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January 1977

INTERMEDIATE SIZE LWR PLANT STUDY FOR PROCESS HEAT PLUS POWER
VOLUME 1: EXECUTIVE SUMMARY

MANUEL A. HEAD

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INTERMEDIATE SIZE LWR PLANT STUDY FOR PROCESS HEAT PLUS POWER

EXECUTIVE SUMMARY

Volume 1 of 3 Volumes

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

ABSTRACT

The appropriateness of intermediate sized LWRs is evaluated for application to the process industry and for cogeneration of electric power and process steam. This brief study is directed toward determination of whether such plants show enough promise to warrant more detailed investigation. In light of higher fossil fuel costs, the study shows that intermediate sized, standardized power plants potentially are economically competitive for such industrial applications. A representative intermediate sized operating plant of the BWR/4 design class, the Swiss Muhleberg unit (1000 MWt) has been examined with respect to design, licensability, capacity factor and cost. It has operated at high capacity factor (approximately 75%) since turnover 11/72. Its cost when escalated from 1969 to 1976 (620 $/kWe) appears competitive. Cost adjustments (100-250 $/kWe) included at this stage for compliance with current licensing and mandatory design requirements are only a preliminary estimate. Further study is recommended to confirm necessary regulatory upgrades for this BWR/4 nuclear plant and to explore specific cost economies through replication leading to a program for construction of a demonstration plant.

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1. INTRODUCTION

Standardized nuclear plants of intermediate size (300-600 MWe equivalent) may be an economic source for electric power and industrial process energy applications. The U.S. industrial process energy requirements are potentially a significant market for nuclear energy, especially in a dual process steam-plus-electric power application. In the past, the estimated high cost of smaller nuclear plants has discouraged serious consideration of these applications. However, new insights into capacity factor performance and plant costs over the range of plant sizes, plus the major increase in fossil fuel prices, have indicated that nuclear process heat generation using a replicated design of intermediate sized plants may now be competitive.

The study discussed in this report was performed for the United States Energy Research and Development Administration under subcontract to Oak Ridge National Laboratory and represents an early stage in the analysis by General Electric on the subject of unit size, costs and performance expectations for nuclear plants. Findings are thus preliminary in nature and would need to be refined in future work on this subject. It is, however, judged unlikely that the suggested "limited economic penalty for multiple standard 300-600 MWe units relative to the more recent 1000-1300 MWe LWR standard units" would be reversed in this refining process.

KKM (Muhleberg), a 306 MWe BWR with four years operation and 74 percent capacity factor, was selected as the reference plant for this study, and Humboldt Bay 3, a 63 MWe BWR with ten years operation and 69 percent capacity factor was given brief review as a possible alternate technology. On these plants, costs, core and fuel performance, sources of unavailability, current licensing and safety requirements, and intermediate heat exchanger requirements were investigated. In addition the study was directed at determining cost trends versus size, capacity factor performance versus size, natural circulation concept applicability, process heat cycles and requirements and potential for improved construction techniques (such as rigorous standardization and use of preassembled modules).

The cost of KKM was re-calculated from actual costs incurred. These costs were escalated to 1976, transferred from Swiss francs to dollars, corrected for lower USA labor productivity, and updated for licensing (roughly estimated at 100-250 $/kWe) requirements to yield a 1976 commercial operation cost of 620 $/kWe. This approach assumes a construction schedule similar to the KKM schedule of ~48 months. Fuel cycle costs for this reference plant were estimated to be 66 ¢/MBtu, and operating and maintenance costs to be 18 $/kWe-year. Total energy costs at 80 percent capacity factor* on these bases are estimated in 1976 dollars to be

Electrical	21.6 mills/kW hour
Process heat	204 ¢/MBtu

$$* \text{ Capacity Factor} = \frac{\text{Net Energy Generated}}{\text{Design Rating x Period}}$$

Cost economies through replication of a standard design and the use of modular construction have also been considered. Based on 10 or 20 units at different sites, and the use of one reactor supplier-architect engineer-constructor team, it should be feasible to greatly reduce the front end costs, and such indirect costs as engineering and construction management which otherwise represent an unacceptable economic burden for small or intermediate size nuclear plants. Preliminary economic evaluations for such replicated units (greater than four) show the costs to be

Electrical	19.5 mills/kW hour
Process heat	185 ¢/MBtu

With fossil fuel costs increasing, e.g., oil at 12 $/barrel represents ~200 ¢/MBtu without plant capital costs, these preliminary nuclear costs appear promising and worthy of further study.

2. LWR PERFORMANCE TRENDS

The historical capacity factors of operating plants illustrate that many of the smaller plants are performing better than large plants. As generating costs are strongly influenced by the capacity factor achieved, a sustained, improved performance for small units would markedly improve their economic competitiveness. Table 2-1 segregates operating plants into domestic and foreign, size, and capacity factor (January-December 1976) categories to show this performance. D.C. Cook 1, 1060 MWe, is the only large plant with a capacity factor greater than 75 percent.

This difference in performance with size has been studied to determine preliminary relationships between capacity factor and size. The data base consists of capacity factors from 31 BWRs and 39 PWRs with 285 unit years experience through 1975. Refer to Figure 2-1.

This scattered data appears to fall into five size groups, and when averaged and plotted versus size, the results are as shown in Figure 2-2 with a linear equation of CF versus MWe.

Maximum performance is shown by the 400 to 700 MWe size group. The performance of the 100 to 400 MWe is down, probably because they are the early generation plants--first of a kind, immature in design, and impacted by retrofitting for updated licensing. If these immature units are ignored, the slope of the capacity factor decline with size increases from 6.2 percent to as much as 30 percent per 1000 MWe.

An evaluation of the causes of plant outages or derate and their relation to size was undertaken for BWRs in order to estimate future performance. Tables 2-2 and 2-3 show the outage categories applicable to BWRs in 1974-1975, and projected for after 1985. From these projections the capacity factor performance is estimated to be

$$CF = 0.842 - 0.092 \left(\frac{R}{1000}\right)$$

A more direct evaluation of the performance of small and large plants was carried out by studying KKM at 306 MWe and a 1050 MWe BWR. KKM through 1975 had a 73.7 percent CF, and the 1050 MWe unit had a 58.5 percent CF. A breakdown of the reasons for this difference in capacity factor revealed three major categories of equal weight

1. Fundamental performance differences related to plant size given the same generic plant design.
2. Differences between the regulatory environments in which the two plants operated.
3. Differences in the effectiveness of the operation and maintenance.

TABLE 2-1

LWR CAPACITY FACTORS - 1976

CAPACITY FACTOR	PLANT SIZE (MWe)					
	< 400		400-1000		> 1000	
> 75%	Yankee Rowe	Garigliano Dodewaard Zorita Obrigheim Muhleberg Beznau 1 Beznau 2	Connecticut Yankee Maine Yankee Nine Mile Point 1 Calvert Cliffs 1 Robinson 2 Point Beach 1 Point Beach 2 Monticello	Doel 1 Genkai Borssele 1 Stade 1	Cook 1	
60-75%	Dresden 2	Tarapur 1 Tarapur 2 Trino Tsuruga Lingen	Dresden 3 Millstone 1 Millstone 2 Vermont Yankee Oyster Creek Three Mile Island 1 Surry 1 Hatch 1 Quad Cities 2 Kewaunee Prairie Island 1 San Onofre 1 Oconee 3 Turkey Point 3 Turkey Point 4	Wuergassen Doel 2 Oskarshamn 1 Barsebaeck 1 Garona Shimane Fukushima 2 Fukushima 3 Mihama 2	Peach Bottom 2 Peach Bottom 3	
< 60%	Big Rock Point Dresden 1 LaCrosse Humboldt Bay 3	Chooz Mihama 1 Gundremmingen	Pilgrim 1 Indian Point 2 Ginna Fitzpatrick Beaver Valley 1 Surry 2 Brunswick 2 Oconee 1 Oconee 2 St. Lucie 1 Palisades Quad Cities 1 Arnold Fort Calhoun 1 Cooper Arkansas 1 Rancho Seco Dresden 3 Prairie Island 2	Fukushima 1 Mihama 3 Takahama 1 Takahama 2 Oskarshamn 2 Ringhals 1 Ringhals 2 Brunsbuettel Neckar Tihange 1 Hamaoka 1	Indian Point 3 Zion 1 Zion 2 Browns Ferry 1 Browns Ferry 2 Browns Ferry 3 Trojan	Biblis A Biblis B

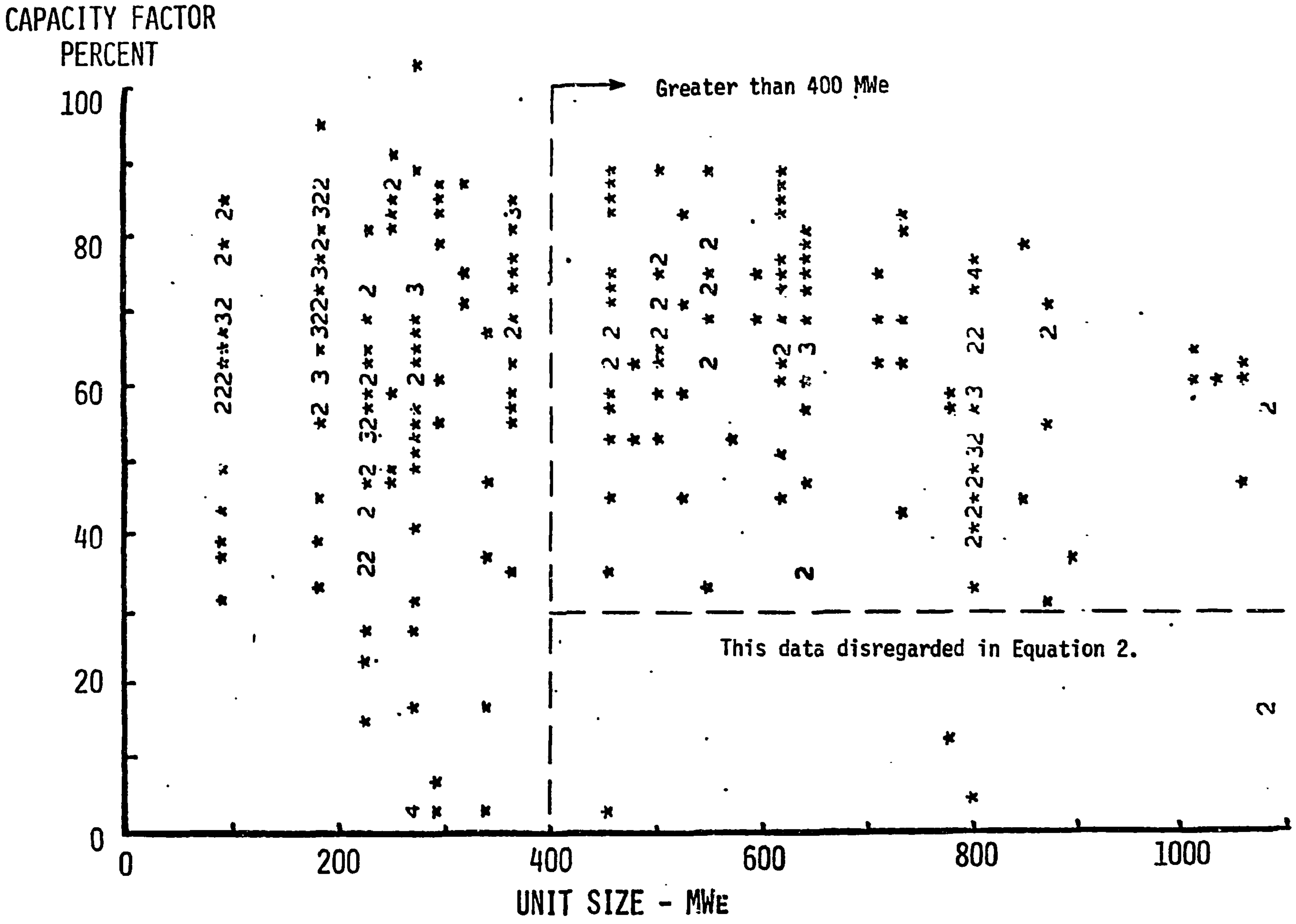


FIGURE 2-1. ANNUAL CAPACITY FACTOR - ALL PLANTS

NOTE: Each point represents a unit year of reactor operation, numerical values indicate coincident points.

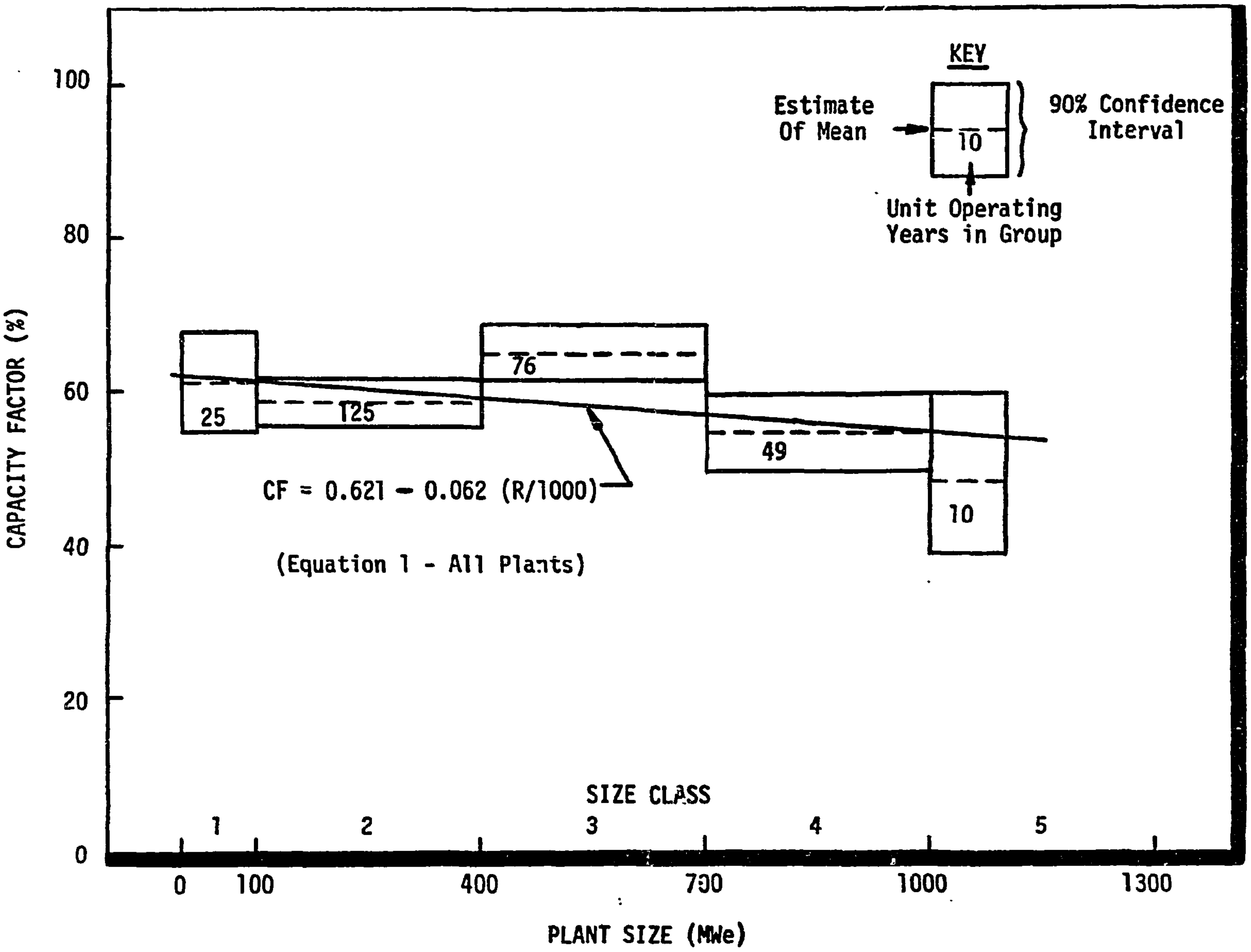


FIGURE 2-2. CAPACITY FACTOR CONFIDENCE INTERVAL - ALL PLANTS

TABLE 2-2

MAJOR CAUSES OF UNAVAILABILITY OF NSSS
(% REDUCTION OF CAPACITY FACTOR - CRITICAL PATH DOWNTIME)

	1974 - 1975		> 1985 PROJECTIONS	
	∿ SIZE*	NOT ∿ SIZE+	∿ SIZE	NOT ∿ SIZE
Fuel Sipping (leaks)	0.8	0	0	0
Inverted Control Blades	0.7	0.1	0	0
In-Core Vibration	0.15	0.4	0	0
Change Out LPRM	0.5	0.05	0.1	0
CRD Return Line Fix	0.7	0.1	0	0
Safety Relief Valve	1.0	0.3	0.8	0.2
MSIV Inst. & Vent Valve	0	0.7	0	1.0
FW Heater & Cond. Tubes	0.6	0.6	0.4	0.4
FW Pumps & Sparger	0	1.6	0	0.5
Recirc Seals, Valve Packing	0.7	0.7	0.5	0.5
Jet Pump Cracks	0	3.2	0	0
Core Spray Nozzles and Pipe Cracks	0	1.8	0	1.0
RHR Valve	0	1.4	0	0.3
Mark I	0	0.7	0	0.2
Refueling	3.0	0.3	3.0	0.3
Off Gas Explosion	0	0.3	0	0.6
Other	0.2	1.9	0	0.7
TOTAL	8.3	14.2	4.8	5.7

* Size dependent.
\+ Not size dependent.

TABLE 2-3
SUMMARY OF CONTRIBUTIONS TO LOSS OF CAPACITY FACTOR (%)

	1974 - 1975(1)			> 1985(2)		
	∿ SIZE*	NOT ∿ SIZE+	TOTAL	∿ SIZE	NOT ∿ SIZE	TOTAL
UNAVAILABILITY						
NSSS	8.3	14.2	22.5	4.8	5.7	10.5
BOP	1.5	1.5	3.0	1.7	1.7	3.4
Browns Ferry	0	6.6	6.6	0	0	0
Pilgrim Intervention	0	3.0	3.0	0	0	0
Other	0.25	0.25	0.5	0.45	0.45	0.9
DERATE						
PCIOMR (4)	0.2	3.3	3.5	0.05	0.95	1.0
Power Limit (Any NSSS Equipment)	0.5	5.0	5.5	0.2	1.8	2.0
Power Reduction (Utility Option)	0	1.5	1.5	0	0.5	0.5
UNACCOUNTED FOR				2.0	4.7	6.7 (3)
TOTAL	10.75	35.35	46.1	9.2	15.8	25.0
RESULTING C.F.			53.9			75.0

---

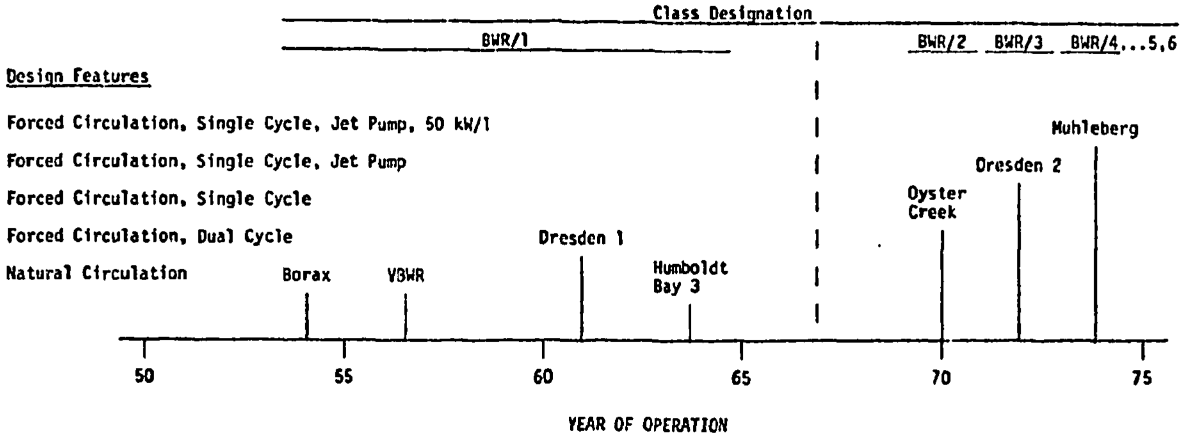
(1) Average Plant Size ∿800 MWe
(2) Average Plant Size ∿1000 MWe
(3) Plug number to give assumed 75% C.F.
(4) Preconditioning Interim Operating Management Recommendation

* Size dependent
\+ Not size dependent

Thus this preliminary investigation indicates the decline in capacity factor with nuclear unit size observed through '75, though clouded by innumerable "unique" events, may also be indicative of several underlying size dependent factors (Tables 2-2 and 2-3). The best estimate of a 9.2 percent decline per 1000 MWe using this data base suggests that whereas a 1300 MWe unit would produce 9.1 x 10^9 kWhrs/year at an 80 percent capacity factor, a 72 percent capacity factor and 8.2 x 10^9 kWhrs/year may be more likely. Using the same relationship, a 300 MWe unit would be expected to perform 9 percent better or a 600 MWe unit some 6 percent better, given the same design, unit maturity, and licensing environment. To a first approximation such differences in performance can be looked upon as direct offsets to percentage increases in unit costs of smaller sized nuclear units.

3. KKM - REFERENCE PLANT DESIGN

The development of the BWR from small, natural circulation reactors to the large, operating BWR/4s of today is shown by the following figure.



The plant names are typical plants constructed for each stage of BWR/1 through BWR/4 development. The various cycles used in this development are shown on Figure 3-1. They range from the small, direct and indirect, natural circulation units, through the dual cycle units, to the direct cycle, forced circulation, jet pump units.

KKM, the reference plant for this study, is a BWR/4 from this latter cycle. It represents the most recent BWR design to go into operation and provide feedback on performance and soundness of design. This model has been through a complete design, construction, and operating cycle. For application to future plants, features that work well would be maintained; those that do not work well would be replaced or improved.

The KKM plant has internal steam separation, jet pump recirculation, a core power density of 49 kW/l, and provides steam at 1000 psi to two, 160 MWe turbine generators. It is enclosed in a Mark 1 containment (drywell-torus), and a circular reactor building (reinforced concrete). Figures 3-2 and 3-3 show elevation and plan views of the KKM plant.

It should be noted that the design-licensing-construction process of BWR/4 has continued since the 1966 concept period, and is still underway on certain plants (Fermi 2, Hope Creek 1, 2).

A major consideration in updating the BWR/4 is compliance with current Codes and NRC requirements. The major issues that have to be addressed are,

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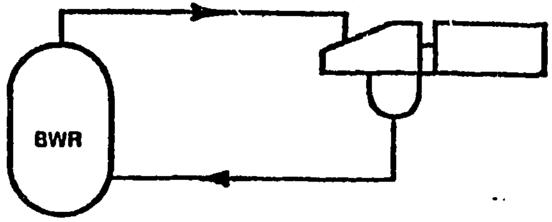
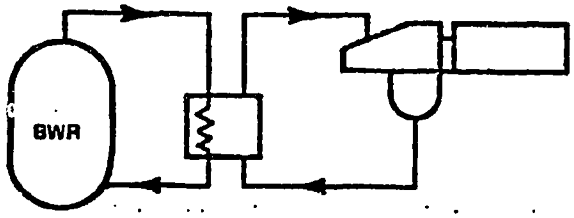
HUMBOLDT BAY 3
(Borax, VBWR)



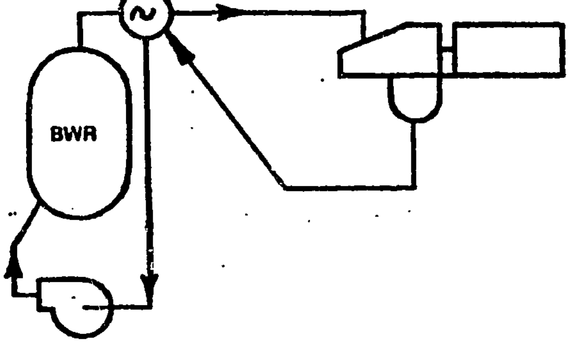
DIRECT CYCLE - NATURAL CIRCULATION

KAHL



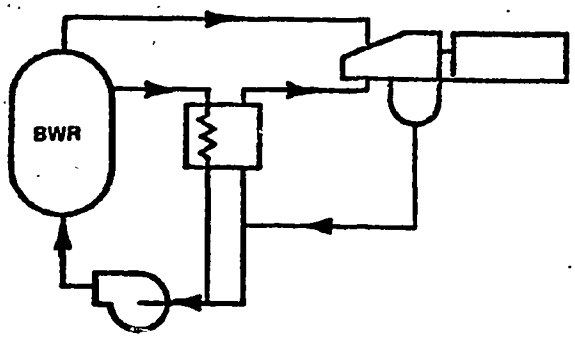
INDIRECT CYCLE - NATURAL CIRCULATION

BIG ROCK POINT
(Oyster Creek)



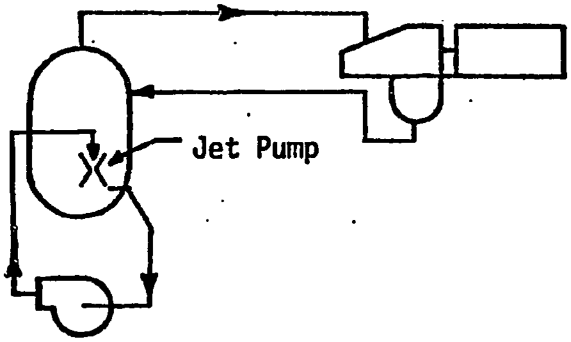
DIRECT CYCLE - FORCED CIRCULATION

DRESDEN 1



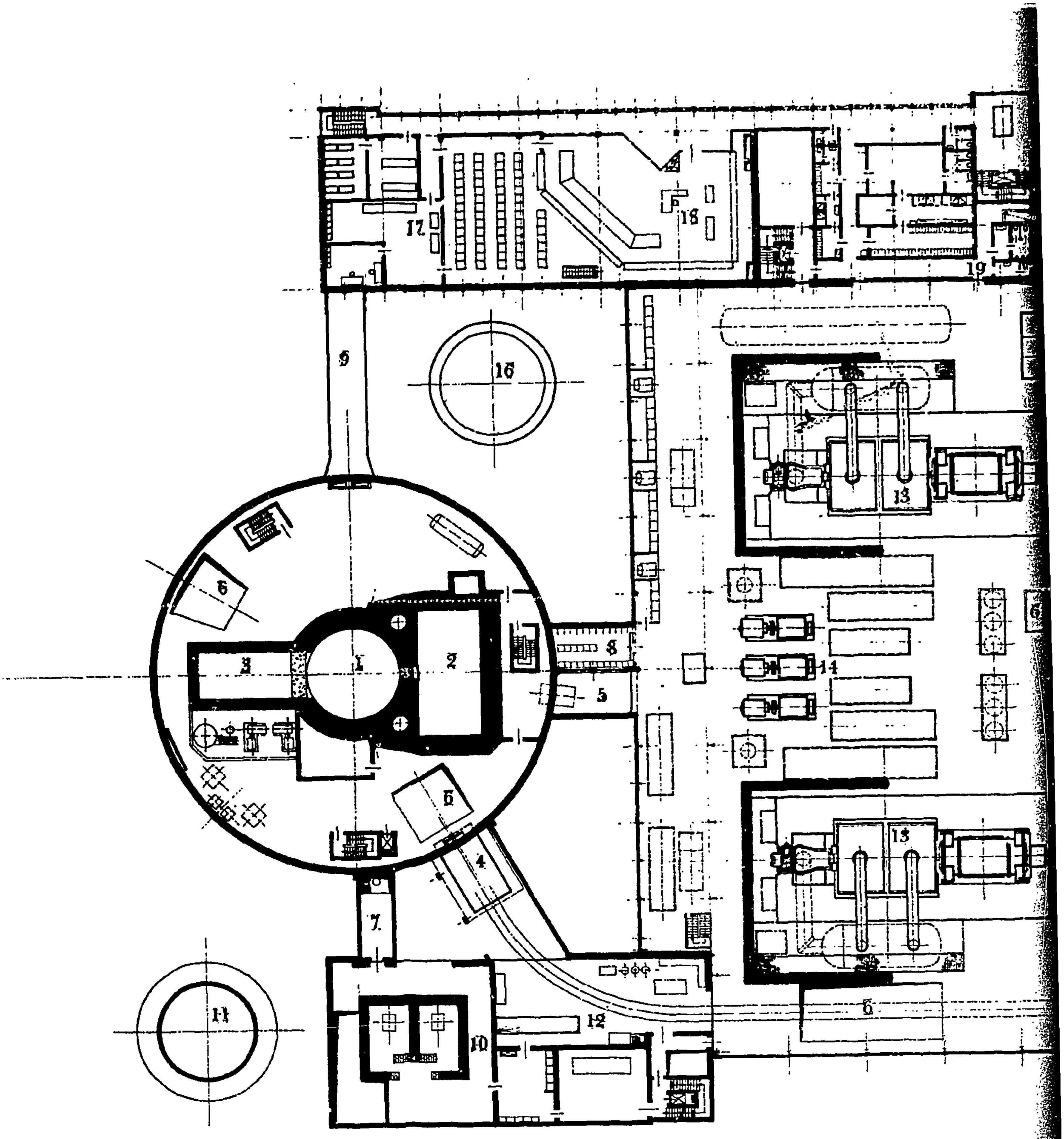
DUAL CYCLE - FORCED CIRCULATION

BWRs 3-4; MUHLEBERG, ETC.
(Dresden 2)

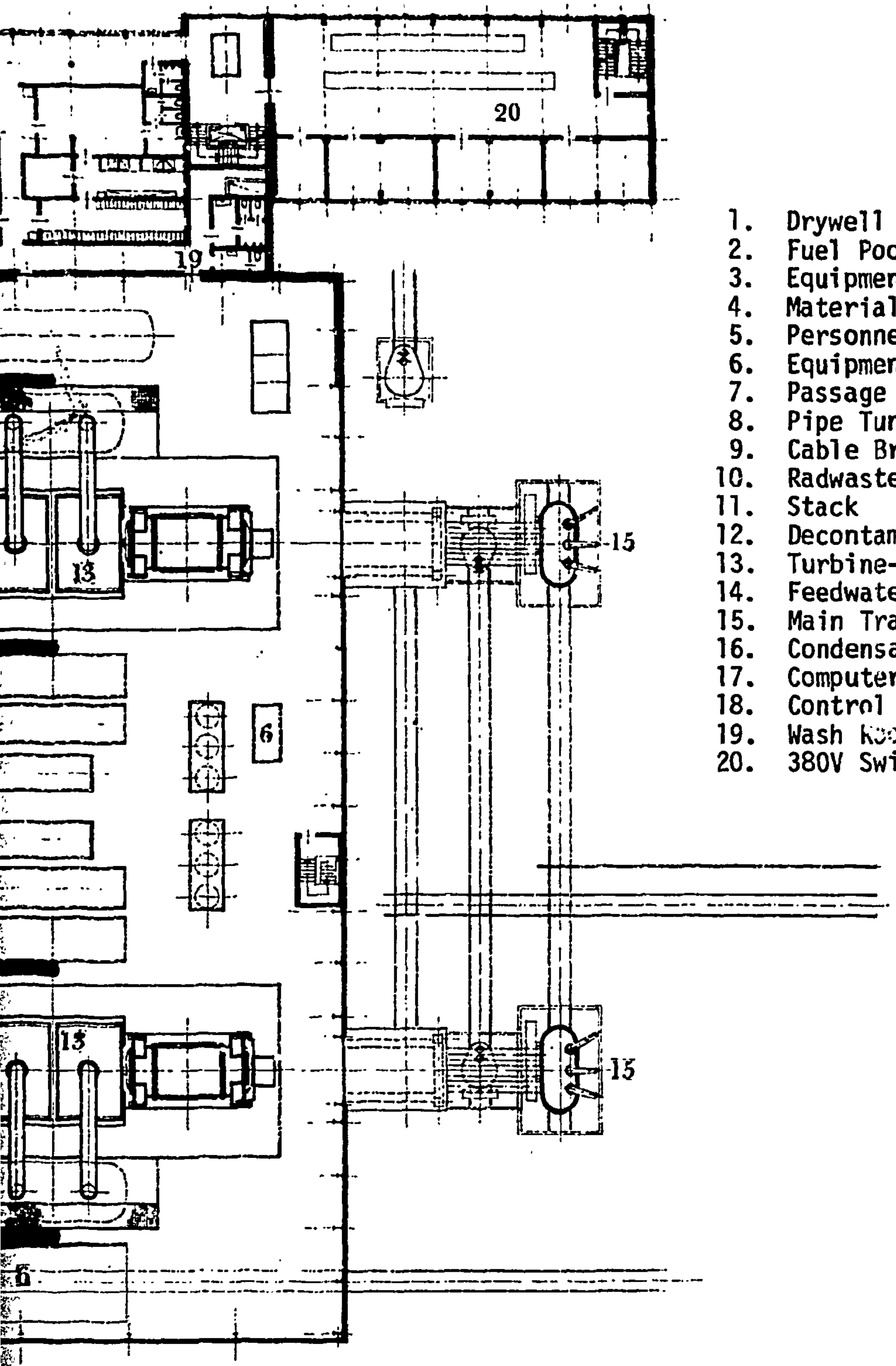


DIRECT CYCLE - FORCED CIRCULATION

FIGURE 3-1. BWR DESIGN EVOLUTION



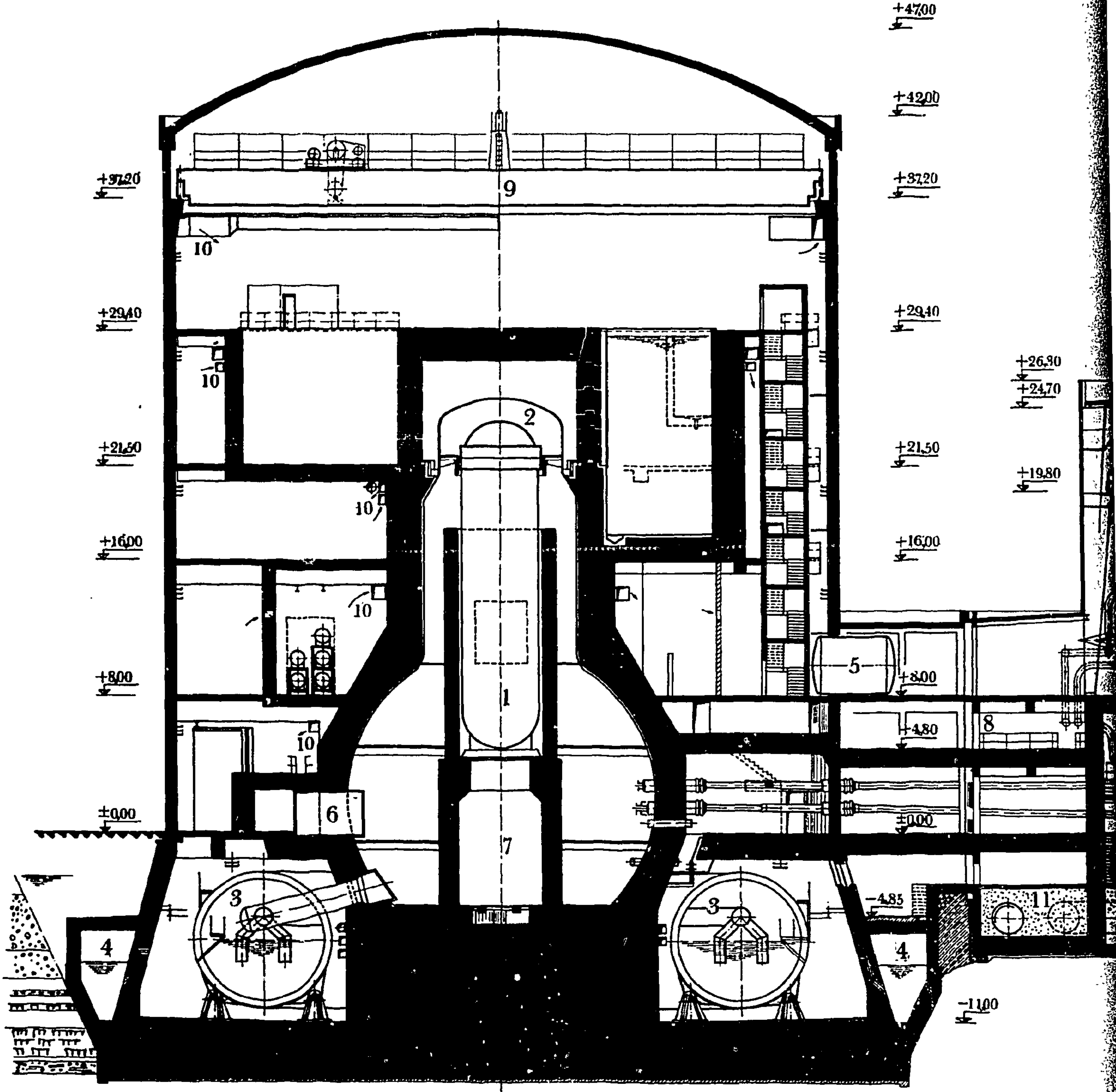
BROWN BOVERI



1. Drywell
2. Fuel Pool
3. Equipment Pool
4. Material Lock
5. Personnel Lock
6. Equipment Opening
7. Passage Bridge
8. Pipe Tunnel
9. Cable Bridge
10. Radwaste
11. Stack
12. Decontamination Area
13. Turbine-Generators
14. Feedwater Pumps
15. Main Transformer
16. Condensate Storage Tank
17. Computer
18. Control Room
19. Wash Room
20. 380V Switchgear

Figure 3-2. MUHLEBERG PLANT -
FLOOR PLAN AT +8M

2



BROWN BOVERI

1. Reactor
2. Drywell
3. Suppression Pool
4. Second Suppression Pool
5. Personnel Lock
6. Personnel Lock
7. Control Rod Drive Area
8. Pipe Tunnel
9. Reactor Building Crane
10. Ventilation Ducts
11. Circulating Water
12. Turbine Crane
13. Turbine-Generators
14. Main Condensers
15. Main Transformer

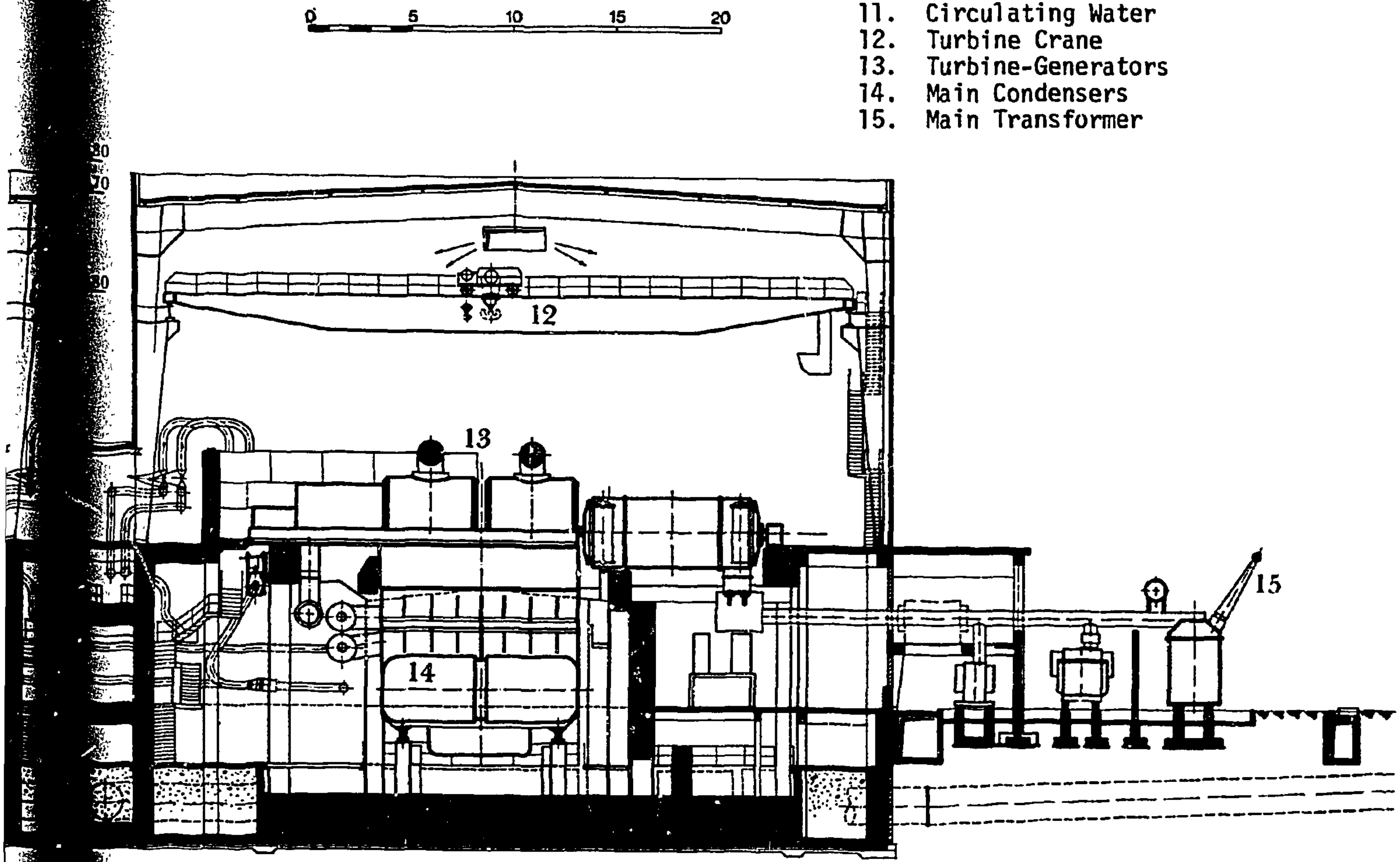


Figure 3-3 MUHLEBERG PLANT - LONGITUDINAL SECTION

2

Emergency core cooling

Containment dynamic loads

Pipe whip

Seismic accelerations

ALARA (as low as reasonably achievable) requirements

ATWS (anticipated transients without scram)

Separation and fire protection

The BWR/4 plants under construction must address these current issues, but necessarily in the retrofit sense, rather from initial concept. A re-design for future plants would logically proceed with current requirements in mind as an integral part of the design. These re-design features are identified and investigated in this study, but with limited detail in keeping with the preliminary scope of this study.

Another consideration is the application requiring process steam for an industrial site. Isolation between primary and secondary steam, process steam specifications, reliability, heat cycle, and reboiler design must be studied. Isolation is assumed necessary between the BWR and process steam, and so an intermediate, steam-to-steam, heat exchanger (reboiler) would be used. It is believed that such a design, essentially an indirect cycle BWR, could meet all drinking water specifications, and would be suitable for supplying process steam (using conventional nuclear plant fabrication techniques to assure reboiler integrity) for use in production of products for human consumption. A single reboiler applied to KKM can be assumed to replace one of the two turbine generators. Such a cycle is shown on Figure 3-4 wherein 460 psig steam is provided for the industrial process. Multiple reboilers for different pressures can be provided by taking primary steam from different points in the turbine cycle.

In brief, the BWR/4 is at this time a proven concept and operations of the Muhleberg unit are an excellent example of the potential of intermediate sized units in this class. The several areas of updating identified in this report relate primarily to changes in Codes and NRC requirements. They do not represent areas of novel design or major development requirements, but they do require substantial design and detail analysis beyond the scope of the present report.

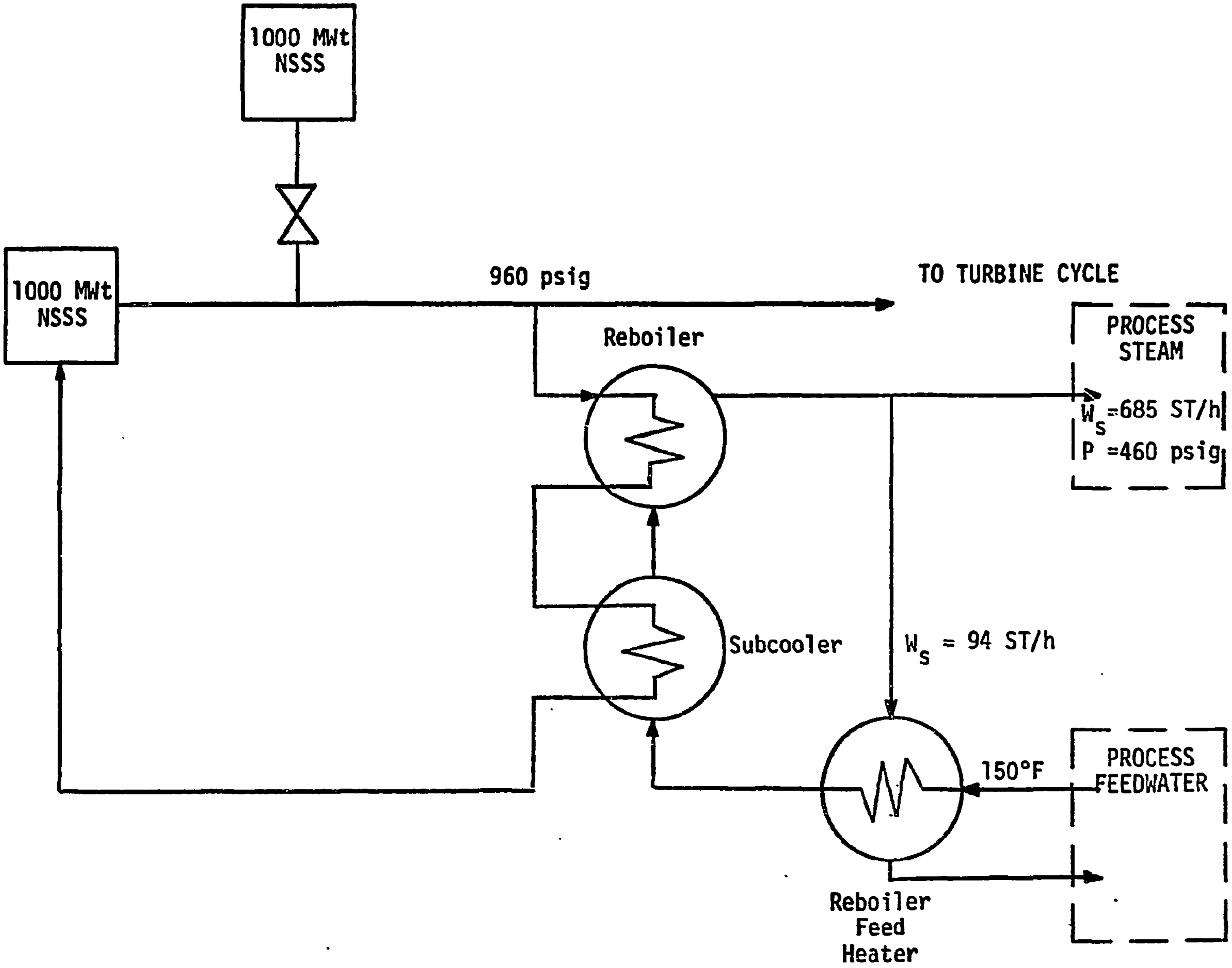
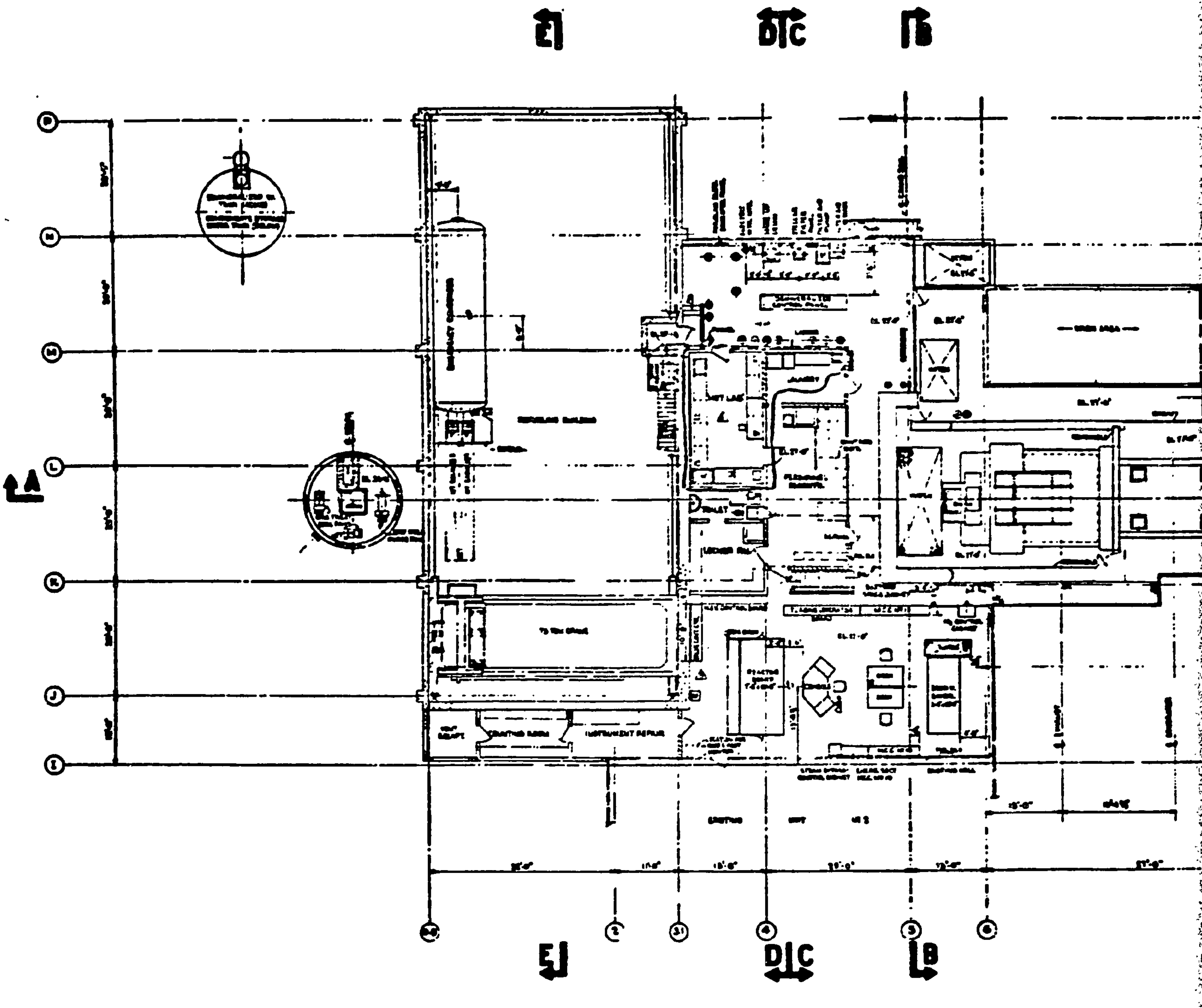


FIGURE 3-4. SINGLE REBOILER PROCESS STEAM

4. NATURAL CIRCULATION SMALL PLANT ALTERNATE

The early BWRs, Borax, EBWR, VBWR, Kahl, JPDR, Elk River, and Humboldt Bay 3 were natural circulation reactors. Humboldt was the largest at 220 MWt, 63 MWe. It was in commercial operation in 1963, and plant availability over the 13 years of operation has been 86 percent. This concept is attractive for an industrial process application because it represents the ultimate in LWR simplicity. It has no loop piping, no large RPV nozzles below the core, and no recirculation pumps. The Humboldt plant is shown on Figures 4-1, 4-2 and 4-3. Questions remain as to whether such designs can be extrapolated from 220 MWt to 1000 MWt (although all BWRs are licensed for partial power operation on natural circulation and data is available to support some extrapolation) and whether manual control or automatic rod control is feasible. Detailed analyses of these areas were beyond the scope of the present study. Key parameters are listed in Table 4-1. It is concluded:

- The natural circulation BWR at 1000 MWt appears technically feasible.
- Licensing and safety should not present any fundamental new problems.
- A favorable capacity factor is contributed to by the absence of an external recirculation system.

E
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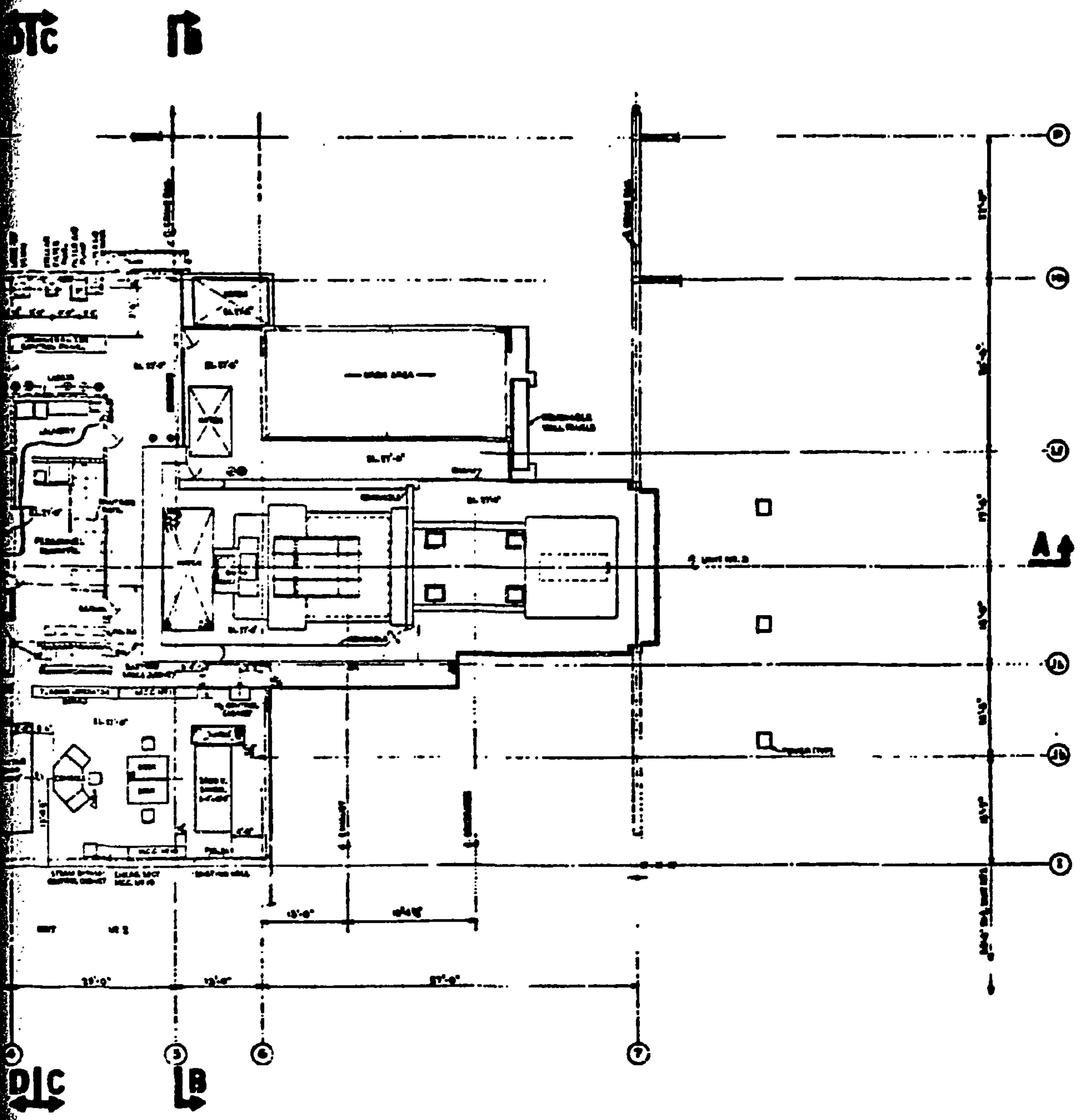

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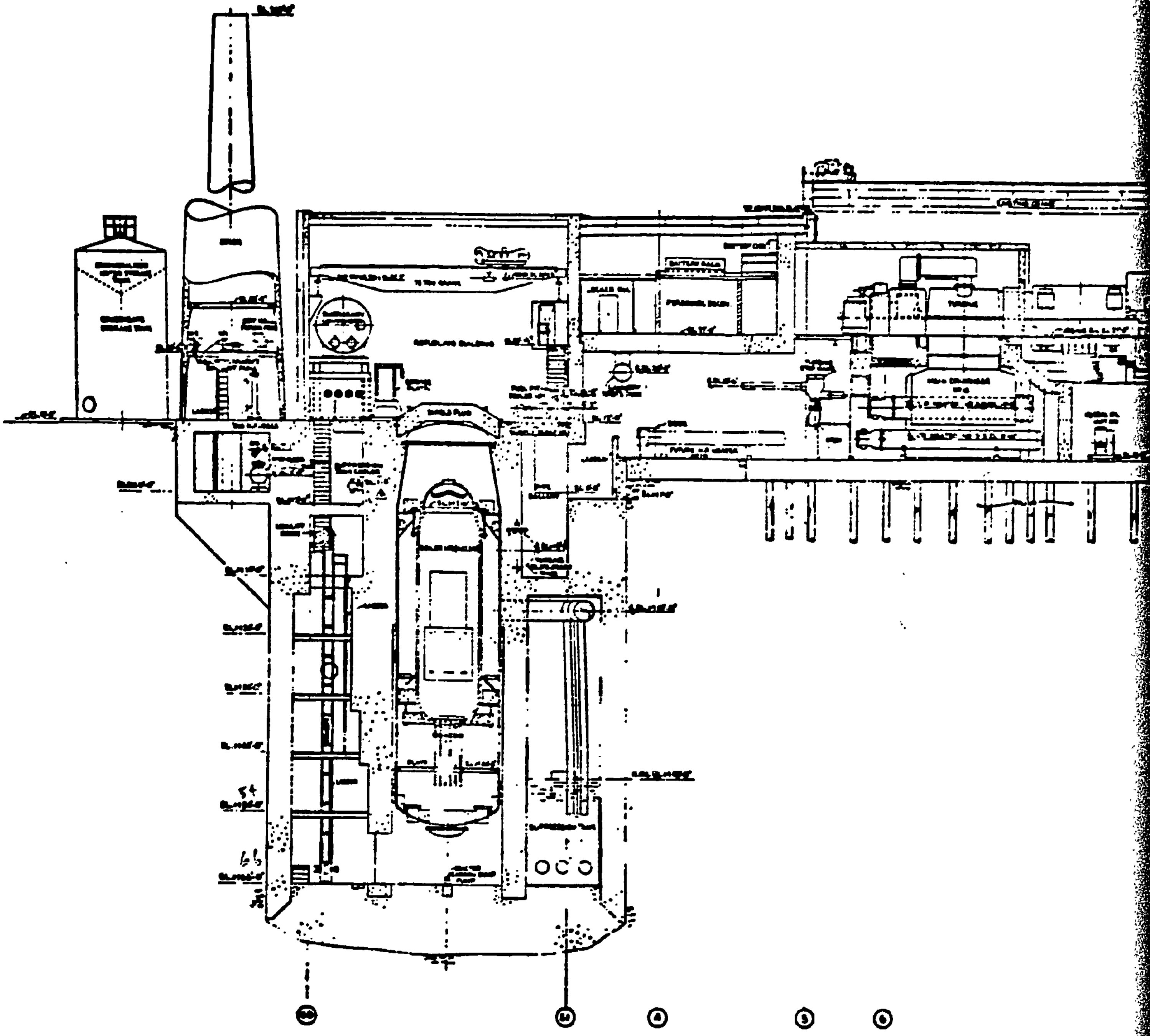
FIGURE 4-1.

HUMBOLDT BAY 3 - OPERATING FLOOR PLAN



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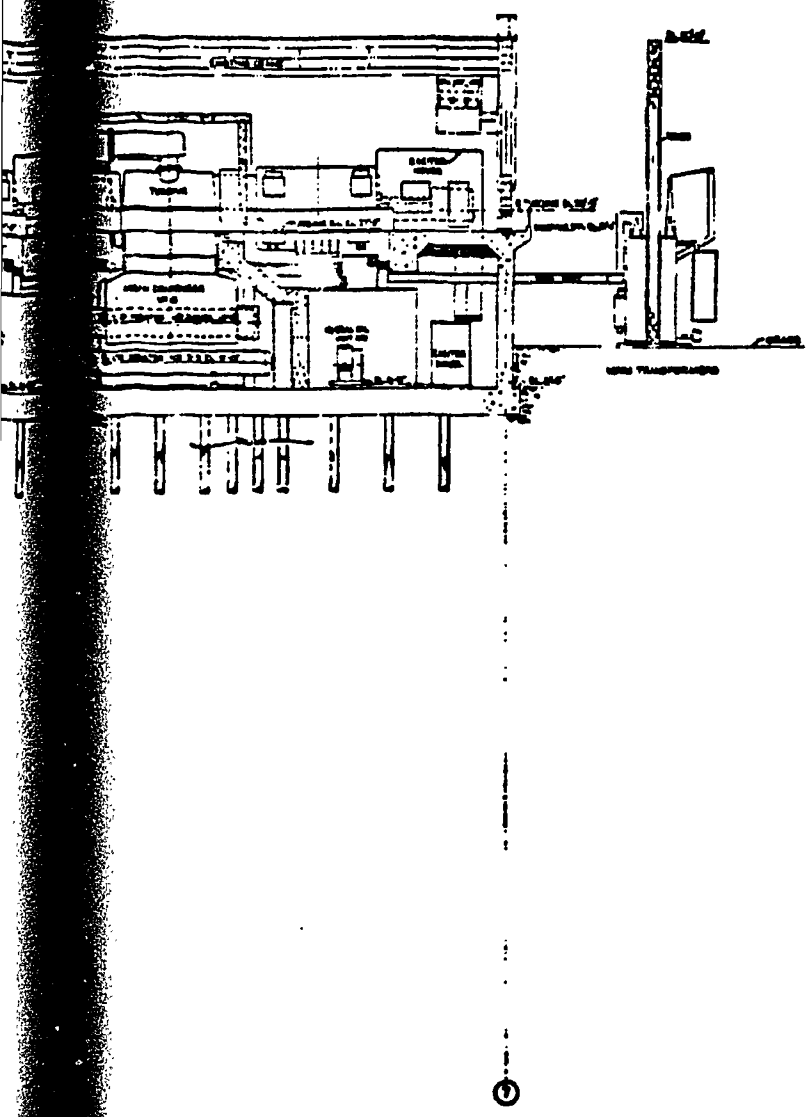

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FIGURE 4-2.

HUMBOLDT BAY 3 - LONGITUDINAL SECTION

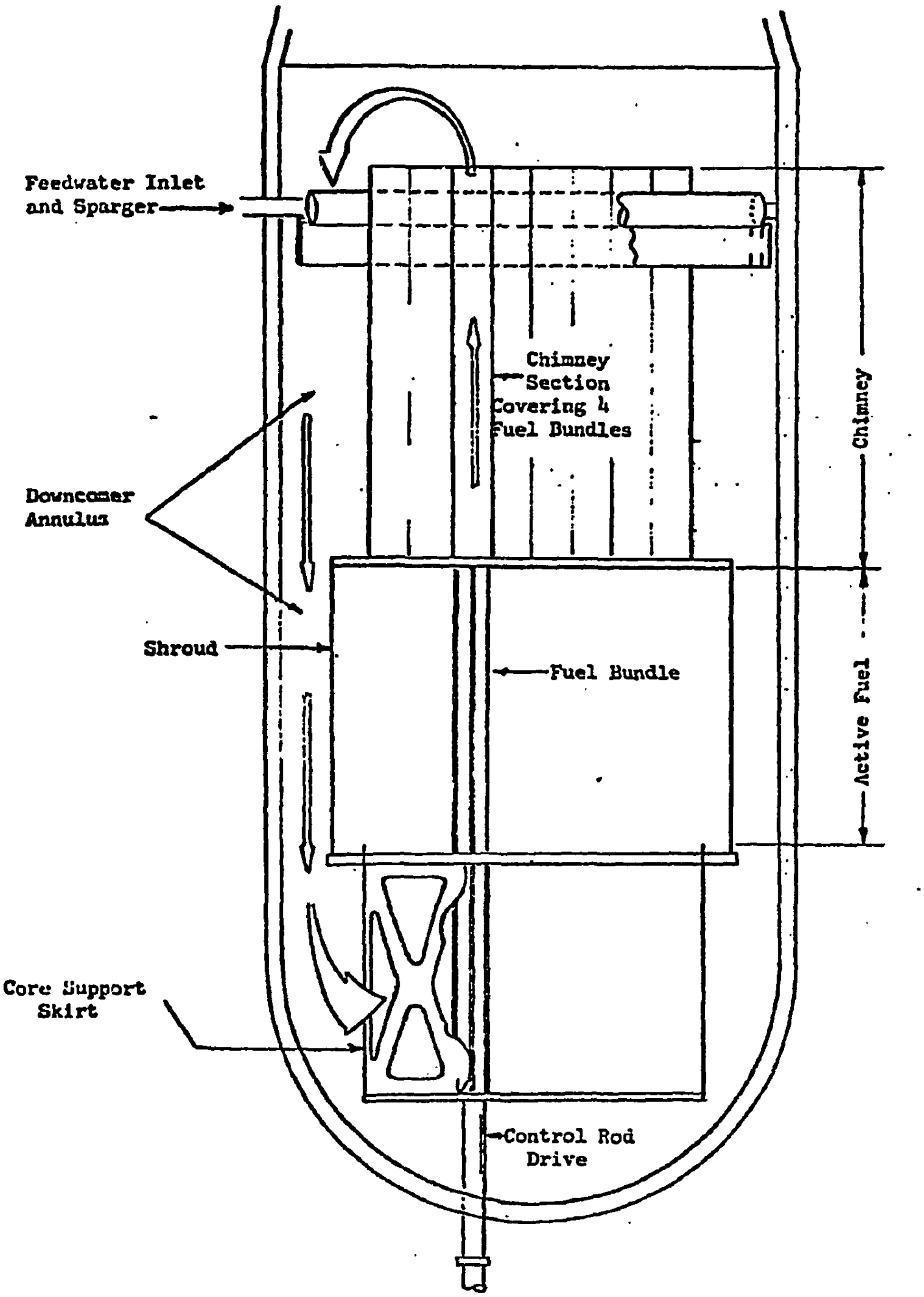


FIGURE 4-3. NATURAL CIRCULATION CONCEPT

TABLE 4-1

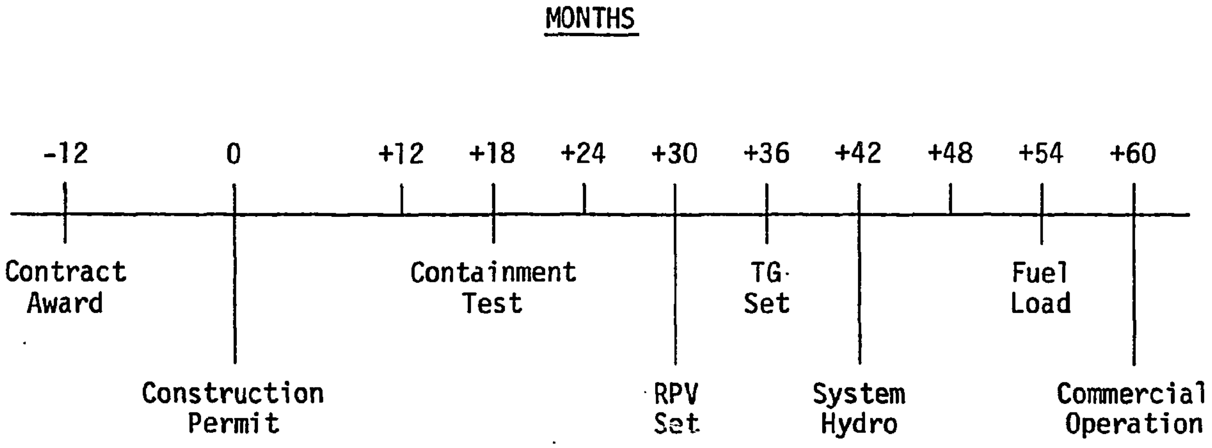
NATURAL CIRCULATION

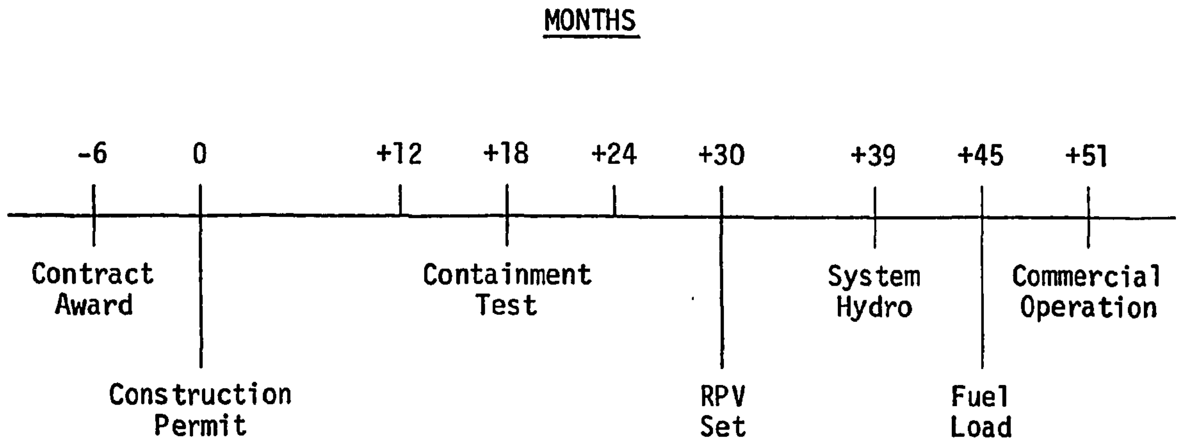
Parameter	Effect of Natural Circulation
Power density	May need to be lower than forced circulation.
Containment	Beneficial reduction in equipment, but increased size per MWt.
Manual power maneuvering	Removes maneuvering by flow control. Limited to control rods.
Automatic control	Removes automatic control by recirculation flow. Potentially could use feedwater temperature or control rods.
Stability	Probably decreased margin. May require additional chimney to compensate.
Availability	Favorably affected via simplification.
Licensability	Previously licensed. Need to develop means of accurately measuring core flow rates. Recirculation line break is eliminated as the limiting LOCA.
Radiation exposure	Significantly reduced by eliminating external loops.

5. PLANT CONSTRUCTION COSTS, IMPROVEMENTS AND REPLICATION

Capital costs of nuclear plants over the past decade have increased by over five times, and schedules have increased from six years to ten years. In the same period the sizes of the plants have grown from 500/800 to as large as 1300 MWe, but not enough to explain these capital cost and schedule increases. Additional causes for these increases include escalation, interest during construction, licensing, quality assurance, lower labor productivity, and incomplete designs prior to start of construction. Many of these causes can be alleviated by rigorous standardization, or at least by design completion prior to start of construction.

In addition it is worthwhile to study construction experience and construction techniques used in order to determine areas of improvement. Although preliminary and limited, this has been done in this study. Construction experience shows that construction cycles (construction permit to operating license) vary with plant size. A preliminary assessment of the data indicates an increase of five months per 100 MWe. Of the construction techniques used the most promising seems to be the use of modular techniques, such as pre-assembled control room modules, off-gas system packages, filter/demineralizer modules, pre-assembled instrument racks, and pre-installed RPV internals. With such techniques and standardization, it is estimated that the construction schedule for a small plant can be improved from 60 months to 51 months as shown below.





These 15 months would be very significant in terms of escalation and interest during construction.

The reference KKM (Muhleberg) plant was built as a turnkey plant by a Brown Boveri-General Electric consortium. Integration in the consortium between design and construction was very close and effective. Construction cost estimates were met, and a short construction cycle of 48 months was achieved. There were no significant licensing delays.

Actual KKM construction costs were compiled and used for this study by transferring the Swiss franc costs to dollars, escalating from the 1967-1971 construction period to July 1976, and making a 25% labor adjustment for lower USA labor productivity. These adjustments, shown in Table 5-1, result in a cost of $98,367,000 for the 306 MWe KKM plant, or a unit cost of 321 $/kWe. This cost does not include the added licensing and safety requirements or interest during construction and other customer costs. Licensing and safety are estimated to range over 100-250 $/kWe, so 175 $/kWe is used. Interest during construction and other customer costs are estimated at 25 percent of total costs, or 124 $/kWe. These added costs bring the total to 620 $/kWe, or $189,720,000.

A comparison and approximate check of this Muhleberg cost is provided by the costs of eight small plants (450 MWe to 545 MWe) built in 1965-1975. These costs are plotted on Figure 5-1, and listed on Table 5-2. These data also illustrate the aforementioned rapid escalation of LWR unit costs with time over the period 1970 through 1975. It can be largely attributed to the effect of labor and materials cost escalation and increased licensing requirements.

Assuming a 306 MWe plant was to be designed and constructed under U.S. methods in the existing U.S. environment, it is estimated that the indirect costs (construction equipment and services, A/E engineering, construction management) would be of the order of $80 million. These and other overhead costs are a very significant part of the $189,720,000

TABLE 5-1

MUHLEBERG (KKM) - 306 MWe

Construction Permit 3/67 - Project Completion 9/71

Price Average Base Date: 1969

	Account	Swiss Francs x 1000			
		Material	Labor	Service	Total
20	Land & Land Rights (estimate by Cost Estimating)	6,500			6,500
21	Structures & Site Facilities	33,315	20,160		53,475
22	Reactor Plant Equipment	50,338	4,377	34,450	89,165
23	Turbine Plant Equipment	41,635	7,085		48,720
24	Electric Plant Equipment	13,545	3,470		17,015
25	Miscellaneous Plant Equipment	11,650	1,685		13,335
	SUBTOTAL - DIRECT	156,983	36,777	34,450	228,210
91	Construction Facilities Equipment & Services	540	940		1,480
92	Engineering & Construction Management Service			7,430	7,430
93	Other Costs	3,275		2,070	5,345
	SUBTOTAL - INDIRECT	3,815	940	9,500	14,255
	TOTAL - SWISS SITE BASIS	160,798	37,717	43,950	242,465
	U.S. $ Equivalent (x 1000)	$37,144	$ 8,713	$10,152	$56,009
	Adjustment for Lower U.S. Productivity		+ 2,718		
	TOTAL U.S. SITE - 1969 $ (x 1000)	$37,144	$11,431	$10,152	$58,727
	Escalation Adjustment Factor	1.75	1.56	1.53	
	July 1976, Cost Level	$65,002	$17,832	$15,533	$98,367
	TOTAL PLANT COST 7/76 BASIS - U.S. SITE		$98,367,000 =	$321/kWe	
	Estimate of Design, Licensing and Safety Requirements ($100 - 250/kWe)			$175/kWe	
	Estimate of Interest During Construction and Other Customer Costs			$124/kWe	
	TOTAL			$620/kWe	

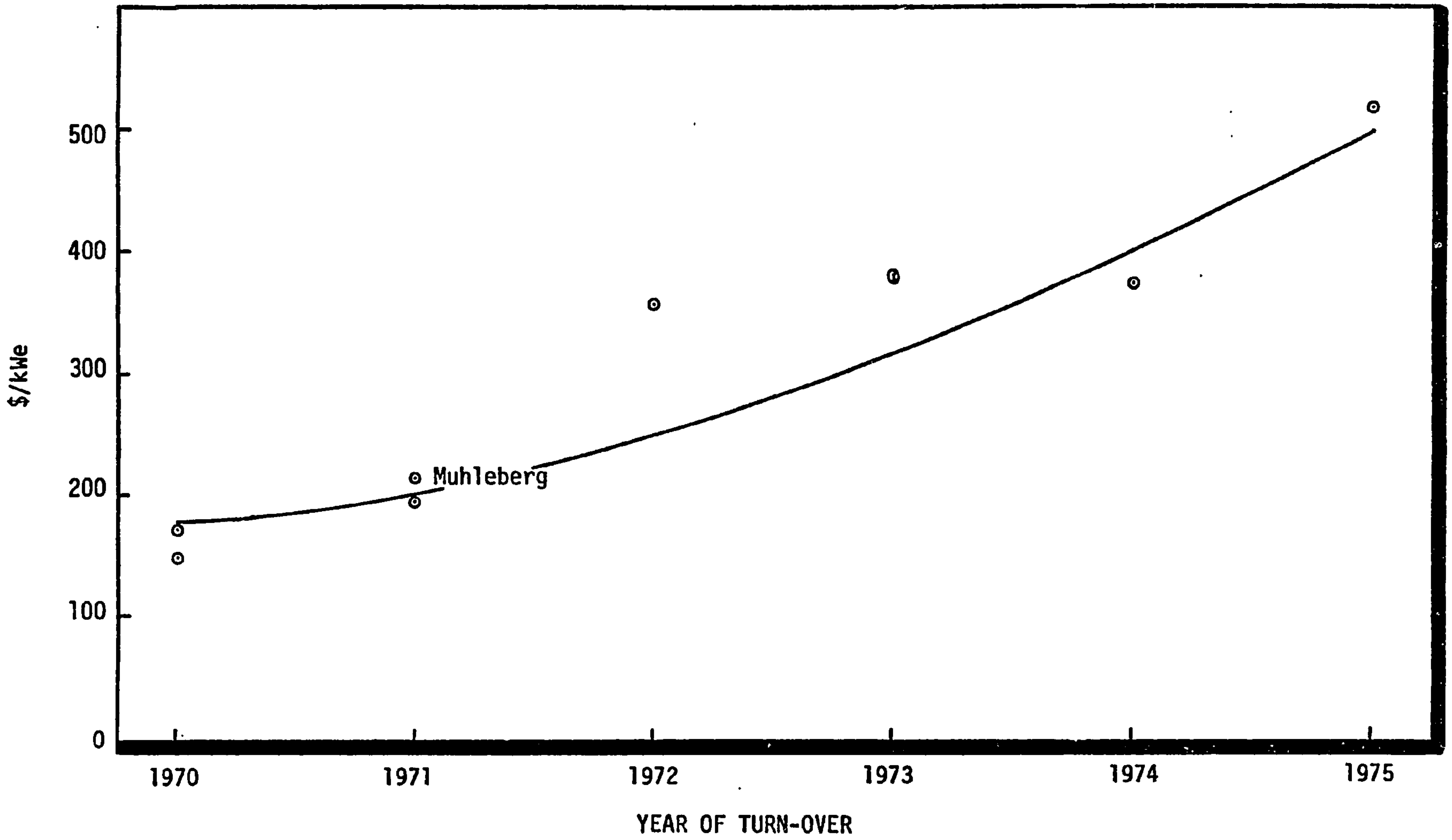


FIGURE 5-1. COMPLETED INTERMEDIATE SIZE LWR PLANT COSTS

TABLE 5-2

COMPLETED INTERMEDIATE SIZE LWR PLANT COSTS
Extract from ERDA Publication (ISL 3/31/76)

Contract	Plant	MWe	Million $	Commercial Operation	$/kWe
1965	Ginna	490	85	70	173
1966	Monticello	545	107	71	196
1966	Fort Calhoun	457	174	73	381
1966	Vermont Yankee	514	184	72	358
1966	Point Beach 1	497	74	70	149
1967	Prairie Island 1	530	200	73	377
1967	Kewaunee	541	201	74	372
1968	Duane Arnold	535	277	75	518

Muhleberg capital cost estimate. One of the main elements is engineering which requires double the manhours required a decade ago. These costs tend to be independent of size and thus they represent a severe burden on a small plant, and are apparently the result of the more stringent licensing and regulatory requirements.

To offset this burden, multiple, standard units (on the same site to one design) can be constructed. If four 300 MWe units are constructed in tandem, it is estimated that the indirect costs per unit will be 81.0, 52.9, 45.1, and 41.0 million dollars, for a total of 220 million dollars for a 1200 MWe site, or 183 $/kWe.

6. COST TRENDS WITH SIZE

The cost economies expected by the increase in nuclear unit sizes have clearly not been realized. For example, two BWRs started up about the same time,

Duane Arnold	BWR/4, 535 MWe, Region IV, private utility 6/70 construction permit, 2/74 operating license $518/kWe -- single unit plant - cooling towers
Peach Bottom	BWR/4, 1065 MWe, Region I, private utility 1/68 construction permit, 8/73 operating license $504/kWe -- first of dual unit plant - cooling towers

or, two PWRs,

Kewaunee	541 MWe, Region IV, private utility 8/68 construction permit, 12/73 operating license $372/kWe -- single unit plant - lake cooling
Cook 1	1060 MWe, Region II, private utility 3/69 construction permit, 10/74 operating license $506/kWe -- two unit plant - lake cooling

Furthermore, current large projects are showing greatly inflated costs. In spite of this there is still a belief in economy of scale.

In principle a diagnosis of existing nuclear plant construction cost experience should permit an improved understanding of the various factors affecting plant costs. One published relationship of plant costs to size is the ERDA Concept Code which generally tracks some earlier utility estimates. It shows a 1/3 reduction in $/kWe for an increase from 300 MWe to 1200 MWe. A more recent set of data for evaluation of the estimated economy of scale is the actual cost data reported by 28 U.S. LWR plants constructed under equivalent conditions. These costs can then be corrected for cost escalation (assumed to be primarily due to the effects of licensing requirements and general inflation). There is, however, some question as to the magnitude of this correction factor. If these costs are corrected at a rate of 20% or more as derived from Figure 5-1, and compounded annually (Table 6-1), the cost trends versus size of Figure 6-1 result. In principle this figure suggests other site and design-related factors can be much more important than size itself over the range of 400 to 1200 MWe.

There are several possible reasons why a more substantial economy of scale has not proved evident:

1. Interest during construction over the longer construction schedule of larger plants,

2. Added difficulty of managing and maintaining productivity of larger construction crews,

TABLE 6-1

LWR NON-TURNKEY PROJECTS

(Published costs and assumed adjustments for inflation and regulatory effects through mid 1976)

	Plant Name	Size	Δ yr*	$(1.21)^{\Delta}$	\$/kW	\$/kW Corrected
1	Fort Calhoun	457	3.0	1.77	381	675
2	Vermont Yankee	514	4.2	2.23	358	800
3	Duane Arnold	535	2.3	1.55	518	805
4	Prairie Is. 1	530	2.9	1.74	377	655
5	Kewaunee	541	2.5	1.61	372	600
6	Turkey Point 3	666	4.0	2.14	165	355
7	Pilgrim 1	670	4.0	2.14	357	765
8	Palisades	700	5.2	2.70	229	620
9	Cooper	778	2.5	1.61	373	600
10	Hatch 1	786	1.9	1.44	480	690
11	Surry 1	788	4.0	2.14	252	540
12	Maine Yankee	790	3.8	2.06	277	570
13	St. Lucie 1	810	0.3	1.06	593	630
14	3 Mile Island 1	819	2.1	1.49	496	740
15	Brunswick 2	821	1.5	1.33	471	625
16	Fitzpatrick	821	1.8	1.41	367	515
17	Millstone 2	828	0.7	1.14	502	570
18	Calvert Cliffs 1	845	2.0	1.46	414	605
19	Arkansas 1	850	2.0	1.46	289	420
20	Beaver Valley 1	852	0.5	1.10	649	715
21	Oconee 1	871	3.2	1.84	179	330
22	Rancho Seco	913	1.9	1.44	370	535
23	Indian Point 3	965	0.5	1.10	408	450
24	Zion 1	1050	3.1	1.81	263	475
25	Cook 1	1060	1.7	1.38	506	700
26	Peach Bottom 2	1065	2.9	1.74	504	875
27	Browns Ferry 1	1067	3.0	1.77	251	445
28	Trojan	1130	0.5	1.10	396	435
--	Muhleberg	306			--	620

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* Δ yr is escalation period from turnover to mid 1976.

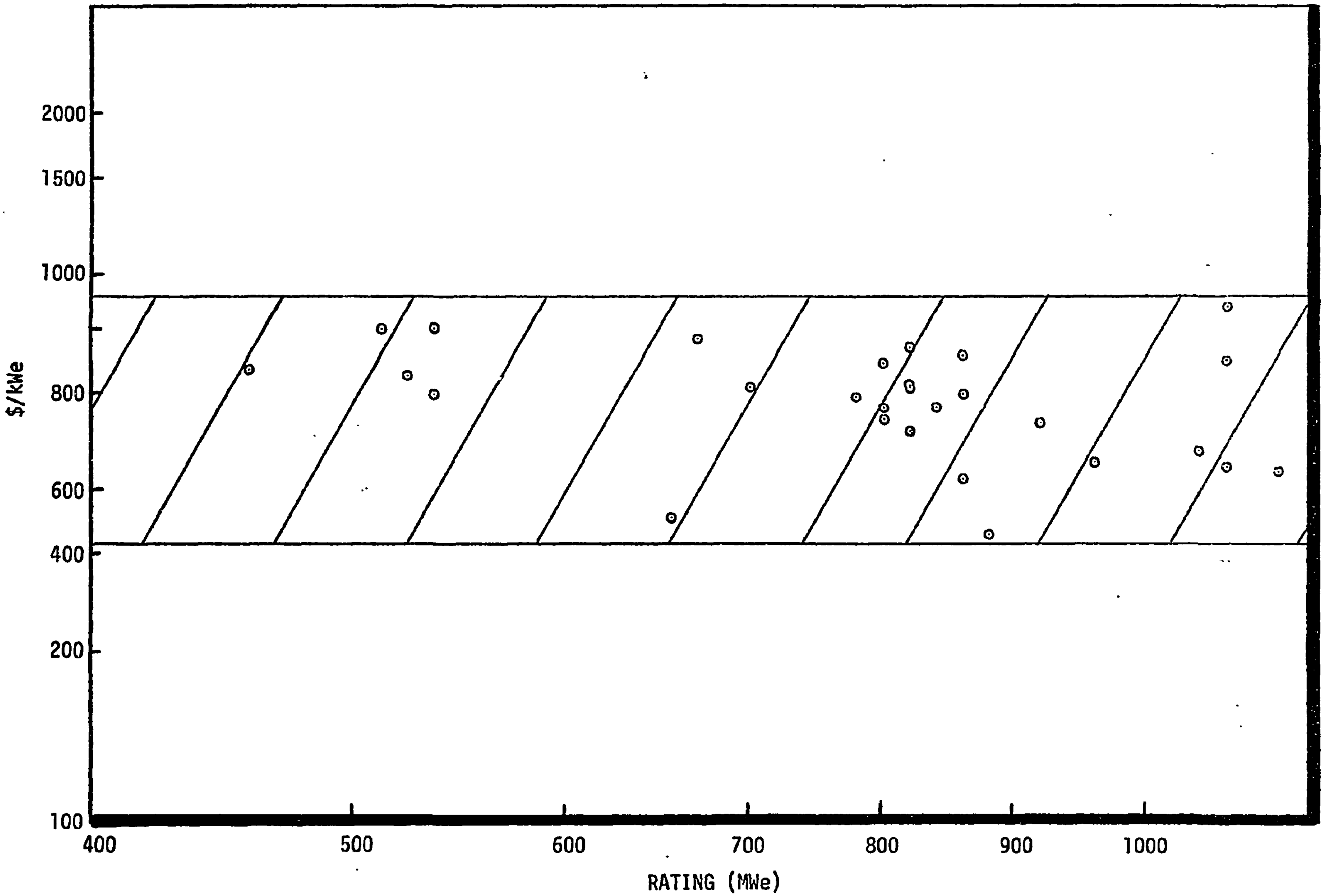

Figure 6-1. POWER GENERATION COST VS. PLANT SIZE
MID-1976 DOLLARS

3. Large components to procure and install, and

4. Larger civil structure and foundations to erect.

Thus although this is a preliminary examination of the cost trends, it is probable that there are effects offsetting the economy of scale. Further analysis with firmer data is warranted. Even without additional historical cost trend analysis, however, it would seem prudent to pay careful attention to the potential of intermediate-sized units as an alternate to current, large units when considering future generation additions. In the special case of possible combined power-plus-process heat applications for smaller sites these considerations are even more significant.

7. ENERGY COSTS

Fuel cycle costs were calculated for an operating, representative small plant, using financial parameters (Table 7-1) suggested by ORNL. The results in 1976 dollars are

1000 MWt	64 ¢/MBtu	66 ¢/MBtu
49 kW/l	equilibrium	10-year levelized
80% CF		

For comparison, current estimates on a large plant are

3579 MWt	56 ¢/MBtu	58 ¢/MBtu
54 kW/l	equilibrium	10-year levelized
80% CF		

These fuel costs for the large plant are about 15 percent lower than for the small plant, because of the higher power density and better nuclear performance, i.e., 22 percent higher fuel exposure of a larger core.

The fuel cost breakdown for the reference plant is shown in Table 7-2.

TABLE 7-1

FUEL CYCLE COST PARAMETERS
(in 1976 dollars)

U_3O_8 price, $/lb	40.00	
Conversion cost, $/kg U_3O_8	3.50	
Enrichment cost, $/SWU	100.00	
Tails concentration, % Uranium-235	0.25	
Bundle fabrication cost		
Initial core, $/bundle	23,000.00	
Reload core, $/bundle	21,000.00	(115 $/kg)
Fuel recovery cost, $/kg heavy metal (includes back-end costs such as transportation and waste disposal)	180.00	
Fissile plutonium value, $/g	30.00	
Discount rate on fuel, %	13.5*	

Lead and Lag Times, Months	
Payments Prior to Batch Insertion	
U_3O_8 purchases and conversion	9
Uranium enrichment	6
Fuel fabrication	3
Payments Subsequent to Batch Withdrawal	
Reprocessing	6
Fissile material credit	9
Losses of Fertile and Fissile Materials, %	
New Fuel	
Conversion	1.0
Fabrication	0.5
Recycled Fuel	
Reprocessing	1.0
Refabrication	1.0

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* Used for present worth valuations, carrying charges, and interest on capital.

TABLE 7-2

FUEL CYCLE COST BREAKDOWN

1000 MWt, 49 kW/l

	Percent
Uranium	50
Separative Work	28
Fabrication	10
Recovered Uranium	(15)*
Recovered Plutonium	(13)
Reprocessing	14
Carrying Charges	26

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* Parenthesis denote credit.

8. PROGRAM RECOMMENDATIONS AND CONCLUSIONS

A review of 300-600 MWe U.S.-designed LWR operating experience and cost suggests that these LWRs may be more competitive than generally recognized. They are designs which are established and well proven by over 100 reactor years of operation. They represent a substantial nuclear industry resource. The Swiss Muhleberg unit (306 MWe) is a leading BWR in this group. Additional study (Phase II) is recommended to cover a more detailed comparison to large plants, and to determine more closely defined cost levels for such a plant up-graded for licensing, safety, and regulatory changes which have transpired over the past 3-5 years. This effort should be based on better definition of regulatory considerations and benefit from a direct interchange between the NRC, the designers and associated architect engineer/constructors.

The process heat energy demands of the nation are large and diverse. Consequently, many of these could potentially be better served by smaller LWRs rather than the more recently developed larger units. Until the onset of the oil embargo, the estimated high cost of smaller LWRs prevented any application to the process heat market. The increase in fossil energy costs plus the savings through replication of many units could provide a basis for a renewed interest in smaller units and broader LWR applications. The extent of market interest in a program of replicated, smaller, proven LWRs (300-600 MWe), and the national approach necessary to bring about low cost construction should be defined. A continued effort by manufacturer and A/E engineering personnel is recommended for this additional Phase II work and associated demonstration plant design and cost definition.

Analysis of the process heat requirements indicates that the addition of a heat exchanger to a small BWR should be sufficient to isolate the process from the radioactivity in the primary system. Questions of required reliability, and extraction versus throttle steam, have not been analyzed in any detail and are dependent on specific applications. Therefore, after developing an updated, more detailed design, studies of specific applications to industrial and utility requirements should be undertaken to gain a better understanding of smaller plant economics. If the results of such a study warrant it, consideration should then be given to an LWR demonstration program and its follow-on.