manipulator. The portion of the manipulator inside the cell can also be remotely removed and replaced with the winch, while the winch itself can be replaced from the top of the cell.

An unforeseen breakdown, or a revision of the process, is handled by entrance to the cell if remote operations are inadequate. This may require that process materials be removed or washed out using the manipulators and that the cell be decontaminated.

The cells are lighted with external light sources which project light into the cells through sealed windows. Metal mirrors inside the cells distribute the light where it is needed. This method of lighting minimizes the heat load which makes possible a simplified cell ventilation system, and makes the light fixtures accessible.

5.8.1 Piping Deck

Transport of process materials and equipment in and out of the cells is accomplished through the top only, in order to maintain compartment isolation. The tops of all the upper process cells form a floor level called the piping deck. Pipelines connecting one cell with another or with the reactor are laid out on this floor in such a way that each line is accessible without disturbing the others. Where radioactive materials are transported, each line is individually shielded with removable slabs of lead or steel so that any portion may be uncovered for maintenance without exposing other contaminated lines. (See Fig. 10.) A small

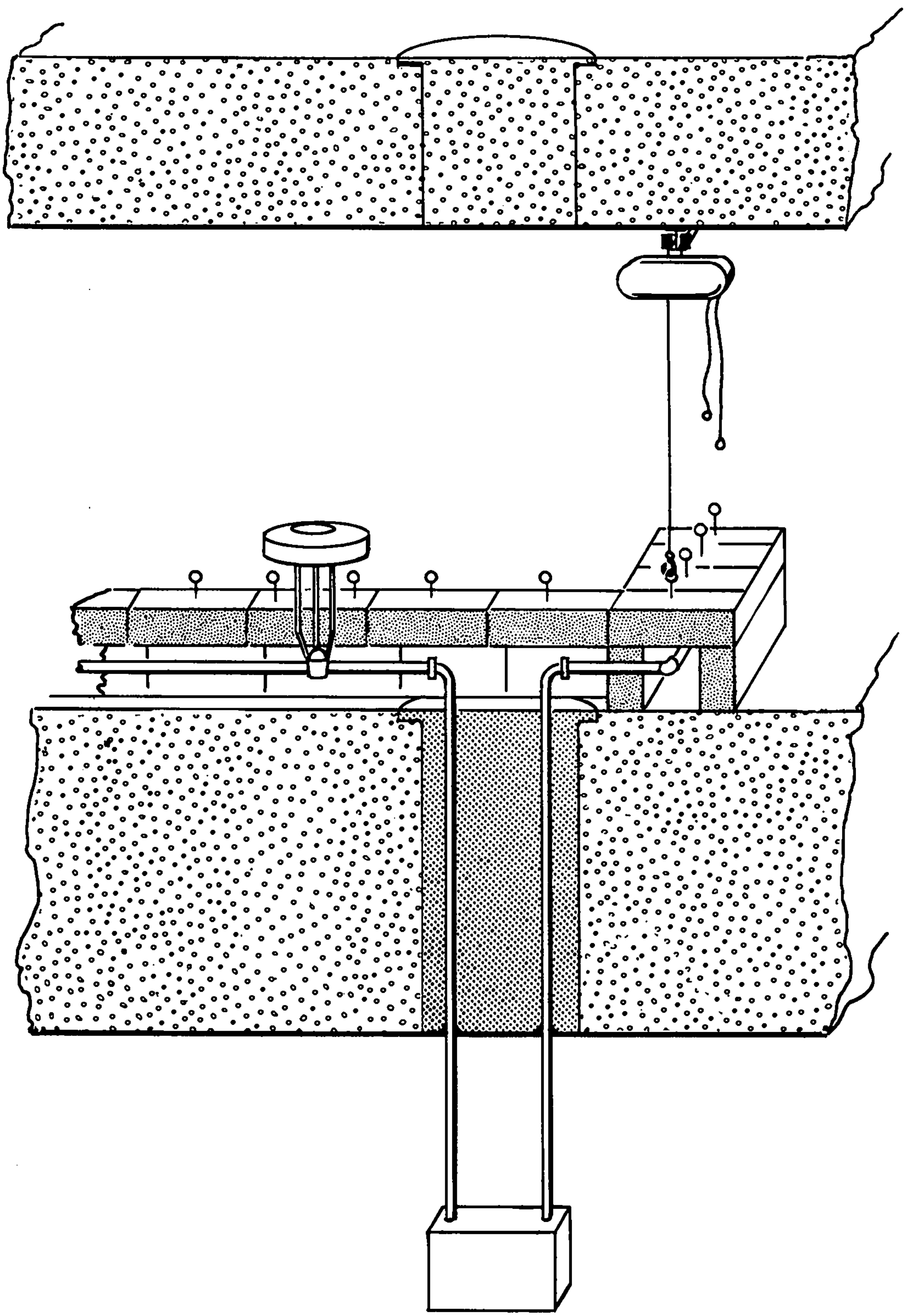

Fig. 10 Schematic View of Piping Deck

monorail hoist system is installed on the ceiling of the deck to assist in moving these shield slabs. Pipe lines of major hazard are built with secondary containment. Above the low ceiling of the pipe deck is the main operating floor of the building. This floor slab is much thinner than the main shielding floor below it, and serves primarily to contain and shield any radioactive materials which might escape from one of the pipe lines, cells, or from the reactor compartment.

5.8.2 Process Cells

As shown in Fig. 8, the process equipment is housed in five of the eight compartments surrounding the reactor. Each compartment is four stories high, and can be arranged to have manipulator operation at any or all of the four levels. Where different operations are carried on at different levels, these can be isolated by horizontal partitions as needed. As laid out in the design, the process equipment can be installed in complete duplicate in the space provided. For certain components which are easily replaced, this duplication would not be necessary, but the extra cell space was provided as an allowance for the unproved nature of the postulated processes.

The first cell contains the fuel storage tanks, into which the cores can be emptied when necessary. The tanks are geometrically safe for the fuel concentration used in the reactor, but not for much greater concentrations. Each tank is double shelled in case of leakage, and is jacketed with sodium to act as a heat transfer medium for decay heat and external electric heating. Other tanks contain the core sodium.

A tank capable of storing the paste from any one of the inner blanket systems is also in this cell. The upper cell level contains the locks and transfer devices needed to add or remove fuel and sodium from the core system and paste from the blanket system.

The second cell receives core sodium and paste from the first, and contains a small continuous still for core sodium and a batch retort for paste. (See process description in Chapter 6.) The solid retort residue is conveyed in closed containers using an automatic dumb waiter system to the next cell. This cell contains the dissolvers and crystallizers used to separate the solid feed material into purified uranium nitrate solution, crude plutonium nitrate solution, and a fission product waste stream.

The fourth process cell has two compartments, one of which purifies the crude plutonium and prepares it for sale or fuel makeup, and the other converts purified uranium nitrate into UO_2 suitable for reuse as paste.

The fifth process cell contains delay beds and gas traps used to remove gaseous fission products from the helium used in the surge volume of the core capsules. The system uses well-known methods to isolate and package the gases for transport to permanent disposal. No fission product gases are voluntarily released to the atmosphere at the plant site.

5.8.3 Service Cells

The remaining cells are concerned with service operations for the process and reactor components. One bank is devoted to the analytical control of the process operations, while another is used to prepare high level waste streams for transport offsite for fission products recovery or final storage. This cell is also equipped to remove sodium and fuel residues from a complete core capsule which is in need of repair or disposal. The last cell receives core capsules from the reactor or the decontamination cell for storage or repair. It is equipped with heavy manipulators such as the General Mills in addition to the Model A type. Disassembly and reassembly of a capsule into major components such as pump, heat exchanger, and core can be accomplished here, as well as minor repair or replacement of any component, such as a jet nozzle,

5.9 Secondary Sodium System

There are three separate secondary sodium systems serving the three steam-generators and superheater units. Each secondary sodium system is associated with one of the core inserts, removing both core and inner blanket heat. Each system consists of a sump type pump with an overflow to a surge-dump tank and pumped return through a hot trap purification stage to the main system. Each system has a capacity of 3,500 gallons. A cold trap, plugging indicator, and circulating pump are provided for each dump tank, which is also used as a loading tank.

5.10 Power Conversion System

Although the primary sodium system temperature entering the intermediate exchanger is 1125°F, the turbine throttle temperature is only 975°F. A perusal of current power plant practise showed that the higher temperature steam systems were not justified even for coal-burning plants in some areas; for a low fuel cost plant such as DCR perhaps even a lower steam temperature would be optimum. As mentioned in Chapter 3, it is believed that a thorough study of the problem of plant optimization for low cost fuel would result in quite a different steam system of considerably lower cost. The system given here, however, has had no such benefit, but is essentially similar to that used in the SFR, with small adjustments required by the higher sodium temperature available in the DCR.

The steam generator is of the once through type similar to that used on the Enrico Fermi plant. An improved design of this type generator has been in steady operation at Los Alamos for over a year, with an excellent performance record.

No detailed description is given of the generator, turbine, or other conventional portions of the plant. The characteristics of the power conversion system are summarized in Table 5.1.

5.11 Heating, Ventilation, and Auxiliary Cooling

5.11.1 Reactor Cell Cooling

Most of the heat generated in the reactor shielding is deposited in the steel and graphite adjacent to the reactor vessel. This heat is conducted into the vessel and absorbed by the outer blanket sodium. Outside the steel shielding is a layer of thermal insulation, covered with steel plates. These plates are cooled by ten small sodium or NaK loops to produce a cell ambient temperature of less than 350°C. The loops overlap so that failure of any one loop will not

TABLE 5.1

POWER CONVERSION SYSTEM DATA

Reactor thermal output	Mwth	800	
Thermal output--each core capsule	Mwth	227	
Thermal output--inner blankets	Mwth	120	
Electrical generation, gross	Mwe	320	
Auxiliary power requirements	Mwe	20	
Electrical generation, net	Mwe	300	
Primary coolant system			
Temperature--@ 1 HX outlet	°F	797	(425°C)
Temperature--@ 1 HX inlet	°F	1125	(663°C)
Flow rate	lb/hr	27.25×10^6	
Flow rate	gpm	66,500	
Secondary coolant system			
Temperature--@ 1 HX outlet	°F	1022	(550°C)
Temperature--@ steam generator outlet	°F	752	(400°C)
Flow rate	lb/hr	34×10^6	
Flow rate	gpm	79,700	
Steam-turbine characteristics			
Final feedwater temperature (5 stages)	°F	450	(232°C)
Steam temperature @ throttle	°F	975	(524°C)
Steam pressure @ throttle	psig	1450	
Exhaust pressure (5 stages)	Hg, abs.	1.5	
Steam flow rate	lb/hr	18.1×10^6	
Turbine cycle heat rate	Btu/kwhr	8525	
Net plant efficiency	%	40	

seriously impair the cell cooling. Above the reactor cell, the loops are manifolded in the piping deck to a common sodium pump and cooler. The system capacity is 500 kw.

A nitrogen atmosphere supply and circulation system is provided for the reactor cell. The principal purpose of the system is the detection of fission gas or sodium leaks within the cell and to prevent oxidation of graphite. A blower with an approximate capacity of 10 cfm and a radioactive gas detector are located in the circulating stream outside of the cell. The cell can be isolated in case of gas leakage by means of quick-acting valves.

5.11.2 Secondary Sodium Cells, and Steam Generator Cells

The ventilation systems for compartments holding the secondary sodium pumps and steam generators and the rupture disc steam blowdown system are considered part of the steam plant. These cells are isolated by firewall partitions and are individually cooled by recirculating the inert nitrogen atmosphere, each cell requiring approximately 100 kilowatts of cooling. The recirculating nitrogen is cooled by river water in heat exchangers.

5.11.3 Sodium Process Cells

The sodium process cells are provided with water-cooled wall panels with a total capacity of about 200 kilowatts of heat. Water tubing is brazed to the outside of the wall panel so that leakage could not enter the cell proper.

In addition each cell will be provided with a circulating nitrogen supply of about 100 cfm capacity, but with no heat removal capacity. The recirculating nitrogen passes through vapor traps and then is filtered with CWS-type filters. Duct work and blowers are of tight construction.

5.11.4 Aqueous Process Cells and Core Capsule Storage Cell

Process heat from the crystallization cells and storage cells is removed by direct water cooling. The cells are ventilated with air or nitrogen recirculating at about 100 cfm. A standard air washer is provided to scrub circulating air, followed by a dry fiber glass filter and a CWS-type filter. All duct work is made of stainless steel with gas tight construction.

5.12 Containment

The construction of the reactor and its enclosure provide a unique multi-layer containment system. The three cores are each contained in a tantalum vessel surrounded by the stainless steel outer capsule. The secondary sodium system and its extensions completely enclose the core capsules at all points, so that any leakage is contained. Within the reactor cell additional enclosure is provided by the inner and outer blanket systems, followed by the main double-walled reactor vessel and the cell liner.

The secondary sodium system is enclosed completely within the piping deck and steam generator cells, so that no communication with the environment exists. The main building above the floor level is of ordinary construction and is not gas tight. The inherent safety of the fluid reactor cores is such that no blast protection is necessary, although the vessels are built so that any such occurrence would lead to failure downward through the bottom of the main vessel.

The hazard of sodium leakage is controlled by compartmentalizing the system and by providing nitrogen atmosphere. The once-through type steam generators have the advantage of containing only a few pounds of water at a time, and they can be quickly isolated. Since the steam pressure is nearly always higher than the sodium pressure, any leakage may be expected to be in the direction of the sodium system, which gives by far the mildest reaction. Appearance of steam pressure in the secondary sodium system would actuate large rupture discs leading to blow-down tanks, which would permit the steam and sodium to be vented safely while the generator was being automatically isolated.

5.13 Low Level Waste Treatment Building

The low level waste system is housed in a separate building adjacent to a tank farm for storing neutralized waste. The tanks have a capacity of 100,000 gallons total. Inside the building are tanks for receiving and batching low level waste, neutralizing tanks and dosers, a continuous feed concentrator or evaporator, ion exchange bed system, effluent receiving tanks, and effluent monitors, together with pumps and necessary piping. The equipment provides the capability of concentrating the waste water to a high degree and of treating and testing the condensate before discharge. The concentrated waste is then stored for long periods in the tank farm.

6. OPERATION AND FUEL CYCLE

The general operating characteristics of the direct contact core have been discussed in Chapter 4. This chapter describes the operating behavior of the DCR plant as a whole and of the fuel processing cycle in particular.

The guiding feature in the design of this plant has been the desirability of continuous operation. The economic characteristics discussed in Chapter 3 show strong incentive for maximum load factor, since this gives the lowest overall cost. It is expected that the plant would remain on the line more than 95 percent of the time, and that the number of shutdowns for essential maintenance would be as few as possible. For this reason a somewhat greater than normal allowance for duplicate equipment at key points is justified, and relatively less attention need be paid to simplification of the shutdown procedure.

6.1 Core Startup

The description following refers to a routine startup, not the initial operation. Startup would be initiated by electrically warming the primary and secondary sodium systems to 150°C, charging them with sodium, and raising the temperature of all systems to about 450°C. The reactor cores would at this time contain no fuel, being filled with primary sodium. Fuel, which is stored in the molten condition in the fuel storage cell, would then be added to one of the cores by means of a small sodium jet pump, the heavy fuel displacing the sodium in the core. The full capacity of the pump is small enough to give a safe approach to criticality, so several hours are required for the transfer. When about two-thirds of the fuel for the first core is transferred, the core proper is nearly full and criticality is reached. An interlock prevents fuel transfer to a core unless the primary sodium pump for that core is off, so that no heat demand will be placed on a core which is not completely full. After criticality is reached, further fuel addition serves to increase the temperature of the core, so that when all the fuel is in, the core is at the hot shutdown temperature of about 525°C. Some heat is transferred by natural convection to the primary sodium and to the inner blanket as soon as the core temperature exceeds the system temperature; by the time fuel addition is completed the core is producing possibly 50 kilowatts. The slow initiation of primary sodium flow produces first temperature equalization between fuel and primary sodium and finally forced fuel circulation. As soon as full fuel circulation is obtained at heat-leak power the inner blanket pump may be started. Then the steam generator associated with that core may be placed in operation, the turbine started, and about 1/4 full plant load carried.

Meanwhile, as soon as the first core is critical, fuel addition to the second and third cores may be started. The very strong source provided by neutron leakage from the first core makes these startups quite safe. When these cores are filled, they are circulated and placed under load similarly to the first.

6.2 Core Shutdown

The removal of load from a core is accomplished by reducing the heat demand at the steam generator or turbine. The core in this condition is operating at heat-leak power with full fuel circulation, and can accept heat demand suddenly. A more complete shutdown consists of interrupting the primary sodium flow, which stops the fuel circulation except for natural convection. The core remains critical and will not freeze, so it may be left indefinitely. If all three cores are left in this condition the heat leak will be sufficient to keep the blanket well above the freezing point of sodium, so that electric heating is required only for the secondary sodium system. If the secondary sodium is drained, no electric power is needed in the plant except for instruments. After a rapid shutdown, the fission-product afterheat may exceed the thermal losses of the reactor system for a time. In this case, one or more of the secondary sodium systems would be left charged, and with natural sodium convection a small amount of feed water evaporated using a pump driven by auxiliary power.

If a complete core shutdown is required, as for maintenance or replacement of a core capsule, the fuel is transferred by jet pump to the fuel storage tank, where it is kept molten electrically, or cooled by sodium if the decay heat level is high.

6.3 Core Operation and Control

As mentioned above, the core power level is determined by the heat demand of the turbine via the secondary sodium system. In operation no regulation of the power level is required, but power in each core system is continuously monitored by means of flow and temperature-rise instruments in the primary core sodium as well as by conventional neutron instruments. In long term operation the principal attention needed by the core is the regulation of the plutonium concentration. Burnup of plutonium is accompanied by a decrease in the average core temperature. If no plutonium were added, the temperature loss at full power would be approximately 15°C per day. The addition of makeup could be done on a daily or weekly basis.

A fuel makeup operation would involve mixing PuO_2 powder from the reprocessing cell with excess cerium-cobalt metal powder and heating in a fused salt bath. After reaction and solidification, the metal slug of Pu-Ce-Co alloy would be transported to the fuel storage cell, and added through a gas lock to the fuel storage tank. A small amount of reactor fuel could then be pumped from the reactor to mix with the new fuel, and the mixture returned to the core. A filter in the return line would remove any undissolved impurities, such as CeO_2.

6.4 Blanket System Startup, Shutdown, and Operation

The initial loading of the blanket system would be accomplished by heating the system electrically, charging with sodium only, and circulating through a cold trap on the charging system until the system was purified. Then degassed

UO_2 would be added through a gas lock on the paste storage tank, and circulated into the main system.

Once charged, only the most drastic modification or failure of the blanket system would require its complete drainage, for which special tanks would have to be brought in. The plant is equipped to store paste from only one at a time of the three inner blanket systems. In a normal shutdown no paste at all would be removed from the reactor, and the main vessel would be maintained at about 150°C by heat leak from the cores, or by electric heat if all the cores were to be drained.

Operation of the blanket system consists of maintaining circulation of paste in the main tank and in each inner system that is operating, control of the blanket temperature by adjustment of secondary coolant bypass flow, and withdrawal and replacement of paste from the various systems as required by the processing system.

6.5 Operation of Fuel Cycle

The flow of materials in the fuel cycle of the DCR is outlined in Fig. 11. The system is depicted after the blanket has reached equilibrium, which would occur in about 3 years. The scheme of operation is to withdraw each day from the inner blanket a quantity of paste which will contain the same amount of plutonium as was produced in the entire blanket during the previous day. This paste is mixed with a quantity of core sodium which will contain one day's production of core fission products, and the mixture is processed for separation of sodium, UO_2, PuO_2, and fission products. The UO_2 and sodium are returned as paste to the outer blanket, and an equivalent amount of paste moved from outer to inner blanket. The PuO_2 needed for core makeup is converted to fuel alloy and added to the core, the excess being sold. In the flow sheet the inner blanket is assumed to be operated at a level of 0.5% Pu/U; the optimum level would be determined by the cost of processing chemicals and by the price of plutonium.

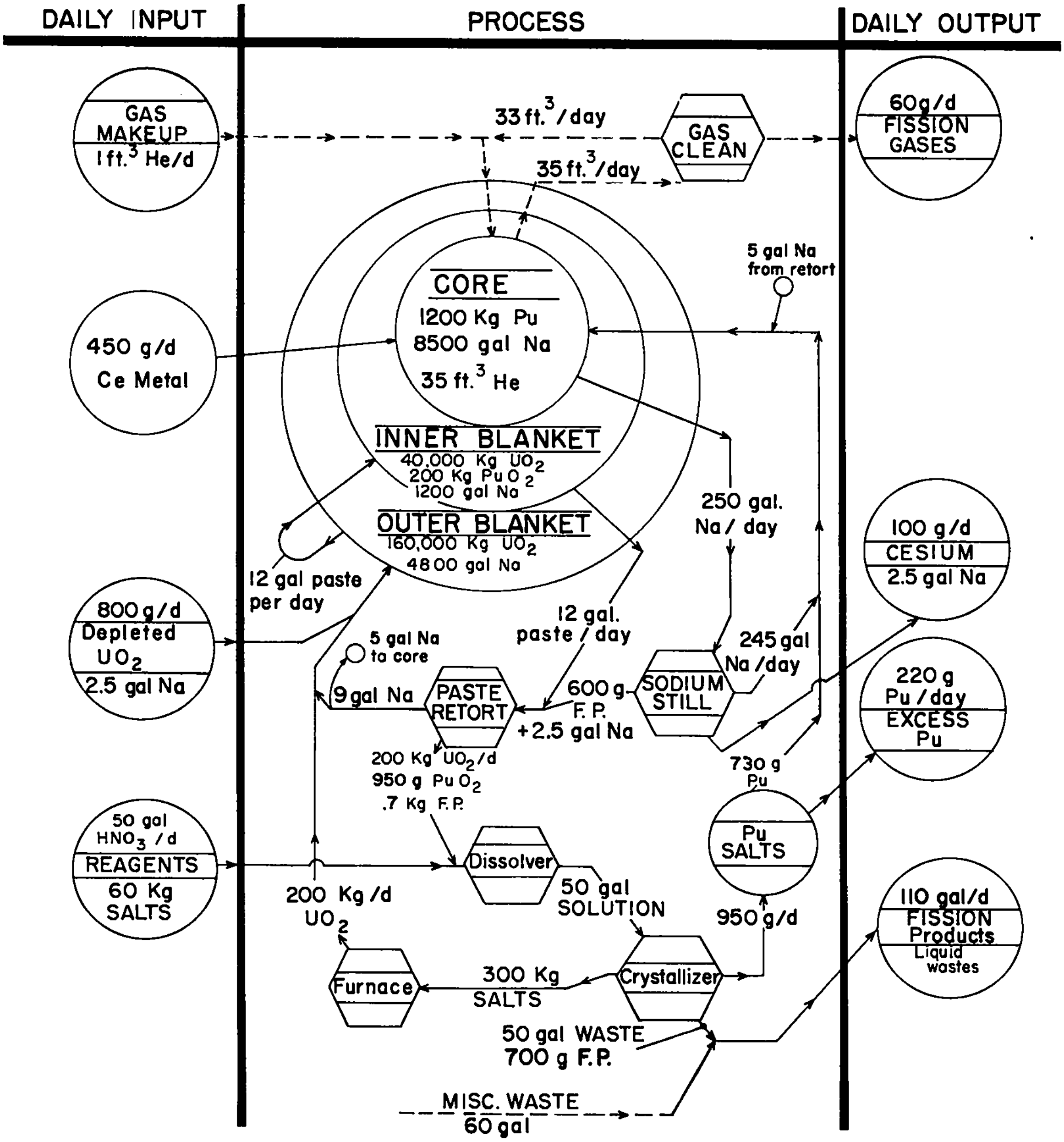

Fig. 11 Flowsheet for 300 Mwe Plant

6.5.1 Purification of Sodium

As mentioned above the plant includes means for purification of the core sodium, so that extracted fission products do not accumulate inside the reactor system. This is accomplished by means of a small continuous fractionating tower with a sodium throughput of about 10 gallons per hour. A small overhead fraction from this tower contains nearly all the cesium, and is packaged for disposal. A similar small bottom cut contains non-volatile fission products and is added to the daily batch of paste for processing. The main portion is discharged from the center of the tower and returned to the core.

At the processing rate assumed above, about 12 gallons of paste constitutes the daily batch drawn from the inner blankets. This is mixed with the bottom fraction of core sodium (2.5 gallons) and charged to a batch type retort. Slow heating drives off the sodium, which is condensed and returned to the blanket and core. The residue consists of about 200 kg of UO_2, PuO_2, and fission products.

6.5.2 Separation of UO_2, PuO_2, and Fission Products

The method of separation described herein utilizes a fractional crystallization scheme based on experiments recently done at the Los Alamos Scientific Laboratory by one of the authors. The advantages of the method are that it works with concentrated solutions so that only very small equipment and space is required, and that any desired degree of purification can be obtained by continuing the fractionation without further expenditure for chemicals or materials.

The daily batch of mixed oxides is dissolved in concentrated nitric acid, forming about 50 gallons of solution. The dissolved salts are fed to a small continuous crystallizer adjusted to yield half the uranium in the crystal fraction and the other half in the mother liquor. From this point in the process all the equipment is sized to be critically safe even if filled with pure plutonium solution. The crystals and mother liquors from the first crystallizer are sent to other crystallizers and refractionated according to a set scheme yielding the desired purity. The scheme shown in the diagram below is illustrative, but the type of equipment, the method of operation, the salt chosen, and the process economics would all affect the optimization of the crystallization scheme.

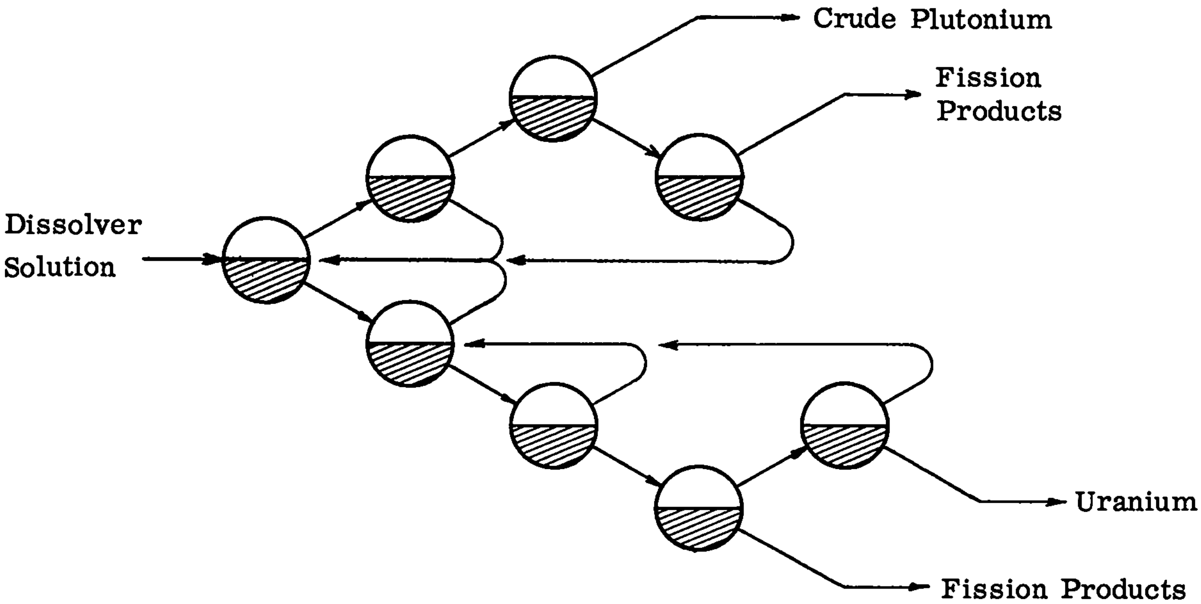

Fig. 12 Crystallization Scheme

The equipment for each crystallizing stage consists of a reservoir tank and feeder, temperature controller, a trough type crystallizer, and a rotating disc or other type of continuous filter. The components of each stage can be built into a compact unit which is replaceable in a "plug-in" fashion. The capacity is small per stage, being on the order of 5-100 cc of feed per minute. In the example shown above eight stages are required.

6.5.3 Treatment of Separated Materials

For the separation of most of the uranium in a form sufficiently freed from plutonium and fission products for return to the outer blanket, crystallization of the simple nitrates is probably sufficient. It would be difficult to justify more than about a 90% separation of these materials, since the cycle is closed and repetitive.

The uranium is prepared for return to the blanket by heating the nitrate crystals in a retort, condensing the nitric acid fumes for reuse, and milling and firing the resulting UO_3 in hydrogen to form UO_2. Work at the Los Alamos Scientific Laboratory[7] has shown that with proper controls and recycling these steps can produce a uniform particle size, dense UO_2 in 100% yield.

For final purification of the plutonium further crystallization of the same salt may be done, but the process is easier to control if a less soluble double salt such as $UO_2 \cdot (NH_4)_2 \cdot (NO_3)_6$ is formed. In this salt (and others) the plutonium is isomorphous with the uranium, allowing very complete separations to be obtained if desired. The uranium and fission product fractions obtained in plutonium purification are returned to the main system, and the pure product evaporated to form plutonium nitrate for shipment. The portion to be used for core make-up is ignited to PuO_2 and reduced to metal slugs with cerium and cobalt as mentioned above.

The fission product streams from the fractionation are combined and concentrated for disposal as high-level waste. This operation is conducted in a separate cell, which is equipped with remotely operated batch retorts having removable liners which can be sealed and packaged for transport in shielded casks.

ACKNOWLEDGEMENTS

As mentioned above, the assistance of the Detroit Edison Company, and its affiliates, contributed materially to the precision of the construction cost estimates. Many members of the staff of the Los Alamos Scientific Laboratory contributed to the Direct Contact Reactor concept described here. Of particular importance was the work of George L. Ragan, who performed the nuclear calculations, and of Harold E. Busey, who assisted with the editorial work.

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Appendix A

DETAILS OF COST ESTIMATE FOR DCR

ACCOUNT NO.	ITEM	AMOUNT (Dollars in Thousands)	REMARKS
21	STRUCTURES AND IMPROVEMENTS		
211	Ground Improvements		
.1	Access Roads	0	Per ground rules
.2	General Yard Improvements		
.21	Fill, grading, landscaping	200	
.211	Shore protection around canals	30	
.22	Roads, walks, parking	40	
.23	Fences and gates	25	
.24	Yard piping system	90	
.25	Storm and sanitary sewers	40	
.251	Sewage disposal facilities	40	
.26	Yard lighting	35	
.3	Railroad Spur	300	
	TOTAL, Item 211	800	
212	Buildings		
A	Turbine Bay		
.1-3	Substructure	360	
.4	Superstructure	670	
.6	Services	170	
	TOTAL, Item 212A	1,200	
B	Office and Service Buildings (130,000 cu. ft. of feed water bay plus attached structure)		
.1-3	Substructure	60	
.4	Superstructure	115	
.6	Services	60	
.7	Space heating equipment	115	
	TOTAL, Item 212B	350	Handbook figure (225.2) 130. Additional space for reprocessing staff, etc.

21 212	C	Fuel Receiving, Storage, Decay, Etc.	None	Included in Account 224
	D	Radioactive Waste Disposal Facility		
		Substructure	10	
		Superstructure	45	
		Services	5	
		TOTAL, Item 212D	60	See also Account 225.1
	E	Steam Generator and F.W. Bays		
	.1-3	Substructure	250	
	.4	Superstructure	465	
	.6	Services	150	
		TOTAL, Item 212E	865	
	F	Control Room Bay		
	.1-3	Substructure	20	
	.4	Superstructure	50	
	.6	Services	40	
		TOTAL, Item 212F	110	
	G	Health Physics Facilities		Located below control room
	.1-3	Substructure	None	Included in 212F
	.4	Superstructure	15	
	.6	Services	10	
		TOTAL, Item 212G	25	
	H	Miscellaneous Buildings		
		Screen house	40	
		Gate house	5	
		TOTAL, Item 212H	45	
		TOTAL, Item 212	2,655	
218		Stack	20	
219		Reactor Bay		Building only. This bay houses reactor(s), process equipment for fuel, blanket, sodium, gas and high level wastes. Also control laboratories, hot maintenance and shipping facilities.
	.1-3	Substructure	400	
	.4	Superstructure	490	
	.6	Services	190	
		TOTAL, Item 219	1,080	
		TOTAL, Account 21, STRUCTURES AND IMPROVEMENTS	4,555	

22		REACTOR PLANT EQUIPMENT		
221		Reactor Equipment		
	.1	Reactor Vessels and Support Structures		
	.11	Circular support girder	250	
	.12	Reactor tank	80	
	.121	Inner sleeves (2)	150	
	.122	Blanket tanks (2)	130	
		TOTAL, Item 221.1	610	
	.2	Reactor Controls--3 Systems		
	.21	Control rods	60	Emergency device only
	.22	Control rod guide tubes	30	
	.23	Control rod drives	150	
		TOTAL, Item 221.2	240	
	.3	Reactor Shielding		
	.31	Neutron shield--graphite	150	
	.32	Biological shield		
		Cell liner	50	
		Cell structures, including foundations	750	
		Operating floor	150	
		Access plugs	20	
		Plugs (4)--core and blanket inserts	600	
		Pipe gallery	60	
		Removable shielding	40	
	.33	Thermal insulation	50	
	.34	Cell cooling system	20	
		TOTAL, Item 221.3	1,890	
	.4	Auxiliary Heating and Cooling Systems		
	.45	Induction and/or Resistance Heating		
	.451	Reactor cell, incl. blankets	50	Steam dump incl. in Accounts 223 and 228
	.452	Primary sodium systems	30	Decay heat incl. in Accounts 212E and 227
	.453	Secondary sodium systems	50	
	.454	Cover gas lines	15	
		TOTAL, Item 221.4	145	

22 221	.7	Cranes and Hoists		
	.71	Plant crane	180	Prorated
	.72	Pipe gallery hoist	5	
		TOTAL, Item 221.7	185	
		TOTAL, Item 221	3,070	
222		Heat Transfer Systems		
	.1	Primary Coolant System		
	.11	Core pumps (3) incl. drives and rheostats	1,045	
	.111	Blanket pumps, complete (4)	400	
	.12	Core thimbles (3)	300	
	.121	Blanket systems	160	
		TOTAL, Item 222.1	1,905	
	.2	Secondary Coolant Systems		
	.21	Pumps (3)	750	
	.22	Piping, incl. insulation	600	
	.221	Traps, surge tanks, etc.	150	
	.23	Core heat exchangers (3)	3,700	
	.231	Blanket heat exchangers (4)	380	
	.251	Thermal insulation (ex reactor)	75	
	.252	Shielding (not incl. S. G. bays)	50	
		TOTAL, Item 222.2	5,705	
	.3	Steam Generators		
	.31	Steam generator units	1,850	
	.311	Thermal insulation and heaters	100	
	.312	Shielding	200	
		TOTAL, Item 222.3	2,150	
	.4	Coolant Receiving--Supply and Treatment		
	.42	Sodium purification, secondary system	100	Primary sodium purified by contact with fuel
	.421	Interconnecting piping w/primary sys.	25	
	.44	Sodium receiving, storage and makeup		
	.441	Tank car unloading station	35	
	.442	Storage tanks, fill piping, insulation	35	
	.45	Inert gas systems		Secondary system only. Primary system covered in Account 225
		Cleanup equipment, incl. vapor trap	50	
		Piping, incl. bottle station	65	

22 222	.45	Pressure regulating equip.,incl. valves	20	
		Insulation, painting, etc.	10	
		TOTAL, Item 222.4	340	
	.6	Coolant--Initial Charge		
		Sodium	150	
		Inert gas	20	
		TOTAL, Item 222.6	170	
		TOTAL, Item 222	10,270	
223	.4	Shipping Casks--Pu Product	15	
224		Processing Equipment, Core and Blanket		
	A	Cell Structure		
		Concrete, incl. liners	250	
		Plugs	25	
		TOTAL, Item 224A	275	
	B	Basic Cell Equipment		
		Windows	480	
		Manipulators, hoists, etc.	440	
		Ventilation and cooling equip., total	100	Primarily in maint. and sodium proc. cells
		Lighting	25	
		TOTAL, Item 224B	1,045	
	C	Core Operating Cell		
		Fuel makeup	25	
		Core sodium makeup	55	
		Core sodium still	40	
		TOTAL, Item 224C	120	
	D	Paste Blanket Operating Cell		
		Paste blowdown and storage	20	
		Makeup and recharge	30	
		Sodium still	20	
		TOTAL, Item 224D	70	
	E	Dissolver and Crystallizer Cell	50	
	F	Oxide Conversion Cell	25	
	G	Pu Preparation Cell	5	
	H	Analytical Cell	20	
		TOTAL, Item 224	1,610	

22 225	Active Wastes--Treatment and Disposal		
.1	Liquid Wastes		Low level waste facilities shown in Account 212D
	Cell structure	50	
	Equipment	275	Incl. $75,000 low level waste disp. equip.
	TOTAL, Item 225.1	325	
.2	Gaseous Wastes		
	Cell structure	50	
	Equipment--5 systems	250	
	TOTAL, Item 225.2	300	
.3	Solid Wastes	---	Incl. in 225.1
.4	Shipping		
	Packaging facility		
	Structure	200	
	Equipment	50	
	Decay storage and shipping containers	150	
	TOTAL, Item 225.4	400	
.5	Decay Storage Facility	500	
	TOTAL, Item 225	1,525	
226	Instrumentation and Control		
.1	Reactor and Processing Cells	790	
.2	Heat Transfer Systems	200	
.4	Waste Systems	200	
.5	Radiation Monitoring	150	
.6	Steam Generator	100	
.7	Piping and Wiring	200	
	TOTAL, Item 226	1,640	
227	Feed Water Supply and Treatment		
.1	Raw Water Supply--Pumps and Drives	55	General service water supply
.2	Elevated Storage Tank	55	
.3	Feed Water Purification	215	
	Condensate storage	50	
	Cooling loop and drain cooler	45	
	Other chemical feed equipment	10	

22 227	.4	Feed Water and Deaerating Heaters	290	
	.5	Feed Pumps and Drives	240	
		TOTAL, Item 227	960	
228		Steam, Condensate and F.W. Piping		
	.1	Main Steam	1,600	
	.3	Condensate	125	
	.4	Feed Water	200	
	.5	Drips, Drains and Vents	25	
		TOTAL, Item 228	1,950	
229		Other Reactor Plant Equipment		
	.1	Decontamination Facilities	50	
	.2	Reactor Plant Maint. Equipment		
		Equipment decay tanks	150	Incl. installation, not in repair cell
		Transfer containers	150	Flexible bags w/valves and adapters
		Remote seal cutter and welder	30	
		Portable shields, checking equip., etc.	50	
		Vacuum distillation unit	20	For sodium removal
		Manipulator and special tools	100	
		Cell structure	200	
	.3	Yard Crane	50	
		Fork lift truck	10	
		TOTAL, Item 229	810	
		TOTAL, Account 22, REACTOR PLANT EQUIPMENT	21,850	
23		TURBINE GENERATOR UNITS		
231		Turbine-Generators		
	.1	Foundation	160	
	.2	Turbine-Generator	7,950	
		TOTAL, Item 231	8,110	
232		Circulating Water Systems		
	.1	Pumping and Regulating Equipment		
	.11	Pumps, drives, controls	220	
	.12	Travelling screens, etc.	80	

23 232	.2	Circulating Water Lines	
	.21-2	Supply and discharge piping	130
	.3	Intake and Discharge Structures	
		Screen wells, pump wells, slab	250
		Intake tunnel	50
		Recirculating tunnel	35
		Dredging-intake channel	100
		Intake canal protection	75
	.4	Water Treatment System	
		Chlorination equipment	35
		TOTAL, Item 232	975
233		Condensers	
	.1	Condenser	1,000
	.2	Condensate pumps	80
	.3	Vacuum pumps	45
		TOTAL, Item 233	1,125
235		Turbine Plant Boards, Insts. and Controls	
	.1	Control equipment and boards)	
	.2	Instruments)	200
	.3	Tubing and wiring	90
		TOTAL, Item 235	290
		TOTAL, Account 23, TURBINE GENERATOR UNITS	10,500
24		ACCESSORY ELECTRIC EQUIPMENT	
	A	Reactor Plant--Aux, Power Equip.	
		Transformers	75
		Switchgear	175
		Switchboards and panels	80
		Starters, control centers, etc.	120
		Power and control cables	200
		Conduits and cable trays	180
		Grounding	30
		Emergency power supply	65
		Subtotal, Reactor Plant	925

Items 236, 237 and 238 covered elsewhere

24	B	Turbine Plant--Acc. Elec. Equip.		
		Generator leads	100	
		System service transformer	145	
		Aux. power transformers	110	
		High voltage switchgear	125	
		Low voltage unit substations	75	
		Switchboard panels and instruments	100	
		Starters, control centers, etc.	45	
		Battery and charging equip.	75	
		Power and control cable	240	
		Conduit, cable trays, etc.	180	
		Grounding system	25	
		Subtotal, Turbine Plant	1,220	
		TOTAL, Account 24, ACCESSORY ELECTRIC EQUIPMENT	2,145	
25		MISCELLANEOUS POWER PLANT EQUIP.		
251		Misc. Turbine Room Hoists	5	
252		Compressed Air System	40	
253	.1	Signal and Call System	80	
	.2	Diesel Driven Fire Pump	20	
		Portable sodium fire extinguishers	10	
	.3	Furniture and Office Equipment	40	
	.4	Lockers, Shelves and Cabinets	5	
	.5	Laundry and Station Maint.	25	
	.6	Machine Shop	50	
		Physics and chem. lab. equip.	50	In addition to Item 224H
	.7	Weather Tower	5	
	.8	Potable Water Supply System	125	
		Lunch room equipment	5	
		Transportation equipment	15	
		First aid equipment	5	
		TOTAL, Account 25, MISCELLANEOUS POWER PLANT EQUIPMENT	480	

	TOTALS	
21	STRUCTURES AND IMPROVEMENTS	4,555
22	REACTOR PLANT EQUIPMENT	21,850
23	TURBINE-GENERATOR	10,500
24	ACCESSORY ELECTRIC EQUIPMENT	2,145
25	MISCELLANEOUS POWER PLANT EQUIPMENT	480
	Total, Direct Construction Cost	39,530

APPENDIX B

ANNUAL FUEL CYCLE COSTS OF SFR

Basis

Fuel--$PuO_2 \cdot UO_2$, canned in S. S. tubes

Burnup--5% of contained U and Pu per cycle   Plant factor--80%

Throughput-- 4000 kg of oxide per year

Core	
Fabrication	
Shipping of nitrate--@ $5.50/kg	$ 22,000
Pin fabrication--@ $400/kg	1,600,000
Axial blanket procurement--100 kg @ $25	2,500
Pin inspection--17,000 pins @ $10	170,000
Shipment of pins to subassembly fabrication--@ $1.50/pin	25,500
Subassembly fabrication--175 @ $4000	700,000
Subassembly shipping--175 @ $400	70,000
Total fabrication	$2,590,000
Reprocessing	
Shipping charges--175 @ $1000	175,000
Reprocessing--40 days @ $16,400	656,000
Total reprocessing	831,000
TOTAL CORE COSTS	$3,421,000
Blanket	
Fabrication--100 subassemblies @ $2500	250,000
Inspection and shipping	103,000
Reprocessing--16 days @ $16,400	262,000
Total blanket	615,000
Gross Fuel Cycle Costs	$4,036,000