Battelle

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Richland, Washington 99352

AEC Research and Development Report

POTENTIAL THERMAL EFFECTS
OF AN EXPANDING POWER INDUSTRY:
COLUMBIA RIVER BASIN

APRIL 1972

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POWER INDUSTRY: COLUMBIA RIVER BASIN

by

R. T. Jaske

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April, 1972

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ABSTRACT

The once-through cooling capacity of the Columbia River Basin in the reach between the International Border and Bonneville Dam (River Mile 146.4) was predicted for a number of weather conditions, flow management options, and upstream developments resulting from the Columbia Treaty Dams. The research is part of a national survey authorized by the United States Atomic Energy Commission, Division of Reactor Development and Technology in 1970. The study used the MAXPWR version of the COLHEAT simulation system to locate plants and compute thermal assimilative and dissipative capacity entirely within the envelope of water quality criteria promulgated by the states of Washington and Oregon. The study reveals that under these published criteria some 20 GW_e of thermal plants of 31% thermal efficiency could be sited between the International Border and the city of Pasco, Washington. An additional 10 GW_e could be accommodated on the Middle Columbia above Bonneville Dam, but the operational continuity would be subject to interruption without full integration of water management in that reach.

The study also indicates that daily weather is a secondary variable in planning for plant siting. The principal factors which determine the feasibility of future use of the Columbia for once-through cooling would be the effects of the Columbia Treaty Dams on the seasonal cycle of water temperatures and the actual water management plan as it affects these temperatures down stream. Low flows raise Columbia River

temperatures and tend to move thermal peaking dates forward in time by substantial amounts: as much as 60 days under post 1980 conditions. The Snake River was determined to have little or no potential capability for once-through cooling because of the extended travel time of water passing through the Lower Snake impoundments; these are projected to raise summer water temperatures above 23°C.

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POTENTIAL THERMAL EFFECTS OF AN EXPANDING
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INTRODUCTION

The projected expansion of steam electric generation facilities in the United States at a rate of approximately 7%, compounded annually ⁽¹⁾ between 1970 and 1990 has created a need for an assessment of the capacities of natural watercourses to assimilate and dissipate the waste heat associated with these facilities. As a consequence, in FY-1969, the Division of Reactor Development and Technology, U. S. Atomic Energy Commission, requested that Battelle Pacific Northwest Laboratories undertake reconnaissance studies of the thermal regimes of major rivers in the United States. The studies are a partial outgrowth of research and development which has been supported since 1963 by the United States Atomic Energy Commission, for the purpose of examining the response of receiving waters to thermal effluents, and of developing simulation capabilities applicable to cause and effect problems associated with steam electric generating plants.

On July 1, 1970, the principal responsibility for the carrying out this program was transferred to the Hanford Experimental Development Laboratory (HEDL), which has continued the national summary. However, since the work on the Columbia Basin was highly advanced and directly related to previous work involving the operational features of the Hanford facilities, it was determined that this portion of the work would be reported by Battelle Pacific Northwest Laboratories. This report and the entire series enumerated in the reference section will be published by HEDL as a single volume summarizing the once-through cooling capability of the contiguous United States.

Although the Pacific Northwest is a relatively under-developed area in terms of population density, it is relatively highly developed from the stand point of residential electrical consumption and per capita consumption in general. Based on population and related load growth forecasts, the total energy consumption in the Pacific Northwest will reach 1.65×10^{11} kw-hr by 1980 and 2.9×10^{11} kw-hr by 1990. These represent rates of growth slightly lower than the national rate of 6%. While a range of potential growth possibilities can be forecast, present official forecasts in the Northwest Region reflect a compound rate of just above 5% through 1990.⁽²⁾

In any event, the use of thermal power in the area (Figure 1) is expected to increase dramatically. The 1970 energy load of 1×10^{11} kw-hr was served almost totally by existing hydro installations. Commencing with the Centralia Fossil station in 1971 and continuing from then on through 1980, utilities in the region plan to operate a minimum of 1 GW_e of new thermal power each year. Beyond 1980 this rate will be increased to about 2 GW_e each year until a firm regional capability of about 35 GW_e is in place by that date. Essentially all of the energy additions to the Northwest load will be from thermal sources, the hydro gradually being converted to the use as peaking power instead of net energy. Peak loads in 1990 are expected to exceed 50 GW_e so that even the 30 GW of thermal capacity which would be installed by 1990 would still need supplementary installation of additional hydro to meet peak power requirements for the area.

Aside from the large incremental additions of net capacity required in the region, the single dominating factor in the management of power resources is the regional Hydro-Thermal Power Program and the closely related effects of the Columbia Treaty. In no other river basin is the water quality of the major river so closely related to the everyday operations of the power industry. The international obligations of the United

FIGURE 1. Regional Map Showing FPC Marketing Regions and General Study Location

States and Canada as regards the Columbia Treaty were set years before the passage of the National Environmental Policy Act of 1969 and are based almost entirely on power and flood control. This study is a relatively preliminary effort to illustrate a few of the interactions of the water management and related thermal power aspects of the future. It is hoped that a better understanding of these interactions will permit the industry to better serve the public while conforming to the many legislative and regulatory factors which may be expected to place constraints on the extent of future development.

COMPUTATIONAL BASIS

The experimental design of the computations in this report uses the Water Quality Criteria-Interstate Waters of the State of Washington as the technical basis for the location of plants in the individual reaches in question. These criteria are listed below. In using these criteria for this purpose, a number of arbitrary locations were assumed based entirely on the mathematical interpretation of the numerical formula in the criteria. The power density summaries then represent a digest of the numerical thermal capacity of the Columbia River and tributaries without respect to judgments as to the administrative feasibility of individual site locations, plant size increments, and level of industrial development. Therefore, the report which follows is not a plan or a recommendation, but an example of the means by which technical criteria can be used to guide developments along structured lines. The report also attempts to show the relative sensitivity of levels of development to these numerical criteria.

APPLICABLE WASHINGTON STATE REGULATIONS

WATER QUALITY CRITERIA--INTERSTATE WATERS

The following classes and their respective water quality criteria are applicable to the interstate waters of the State of Washington. Interstate waters comprise the entire reach, within the State, of all rivers and lakes that flow across or form a part of the state or international boundaries. They also include the coastal waters which are subject to the ebb and flow of the tides.

Class AA Extraordinary (Interstate)

General Characteristic

Water quality of this class markedly and uniformly exceeds the requirements for all or substantially all uses.

Characteristic Uses

Characteristic uses include, but are not limited to, the following:

- Water supply (domestic, industrial, agricultural)
- Wildlife habitat, stock watering
- General recreation and aesthetic enjoyment (picnicking, hiking, fishing, swimming, skiing and boating)
- General marine recreation and navigation
- Fish and shellfish reproduction, rearing and harvest.

Water Quality Criteria

- Total Coliform Organisms shall not exceed median values of 50 (fresh water) or 70 (marine water) with less than 10% of samples exceeding 230 when associated with any fecal source.
- Dissolved Oxygen shall exceed 9.5 mg/l (fresh water) or 7.0 mg/l (marine water).

- Temperature No measurable increases shall be permitted within the waters designated which result in water temperatures exceeding 60°F (fresh water) or 55°F (marine water) nor shall the cumulative total of all such increases arising from nonnatural causes be permitted in excess of $t = 75/(T-22)$ (fresh water) or $t = 24/(T-39)$ (marine water); for purposes hereof "t" represents the permissive increase and "T" represents the resulting water temperature.
- pH shall be within the range of 6.5 to 8.5 (fresh water) or 7.8 to 8.5 (marine waters) with an induced variation of less than 0.1 units.
- Turbidity shall not exceed 5 JTU.
- Toxic, Radioactive or Deleterious Material Concentrations shall be less than those which may affect public health, the natural aquatic environment, or the desirability of the water for any usage.
- Aesthetic Values shall not be impaired by the presence of materials or their effects, excluding those of natural origin, which offend the senses of sight, smell, touch or taste.

Class A Excellent (Interstate)

General Characteristic

Water quality of this class exceeds or meets the requirements for all or substantially all uses.

Characteristic Uses

Characteristic uses include, but are not limited to, the following:

Water supply (domestic, industrial, agricultural)
 Wildlife habitat, stock watering
 General recreation and aesthetic enjoyment (picnicking, hiking, fishing, swimming, skiing and boating)

Commerce and navigation

Fish and shellfish reproduction, rearing and harvest.

Water Quality Criteria

- Total Coliform Organisms shall not exceed median values of 240 (fresh water) with less than 20% of samples exceeding 1,000 when associated with any fecal source or 70 (marine water) with less than 10% of samples exceeding 230 when associated with any fecal source.
- Dissolved Oxygen shall exceed 8.0 mg/l (fresh water) or 6.0 mg/l (marine water).
- Temperature No measurable increases shall be permitted within the waters designated which result in water temperatures exceeding 65°F (fresh water) or 61°F (marine water) nor shall the cumulative total of all such increases arising from nonnatural causes be permitted in excess of $t = 90/(T-19)$ (fresh water) or $t = 40/(T-35)$ (marine water); for purposes hereof "t" represents the permissive increase and "T" represents the resulting water temperature.
- pH shall be within the range of 6.5 to 8.5 (fresh water) or 7.8 to 8.5 (marine water) with an induced variation of less than 0.25 units.
- Turbidity shall not exceed 5 JTU over natural conditions.
- Toxic, Radioactive or Deleterious Material Concentrations shall be below those of public health significance, or which may cause acute or chronic toxic conditions to the aquatic biota, or which may adversely affect any water use.
- Aesthetic Values shall not be impaired by the presence of materials or their effects, excluding those of natural origin, which offend the senses of sight, smell, touch or taste.

Special Condition

Snake River Temperature

No measurable increases shall be permitted within the waters designated which result in water temperatures exceeding 68°F nor shall the cumulative total of all such increases arising from nonnatural causes be permitted in excess of $t = 110/(T-15)$; for purposes hereof "t" represents the permissive increase and "T" represents the resulting water temperature.

Columbia River Temperature

No measurable increases shall be permitted within the waters designated which result in water temperatures exceeding 68°F nor shall the cumulative total of all such increases arising from nonnatural causes be permitted in excess of $t = 110/(T-15)$; for purposes hereof "t" represents the permissive increase and "T" represents the resulting water temperature (Washington-Oregon border to Priest Rapids Dam only).

SIMULATION MODEL

The COLHEAT simulation model has been discussed in a number of previous publications and, consequently, will not be examined here (See Appendix). The model applies a heat budget to a given section of a river in order to calculate the water temperature as a function of radiation exchange, evaporation, conduction, and advected energy. For this study, the code used a modified version which was originally described in BNWL-1405, called MAXPWR.⁽³⁾ The latter code uses quasi-steady-state assumptions to determine the maximum number of power plants of a fixed thermal incremental size that could be placed along a stream system within a given temperature increment above natural background. Because of the unique nature of the Washington State Water Quality Criteria in using a feed-back type

restriction, this computation must be performed on an approximation basis with feed-back in order to establish conforming installations. MAXPWR is not programmed for this computation and as a result, the study has relied on a number of approximations such as monthly averaging and area averaging of thermal rises for entire reaches. These steps were taken to permit a quantitative look at the stream capacity without becoming excessively involved in the computational detail which would be required by an actual siting plan.

SUMMARY AND CONCLUSIONS

Using published state water quality standards as a guide, this study revealed a significant amount of once-through cooling capacity on the Upper Columbia River reaches above Pasco, Washington. Depending on the interpretation of published standards, a considerable amount of thermal assimilative capacity is also potentially available on the Middle Columbia as far down as Bonneville Dam, but the development potential is closely related to basin wide water management practices which will result from the Columbia Treaty Dams and resulting implementation of hydroelectric and flood control operations both above and below the International Border. From a system planning standpoint, and considering the growth patterns and population density of the Northwest power marketing area, it can be stated that essentially all of the thermal plant capacity required to meet the project load growth of the area through 1990 could be sited on the Columbia River main stem above the confluence of the Snake River. This is possible primarily because of large, expected reductions in temperature potentially possible from flood storage and water management activities related to the Columbia Treaty dams, particularly after construction of Mica. However, despite the significant size of these benefits, it is possible to vitiate them by water management plans which do not recognize water temperature management as a part of the total

basin resources. The study has shown that temperature differentials which will appear as significantly lowered temperatures at the International Border resulting from non-optimized operation of the Columbia Treaty system, vary widely depending on water supply, and are relatively unrelated to local weather. The primary finding of the study is not the development of a specific plan for the siting of thermal stations, but the determination that water management practices are sensitive enough to permit such siting if the overall cost-benefit relationships can be developed to the point where an integrated operation scheme is possible. The present Hydro-Thermal Power Plan could be materially improved in both siting options and cost-benefit by inclusion of temperature management as one of the resources criteria under active control.

Also of significance is the evaluation of the use of the 68°F upper limit as a stream development and environmental protection criterion. The study shows that application of a 2°F Δt limit with an upper limit of 70°F would permit substantial siting of once-through cooled plants above the Washington-Oregon border. The simulations show that with and without power development, the Middle Columbia River will exceed 68°F in a majority of years, and in critical flow years, or years in which management practices severely restrict water flows in July and August, temperatures can be expected to exceed 72°F with a high level of confidence.

The study has determined that, without affecting downstream temperatures by amounts greater than 1°F at the Washington-Oregon border, the majority of projected area thermal plant cooling needs through 1990-95 could be met using once-through cooling providing that plant spacing and size were appropriately controlled and that the design of intake and discharge facilities could meet other requirements for environmental protection of valuable Columbia River Basin resources.

The following detailed conclusions give additional support to the generalized summary above.

- Independent of thermal additions from power plant cooling, the operations of the Columbia Treaty dam system can be expected to have large thermal effects on the water of the Columbia River down to the Washington-Oregon border. Below this point, effects will be noted, especially in years when reservoir management practices produce low flows in July and August. Of special importance is the shifting of the timing of thermal peaks by as much as 60 days in response to water availability. In critical flow conditions, the study shows that peak temperatures in the reach below Priest Rapids Dam will occur as early as late June or early July: 60 to as much as 85 days earlier than the peak occurred during the 1941-1970 period. This occurs because the impoundments slow the time of travel of the river significantly. Under these conditions, the temperature of the river more closely approaches equilibrium temperatures, which in turn are related to mean air temperatures. Under average flow conditions, temperature maximums will occur about the middle of August, somewhat earlier than during the 1941-70 period. This is also the result of materially decreased water flow during June and early July, under normal, average conditions, when compared with the 1941-1970 averages. The study permits the conclusion that water supply in the Columbia Treaty dams will be the principal factor in determining temperature variations of from 1.0 to 1.4°C at Columbia River Mile 324.5 in response to such supplies, and potentially shifting peak temperature arrival times by from 60 to 85 days on a year-to-year basis.

- Relatively high temperatures will occur at Bonneville Dam, Columbia River Mile 146.4, independent of the degree of upstream thermal plant development. This will occur principally because materially reduced flow times through McNary and John Day reservoir can be expected to warm water closer to equilibrium than was the case prior to the filling of either of these projects or the reduction of flows for filling Columbia Treaty obligations. Under average conditions, with an incremental thermal addition of 19.3 GW_{th} in the Hanford reach, it has been shown that temperature will exceed 20°C (68°F) 15 days each year in average years.⁽⁴⁾ The residual effect of an addition of this magnitude is less than 0.1°C in winter at River Mile 146.4. Further, the study shows that differences in weather will not affect the temperature at River Mile 146.4 by more than 1.0°C . Therefore it can be stated that the single most important factor in determining temperature conditions below Bonneville Dam will be the flow of water during the summer months, and the temperature of the water leaving Grand Coulee Dam as a result of Upper Columbia River management practices. However, these operations will not cause large effects below Bonneville Dam, their principal relevance being to the reach above the McNary Project. Under some conditions, the temperature of the Snake River will have large effects on Lower Columbia temperatures principally in periods when Columbia flows are relatively low and Snake flows high.
- Lake Roosevelt will support a large incremental thermal addition, probably a minimum of 20 GW_{th} (9 GW_e nuclear) at the upper end under all but the most severe flow reductions and water temperature conditions which could be postulated, without exceeding 66°F (15.5°C) upper temperature limits for Class AA waters. This is due

principally to large expected reductions in water temperature below the Arrow Dam resulting from Mica storage and other related Columbia Treaty reservoir management. This favorable thermal differential is closely related to reservoir management practices and natural water supply. Variations of two standard deviations can be expected to occur in a 30 year interval, this being on the order of $\pm 2.5^{\circ}\text{C}$ from the mean. Under average conditions, a thermal capacity in excess of $20 \text{ GW}_{\text{th}}$ would exist in all months but August, and could, with appropriate flow management, be extended to include this month as well. Under conditions of thermal optimization, an average capacity of $30 \text{ GW}_{\text{th}}$ could be supported with the Δt and upper temperature limits for Class AA waters. Under conditions of relatively full development ($20 \text{ GW}_{\text{th}}$ thermal increment) the temperatures below the Grand Coulee Dam would range from 1.2 to 1.8°C higher than natural background temperatures. However, even with this level of net thermal increment, and considering the 95% probable maximum ($\bar{T} + 2\sigma$) of upward variation in discharge from water management alone, the temperatures of the Columbia River below Grand Coulee Dam will be lower than the average for the 1941-70 period and almost 2.0°C lower than the highest temperatures recorded in September 1970, (18.7°C). It can be concluded that under appropriate advanced planning, Lake Roosevelt is a significantly important location for siting once-through thermal stations.

The reach between Grand Coulee Dam and Pasco, River miles 595 to 325.5, although fully impounded above River Mile 394, is essentially non-stratified and relatively turbulent. Water management practices which emphasize peaking are expected to increase mean levels of turbulence by increasing mean flows. However, water flow is still the principal factor in determining river temperatures in the reach. Weather, while important, is a secondary variable to upstream

water temperature at Grand Coulee and the average flow condition. For these reasons, under post Columbia Treaty conditions, a relatively large thermal capacity exists under published water quality criteria. Even under critical flow conditions, highest probable temperatures of discharge below Grand Coulee, and the hottest weather, some 20 GW_{th} of thermal capacity exists. Under average conditions, this increases to about 25 GW_{th} in winter months and 30 GW_{th} in the April-June period, although there is little or no difference in mean capacity in the summer period between critical and average flow conditions. Again, as is the condition for the more northerly reaches, weather is a relatively small variable compared to the variations in temperature below Grand Coulee Dam. The unique insensitivity of this reach to flow management under existing standards and criteria as a result of the hydrodynamics of the impoundments, make this reach an especially important segment to consider for thermal plant siting using once-through cooling. This is especially true since, because of the way the standards are contrived, Δt is the principal governing factor under all conditions under post Columbia Treaty dam operations. With or without thermal additions from once-through plants, significant thermal modifications will occur as a result of the hydro operations. Actual temperature differences between critical and average flows are relatively small, from 1.0 to 1.4°C. However, in this reach, the date on which temperature peaks will occur will be subject to severe changes from year to year. Under critical flow conditions, temperature peaks can be expected as early as late June or early July, while in average years peaks will not occur until after August 15th. It is concluded that within present state water quality criteria a large capacity in excess of

20 GW_{th} exists, (in the Upper Columbia between Grand Coulee and Pasco) and that this capacity is a smaller physical element of contribution to thermal modification of this reach of the Columbia than those temperature changes resulting from water supply and management practices from the Columbia Treaty dam system.

- The study of the Snake River as a potential source of cooling for once-through power plants fails to reveal developable capacity under existing water quality criteria. The hydrology of the Snake River in a fully impounded condition is such as to cause full equilibration of the water temperature below Lewiston, Idaho without regard to the temperature above that point. While the extremes between a critical year and an average year would cause some differences in temperature at Burbank (confluence with Columbia River) these temperatures are expected to range from 23 to 24°C for two to three months every summer. These high temperatures preclude consideration of once-through cooling except in conjunction with off-stream irrigation withdrawal and other ancillary systems beyond the scope of the study. The study also indicates that a relatively large thermal difference will exist under most years between the Snake and the Columbia River during critical fall Salmonid migration periods and suggests that the combination of a cooler Columbia and a warmer Snake would tend to emphasize trends which are currently thought to inhibit upstream migration in the early fall. It is concluded that except for special plants using dual cycle cooling systems the Snake River holds no promise for the use of once-through cooling of thermal electric generating stations. Further the Snake itself is a significant source of thermal input to the Columbia in critical months, ranging from 4 to as high as 8 GW_{th} ,⁽⁵⁾ and suggests that full development of the Snake River for hydro power is an important factor in the thermal modification of that river.

- The middle reach of the Columbia including the McNary, John Day, Dalles and Bonneville reservoirs is a critical thermal reach under most conditions of flow and weather. This is because the reservoirs slow the flow sufficiently to permit a high degree of equilibration in an area with relatively high air temperatures. Therefore, as indicated previously, under existing standards, relatively little capacity can be computed to exist under 12 month or continuous conditions. However, the extent to which equilibration would be expected to occur also increases the probability that stream temperatures will increase to the 70 to 72°F level in most years, independently of local weather and to some extent upstream practices. However, within a given increment, say 1.1°F a relatively large capacity can be identified. For example, on McNary reservoir, some 12 to 15 GW_{th} of capacity exists. Thermal additions of this amount at that location would increase Bonneville water temperatures by less than 2.0°F while at the same time, natural increases, including heat from the Snake, would increase temperatures by 4.5°F in any event. On this basis, it is believed that some 10 to 15 GW_{th} of capacity can be said to exist for average flow from September through June or 10 months out of the year. This amount of incremental thermal addition would not increase the maximum temperature of the Middle Columbia by more than a standard deviation of the normal weather variations, approximately 1.4°F at Bonneville Dam. It is concluded that while some 10 to 15 GW_{th} can be stated to exist on the Middle Columbia, the potential for development is completely related to water management plans for the post Columbia Treaty system. Efforts to fully-integrate thermal modification and flow modification for the Upper Columbia will have direct and corresponding benefit on the Middle Columbia.

- As previously discovered in studies for Portland General Electric ⁽⁴⁾ and as stated above, as the Columbia nears its mouth, conditions for location of thermal plants within limits of present water quality criteria are less promising. This is so primarily because of uncertainties regarding the interpretation of these criteria with respect to flow modifications, both natural and controlled for the Columbia River as a whole, and the Lower Columbia in particular. Therefore, while an interesting numerical exercise could be accomplished using the MAXPWR routine, it was concluded that there is no basis for establishing a capacity for the Lower Columbia River without interpreting the existing state standards. This latter task is beyond the scope of this report. It is believed however, that the facts related to water management practices have been sufficiently identified such that their relationship to future use of the Lower Columbia for once-through cooling is evident and that integrated management practices which are viable for the upper reaches will have commensurate benefits in the Lower River as well.

REGIONAL POWER SITUATION

Because of the unique relationship of the regional hydro resources to the future need for thermal plants in the Pacific Northwest, and for the benefit of those not acquainted with the local situation, this section is a review of the need for power in the region drained by the Columbia River and its major tributaries.

LOADS

Electric energy use in the West Group Area of the Northwest Power Pool more than quadrupled in the 20 year period from 1950 to 1970, (Table 1). The residential energy load, which accounts for about one third of the total electric energy use in the area,

TABLE I

Electric Power Requirements by Major
Consumer Categories in the Pacific Northwest
(West Group Area)

(Data From Power Outlook Bonneville Power Admin. 1971)

	Actual			Estimated	
	1950	1960	1970	1980	1990
Population <u>1/</u>	4,674,671	5,489,729	6,435,000	7,104,000	8,311,000
No. Domestic Consumers	1,072,628	1,406,903	1,985,569	2,461,000	3,161,000
No. Commercial Consumers	140,401	176,807	241,860	310,000	399,000
<u>KWH Per Consumer</u>					
Domestic	5,112	9,841	13,831	19,300	24,600
Commercial	16,799	29,143	50,035	72,600	95,900
<u>Energy Sales (billions of kwh)</u>					
Domestic	5.5	13.8	27.5	47.5	77.7
Commercial	2.4	5.2	12.1	22.5	38.3
Industrial	11.1	22.3	44.1	74.7	118.0
Irrigation	.1	1.0	2.6	5.0	9.0
Other	.6	.8	1.4	2.0	5.0
Total	19.7	43.1	87.7	151.7	248.0
Losses	3.1	4.7	9.6	15.2	24.5
Total Requirements	22.8	47.8	97.3	166.9	272.5
Ten Year Annual Growth Rates	7.7%	7.5%	5.5%	5.0%	

1/ States of Washington, Oregon, Idaho, and western Montana

was greater in 1970 than the total electric load in the area in 1950. Residential average consumption of 13,831 kw-hr/year is the highest in the nation. Figure 2 shows the energy breakdown by sub-regions forecasted through 2000 AD.

Total peakload and energy loads are estimated to increase at a rate of 5.2% per year over the 20 year period through the 1991-92 fiscal year. This represents a considerable slowing in area load growth which increased at a rate of 7.6% a year during the past 20 years. It is considerably below the the 6+% a year average load growth for the next 20 years which the Federal Power Commission forecasts for the Nation. Of the 5.2% per year load increase predicted for the Pacific Northwest, only 1.25% per year is currently assessed against population growth on a constant consumption per person basis. The rest derives from increases in per capita consumption.

PACIFIC NORTHWEST HYDRO-THERMAL POWER PROGRAM

Under the leadership of the Joint Power Planning Council, the public and private utilities of the Northwest have created a regional plan for the optimum use of generation capability with a minimum of duplicative effort and cost to the public. The Hydro-Thermal Power Program is designed to achieve optimum combination of the region's generating and transmission resources, federal and non-federal, public and private to meet regional power requirements reliably, economically, and with effective attention to protection and enhancement of the environment.

The scope of the system under consideration is gained from the geographic arrangement (Figure 1) of the major hydro installations which form the present backbone system, and the interconnected transmission system of the Northwest Power Pool, Figure 3.

FIGURE 2. Pacific Northwest Power Forecast
1965 to 2000 A.D. - by FPC Subregions (Battelle Estimate)

Figure 3 Schematic of Major Transmission
In Pacific Northwest (BPA Annual Report)

Presently, the regional system has installed peaking capability of 21.3 GW, 94% of which is hydroelectric. Two newly completed coal fired thermal plants at Centralia, Washington have added 700 net MW to the gross 1.22 GW of thermal in the entire region. This excludes 800 MW at the Hanford N-reactor which is used primarily for energy generation when available.

1971-72 TO 1981-82 OPERATING YEARS

Additional peaking capacity of approximately 15.1 GW is required to be added in this period. Of this, 52% will be hydro peaking capability and 48% thermal base load capacity. The additional energy capability required in the period is 7.6 GW. In contrast to the present situation, the hydro-generated energy will supply only 25% of the energy requirements, and the new thermal plants will be used to supply 75% of the incremental energy needs. Most of the hydro plant additions and new projects are in federal installations which are either under construction or authorized. Toward the end of the period, some uncertainty is involved because of the doubtful availability of federal funding for continued expansion of hydro generation capacity. In the event short term shortages occur, any deficits would be made up using gas turbines; and such units are currently under order to meet temporary deficits in 1974-75.

1981-82 TO 1991-92 OPERATING PERIOD

During this period, additional peaking capacity of 25.6 GW are needed. Of this amount, 33% would be hydro and 67% thermal, by present estimates. The additional energy capability required during this 10 year period is about 13.5 GW. Of this, only 9% will be derived from hydro, the balance of 91% or 12.3 GW coming from new thermal capability. As the station siting plan matures, it is expected that multiple unit installations would be proposed

for sites already operating. At this stage, environmental considerations related to once-through cooling may have to be considered, and other locations considered which are more suitable for heat disposal. In any event, single unit size is expected to increase to the 1500 MW size by 1990.

From a transmission cost standpoint, the optimum location for the required thermal generation is west of the Cascade mountains. This is true only if the present population distribution trend is sustained and amplified. Newly stated national goals suggest that distributed population and the development of new cities offers much in the way of distribution of amenities, particularly in conjunction with environmental issues which may limit west side siting. The area east of the Cascade mountains will most probably be strongly considered. In addition, to the transmission required in this period, extensive installations will be needed to bring power capability to load centers from new hydro peaking facilities planned for this time under the Hydro-Thermal Program.

BACKGROUND REVIEW OF RELATED STUDIES AND PHYSICAL FACTORS

THE COLUMBIA TREATY (See Reference 6)

Commencing in 1944, and continuing through a number of phases, negotiations leading up to the present Columbia Treaty were carried out on a continuous basis until the present treaty and protocol were signed on January 17, 1961. The United States had early foreseen that any extensive firming up of planning for full management of Columbia River flows must of necessity include the Canadian government. Since a number of planning options which included diverting the Columbia into the Fraser River were considered in the negotiation period, it is understandable that the final agreement represents a series of compromises between the two governments. In the treaty, the United States

obtained additional protection from periodic flooding by means of Canadian reservoir space. In return, the United States and Canada agreed to share in downstream benefits which permitted increased electrical generation by shaving the peak flows during the annual freshet and later use of this water during the fall and winter when the electricity was badly needed. A number of other factors involved in the treaty have preserved the joint rights of the two nations to carry out inter-basin diversions, to agree to value of downstream benefits, and to reopen the protocol for the future management of water quality. At the present time however, water quality considerations are not an official part of the treaty.

The primary goal of the treaty is the reduction of maximum flood flows of the Columbia at the Dalles to 800,000 cfs. In order to do this, a total of 17.5 million acre-feet of storage are needed. At the time of signing the treaty only 10.8 million acre-feet were available to the Corps on the river for this purpose. An additional goal established by the United States was an attempt to control the Dalles flood flow to 600,000 cfs. As signed, the treaty provides for 15.5 million acre-feet of storage of which 8.75 million are assigned to flood control. The treaty provides that the United States, in return for compensation, can call on the Canadian government for additional storage operation within the 60 year period since the facilities actually built will reduce floods at the Dalles to some 720,000 cfs. The goal of flow reduction to 600,000 cfs is used as the basis for permitting a wide latitude in the degree of Canadian management options related to a given flood control situation, and as a basis for determining compensation. From a technical standpoint however, these options have not considered the effects of such management on water quality, and for this reason represent a potential problem remaining for resolution.

Figure 4 indicates the historic distribution of average Columbia River flow at the International Border and the extent to which the hydrology is expected to be modified under provisions of the Columbia Treaty. The availability of large quantities of hydro energy in the winter period is a significant feature of the treaty. The 15.5 million acre feet of storage to be provided by the Canadians is to be operated at the discretion of Canada within the flood control obligations and the negotiated regulations for the disposition of downstream power benefits. The treaty provided for a lump sum payment of \$254 million for power benefits calculated in advance which included both capacity as such and the added increase in average annual usable hydroelectric energy. In making these calculations of downstream benefits the Canadian storage is to be considered as serially incremental and quoting from the treaty, "The hydro-electric facilities included in the base system shall be considered as being operated to make the most effective use... of the improvement in stream flow..." When currently planned Canadian generation facilities are added as markets develop, reductions up to 500,000 acre-feet in storage per year are authorized up to a maximum of 3 million acre-feet. An essential principal of this is the provision for reopening of the benefit assessment as these relatively modest changes are made.

Other provisions authorize construction of Libby Dam and the flooding of Canadian lands, for which a compensation agreement is outlined. An important consideration is provision for diversion of the Columbia at its headwaters in the vicinity of Canal Flats up to as much as 1,500,000 acre-feet each year. This latter diversion can commence within 20 years after signing of the treaty. After 60 years, but before 100 years, Canada can exercise right to diversion of all Kootenay River flow greater than natural (unregulated) or 1000 cfs, whichever is the lesser. And finally, other interbasin diversions can be made provided that the uses are consumptive and related to non-hydro power or navigation objectives.

Neg. No. 0692683-2

FIGURE 4. Breakdown of Hydrology at the International Border
(BPA Data - 1969)

The Columbia Treaty represents a significant advance in the joint utilization of interdependent resources by adjoining countries. However, Utton in his review of the Treaty points out, the following:

"All of the physical, economic utilization and engineering considerations of the water resources system as a whole must be taken into account in order to achieve the optimum utilization. The administrative agency must be able to take into account all of the characteristics and technological characteristics of the water system. It must be able to look at the whole range of alternative ways of meeting the needs for water and water-related products, and its jurisdiction must be regional, although its real jurisdiction should vary with different uses. For example, the effect of discharges of waste may not extend beyond the basin, but the economic effect of the development of hydroelectric power may extend well beyond the drainage basin."

The statement suggests that the large temperature differences in the Columbia River which will result from the final completion and operation of facilities authorized under the Columbia Treaty are at present a moot point in the resolution of joint operating plans which are to be implemented. The question of downstream benefits from such cooler discharges is also a question for resolution, particularly if valuable options are involved.

AEC SUPPORTED STUDIES

During the period 1958 through 1970, a number of studies of the Upper Columbia were made as part of the production operations research for the Hanford plant. These studies were concerned with the prediction of the thermal regimen of the Columbia River in order to relate the effects of plant operational planning to anticipated conditions. In addition, during period 1958 through 1965, a special program of late summer tube releases was carried out

in order to cool the Columbia River during late July and August in order to permit a greater thermal differential for production purposes. The results of the program are contained in a series of reports which are summarized in Reference 7. The evaluation of the use of selective discharges from Lake Roosevelt to cool the Columbia River indicated that the erection of new dams at Rocky Reach, Wanapum and Priest Rapids, as well as difficulties in program management had vitiated the benefits of the program which in earlier days were quite successful in cooling the main stem by from 1 to 2 degrees in August. The essential value of the program was the development of the COL HEAT computer code and the determination that the Columbia River is quite slow in responding to thermal changes. For example under 1965 development conditions, a one degree C change introduced at Grand Coulee was only 15% dissipated in summer and 35% dissipated in winter by time the water mass reached the Hanford plant. Further the studies showed that travel time was a more significant factor than thermal differential in determining the extent of equilibration.

One of the outgrowths of the program was a study of the seasonal shifts of the temperature at key point on the Columbia River as a result of the erection of dams. The period of study included the entire historical period starting with the erection of the Rock Island Dam at River Mile 453.3. The work has been summarized in a number of publications of which the most recent is BNWL-1345, Effect of Hanford Plant Operations on the Temperature of the Columbia River published in November 1970.⁽⁸⁾

Some of the principal conclusions of the up-stream portion of this summary analysis were as follows:

- A sharp and permanent change in the timing of the peak temperature at Rock Island occurred commencing with the filling of Lake Roosevelt in 1941-1942. The permanent change amounted to about 30 days, the average transport time for the mean annual flow through Lake Roosevelt.

- This sharp and permanent shift is also observed at Bonneville Dam although to a lesser extent. The two projects reveal surprisingly similar shifts in response to annual weather cycles. While the Rock Island peak has stabilized at about September 20, the Bonneville peak has continued to occur later and later as longer and longer flow times result from the addition of upstream projects. The close relationship of McNary and Bonneville indicate little or no cooling takes place in the reach between these projects.
- The values for the Priest Rapids Project closely resemble peak temperature patterns for Rock Island. The data differences of about 7 to 10 days appear to be related to the travel time through Wanapum and Priest Rapids reservoirs in about the same manner as Grand Coulee.

The methods used for the statistical handling of data in these comparisons involved special non-linear regression models. These are described in a paper by Jaske and Goebel in 1967.⁽⁸⁾ Figures 5 and 6 which are an extension of the data reported in References 8 and 9 illustrate the long term trends described above.

STUDIES FOR PORTLAND GENERAL ELECTRIC COMPANY (Reference 4)

In 1967, as a part of the preliminary activities which led to the construction of the Trojan reactor as part of the Hydro Thermal Program, a series of studies was authorized to investigate the extent of downstream thermal benefits which might be expected from normal, (unoptimized for any water quality needs) operations of the Columbia Treaty system. Since the conclusions of the PGE study form the basis for much of the information in this report, it appears appropriate to review the previous work and the specific output from the analysis.

COMPUTED TEMPERATURE TRENDS - 1938-1970

Neg. No. 711667-3

FIGURE 5. Fitted Upper and Lower Extremes and Means for Two Points on the Columbia River. Fitted Data for Warrendale Superimposed to Verify Extent of Error in Bonneville Data. Data Fitted to the Expression $T = \bar{T} + B \sin(0.0173d + D)$ See Reference 8.

COMPUTED PEAK ARRIVAL DATES - 1940-1970

Neg. No. 711667-1

FIGURE 6. *Fitted Times of Arrival of Temperature Maximums Showing Effects of Dam Construction and Weather Related Factors Governing Yearly Trends and Relations Between Weather Coupled Basins. Data Fitted to the Expression $T = \bar{T} + B \sin(0.0173d + D)$ See Reference 8.*

The essential features of the study of the Columbia Treaty Dams for PGE were as follows:

- A compilation of thermal profiles for the Arrow Lakes and the supplementary addition of vertical profiles for Kootenay Lake were accomplished to determine the mode of flow of the Kootenay River from a thermal standpoint.
- Using the Corps of Engineers CF-1980 30 year reservoir simulation plan, and a linear programming model with appropriate queing relationships and the thermal inventory relationships developed from field measurements, a temperature for each of the six months of the year with warmest water temperatures was estimated below Grand Coulee Dam. Statistical tests applied to this water temperature array indicated that after releases are made at the United States border water temperature was not coupled to weather, except weakly. The principal factors were net basin supply and the historical sequence of weather-related, volume management factors.
- The thermal output below Grand Coulee was then routed down the Columbia River using the COLHEAT simulation model. (See Figure 7) Statistical test were applied to a 30 year array of weather and hydrology data and it was determined that for the Columbia River, weather and hydrology are weakly correlated, but that flow was strongly correlated with net basin supply, including the Snake. (See Appendix for data compilations from Reference 4.) As a part of this analysis it was necessary to develop a statistical basis for the decoupling of hydrology and weather for heat transfer analysis. The study determined that the use of 1965 weather data with Snake River hydrology from the CF 1980 study was an admissable procedure.

COMPARISON OF MEASURED VERSUS SIMULATED TEMPERATURES
AT PRIEST RAPIDS DAM AFTER TRANSPORT FROM GRAND COULEE DAM. (196-MILES)

Neg. No. 693938-6

Figure 7. Simulation Test of COLHEAT Regional Model

- At this point in the analysis it was necessary to consider the effect of the Hanford plant. For purposes of the investigation, advected heat equal to the maximum permissible under Washington State standards was used for the combined effect of nature and industrial development in the reach between River Miles 394 and 325. The details of this procedure are fully developed in the reference report.
- The CF-1980 flows with adjusted and routed thermal effects from the Columbia were then routed downstream to a number of locations of interest to Portland General Electric Company using the COLHEAT simulation model. By superposition, the effects of the advected energy from the Hanford reach were also estimated at River Mile 146.4, Bonneville Dam.

As a result of the study procedure above, the following conclusions of interest to this report were drawn:

- General "Significant temperature reductions will result from normal, unoptimized operation of the Columbia Treaty dam system. These benefits will be very pronounced in the upper Columbia River above the confluence with the Snake. Due to the extended travel time between the Canadian border and the mouth of the river at Astoria, most of these temperature benefits will be equilibrated by the time a given water mass reaches the Bonneville pool. The two key factors underlying this extensive equilibration are the rising Snake River temperatures and the John Day storage. The study also shows that the effects of the measured perturbation of the temperature record occurring between Priest Rapids Dam and the city of Richland (the Hanford plant reach) are largely dissipated in the summer period before the water reaches Portland under 1975 conditions...."

Figures 8 and 9, taken from Reference 4, show the effect of the Columbia Treaty dam system on the expected water temperatures at Priest Rapids dam and at Bonneville dam for the study conditions specified above. The figures serve to emphasize the rather large reductions which would remain as far down stream as Priest Rapids River Mile 394 or even the city of Richland River Mile 333, but that a majority of these would be dissipated by equilibration as far down stream as Bonneville Dam, River Mile 146.4. Lastly, the report illustrated that natural heat transfer accounts for a majority of this equilibration because a net advection ranging to as high as 19.3 GW in the Hanford reach as a combination of natural and industrial effects was about 80 to 85% dissipated at the Bonneville Dam outlet. Figure 10.

DISCUSSION OF RESEARCH

DEVELOPMENT OF INITIAL TEMPERATURE AND WATER MANAGEMENT BASES

Previous studies conducted for the Atomic Energy Commission and Portland General Electric Company have led to the conclusion that a relatively significant modification of the natural temperature regimen of the Upper Columbia River, above the International Border, can be expected. Although a detailed review of the PGE study⁽⁴⁾ is not possible here, that study used the following methods to establish the data arrays in Appendix A.

Based on information available at the time, in the form of Corps of Engineers water management studies for flood control and power optimization of which CF-1980 was a typical example, and using the thermal history of the Upper Columbia River, (Bureau of Commercial Fisheries, unpublished), (10) the information was programmed into a linear programming model

Neg. No. 0692683-8

FIGURE 8. Day by Day Comparison of Predicted Post Columbia Treaty Water Temperatures with 1961-67 Daily Average Below Priest Rapids Dam - Columbia River Mile 392.0

Neg. No. 0692683-9

FIGURE 9. Predicted Temperature Envelope at Bonneville Dam
for Operational Conditions after 1980.
From Reference 4

Neg. No. 0692683-10

FIGURE 10. Sensitivity Analysis - Comparison of Predicted Average Temperatures at Bonneville Dam With and Without the Addition of Energy in the Hanford Reach

which solved the queing relationship of the various inputs to the net basin supply and in relationship to their temperature estimates, produced a synthetic record of anticipated temperatures below the Columbia Treaty Dam system below the outlet of Grand Coulee. Appendix Table A-7.

Other supporting analyses in the PGE study were concerned with the identification of the degree of conservatism of the thermal changes in passing the Arrow Lakes. Contrary to popular conception, and despite surface temperatures which measure relatively high in the vicinity of the Dams the movement of water through the Arrow Lakes and Grand Coulee is not confined to the upper surface layers, but consists of an integrated sample of all depths down to the maximum density isopleth at 4°C. On the basis of the PGE studies it was possible to conclude that the surface water above the thermocline consisted of only a small fraction of the total flow, and that the use of a queing model was justified. The numerical analysis of the relative surface area of the Arrow Lakes and Lake Roosevelt supported the established fact that weather changes during time of travel through the reservoirs cause only minor changes in temperature differential on an annualized basis.⁽⁹⁾ These observations were confirmed by the results of the two year study performed by Battelle for the Office of Water Resources Research.⁽¹⁰⁾

In Reference 11, A Three Dimensional Study of Parameters Related to the Current Distribution in Lake Roosevelt, detailed current measurements verified the conceptual notion expressed above: the mean sample of water noted as penstock or spill discharge consisted of a sample integrated over a considerable depth. The distribution of heated water in the vertical sample was a function of reservoir velocity. The study also demonstrated that the thermal regime was essentially decoupled from the hydraulic regime and that treatment of either could be done mathematically separate provided continuity was rigorously maintained.

Using the method of Jaske and Goebel,⁽⁹⁾ use was made of the non-linear code LEARN-LIKELY to statistically fit annual sine curves to the available temperature data for the Columbia River above and below Grand Coulee Dam. A complete description of this methodology is contained in report BNWL 1345, Effect of Hanford Plant Operations on the Temperature of the Columbia River.⁽⁸⁾ The annual temperature data is fitted to a function of the form:

$$T = \bar{T} \pm B \sin (Cd + D) \text{ where:}$$

T is the temperature on the day desired

$\bar{T}$ is annual mean

B is a fitted rotating vector such that $\bar{T} + B$ is a fitted, annualized maximum and $\bar{T} - B$ is a fitted, annualized minimum

C is a coefficient equal to $2\pi/365$ radians/day

d is the number of the desired day

D is a displacement term which locates the fitted maximum in time. (In radians)

Figures 4 and 5 are illustrative of the trends observed using the fitted functions developed in Reference 8. These and other details support the procedural method of establishing the relationship of annual sets of water temperature data and the adjustment of these data sets for the purpose of long range planning.

Taking advantage of the methods described above, the procedure was used to develop projected inlet temperatures for the Columbia River at the International Border. These predictions are essential to the initiation of the use of the thermal capacity of the Columbia River.

Actual data for the years 1966 and 1970 for two locations, International Border (Northport) and Grand Coulee are illustrated in Figure 11. The fitted functions describing these data sets are as follows:

FIGURE 11. Comparison of 1966-1970 Monthly Means for Northport and Grand Coulee with Predicted Post Columbia Treaty Monthly Means at Northport and Grand Coulee

Grand Coulee	1966	$T=10.4 + 6.48 \sin (0.0173d + 3.51)^{\circ}\text{C}$
Grand Coulee	1970	$T=10.6 + 7.84 \sin (0.0173d + 3.69)^{\circ}\text{C}$
Northport	1966	$T= 9.3 + 6.66 \sin (0.0173d + 3.88)^{\circ}\text{C}$
Northport	1970	$T= 9.3 + 7.80 \sin (0.0173d + 4.05)^{\circ}\text{C}$

By inspection it can be determined that the difference between the two locations is confined to the annual mean term and that weather patterns which cause the rotating vector to be larger in 1970 affect both data points equally. The fitted functions reveal that the mean thermal rise through Lake Roosevelt is on the order of 1.1 to 1.3°C and that the warm conditions of 1970 all originated in the temperature of the water supply north of the border. In fact, because of water supply management practices involved in the filling of the Arrow pool in the summer of 1970, temperatures reached all-time highs for that location.

As a next step, the output of the Portland General Electric study was fitted using the GENORO code which predicts a sine configuration for a partial year set. Using some manual adjustment, two curves for the predicted temperature patterns at the International Border and at Grand Coulee for the post 1980 period were generated. The Northport mean is displaced downward by 1.1°C and the time of arrival of the peak by 0.35 radians or about 20 days, the mean travel time through the Lake Roosevelt reservoir for the two years under study.

The temperature predictions for post-1980 average conditions are superimposed on the 1966 and the 1970 records in Figure 11. Based on the variances computed for the PGE study, the standard deviation for each month was then calculated. The Grand Coulee curve expected for post-1980 conditions is again illustrated in Figure 14 and curves generated above and below the average curve for two standard deviations from the mean. The envelope of the two curves shows that there is a 95% chance that all data expected in the future will fall

in the envelope of values. These values shown in Figure 12 became the key initiation points for all of the MAXPWR runs made downstream of Grand Coulee. Because of the somewhat tenuous nature of the Northport prediction, the Lake Roosevelt segment was treated as an entity, and downstream data generated were imposed as thermal differentials rather than absolute temperatures because of the approximate nature of the Northport thermal curve used in Figure 11.

Having accomplished an essential task, that of generating a starting point based on a combination of measured and study simulations, the next step of the research was to develop the array of cases which would be carried from the Canadian border to Bonneville Dam. Cases below Mile 140 do not appear justified under present regulatory policy.

CASE ARRAY AND DESIGNATIONS

Four sets of variables were considered as the significant variables for the case array under investigation. In addition, the computations made use of weather data files compiled by Battelle during a number of investigations of stream temperature simulations. The experience gained in the past in the identification of the strength of variables was utilized to minimize the number which needed consideration. An essential feature of this step was the use of the Spearman Ranking Coefficient to determine the rank correlation of the various input parameters. Examples of the use of the ranking coefficient are included in Appendix Tables A-3, A-4, A-5, and A-6. From these computations and the previously published information in the PGE report, the following guideline conclusions were drawn.

- Temperature of the air as an independent variable is only weakly correlated with the water temperature of the Columbia River above Mile 324.5, Pasco. This should not be interpreted to state that weather is

FIGURE 12. Comparison of Post Columbia Treaty Monthly Means for Northport and Grand Coulee and Standard Deviations of Means with Washington State Standards

not a factor in net basin supply, but rather that in separating the variables once net basin supply is assured, the degree of influence of weather on the temperature of the water above Pasco is largely a function of flow or artificial advection in the form of thermal plants.

- No strong correlation between the expected temperature array at the International Border and the air temperature or solar radiation could be developed. Rather, the temperature of the water emanating from the Columbia Treaty system is largely a function of the flow volume, flood control practices, net basin supply and other factors such as upstream advection. This suggests that curtailment of water supply to fill reservoirs is a much more significant variable than differences between hot and average summer temperatures.
- Because of the long travel times in the Snake River system in the fully developed condition after completion of the four low head dams on the Lower Snake, there is a high and direct correlation between the temperature of the water and the annual differences in the weather. This suggests that the Snake becomes relatively fully equilibrated in comparison to the Columbia and has little or no thermal capacity in relation to the Columbia which is not fully equilibrated under normal circumstances at the mouth.
- The 30 year record reveals a relatively direct relationship between net basin supply in the Snake and Columbia Basins. While far from strong, the correlation suggests that critical flows, Appendix Table A-6, have a reasonable probability of occurrence simultaneously in both basins, and that high water temperatures could be expected from this occurrence.

Using these relationships as a guide, Table 2 was developed to design the various cases for study. Comments on each of the three sets follow:

Lake Roosevelt Cases

Cases 1, 2, 3 and 6 were the only ones used because the previous studies had shown low sensitivity of the results to local weather variation. Therefore, the average weather data cases were not run. Similarly, the test design matrix was selected to emphasize differences between critical flow and average flow and differences between average and high ($+2\sigma$) water temperatures emanating from the Columbia Treaty system. The Δt allowable under state standards was computed on the basis of being consistent with the water temperature conditions.

Grand Coulee to Mouth of Snake

Hot and average weather was retained as an independent variable for this array to demonstrate the low effect of local weather on the case array. In computing the allowable Δt under state standards, the input heat from the incoming reach was added, thereby reducing the total allowable permitted. The term Δt_H is used to describe the computed allowable difference under high temperature conditions. Because the differences between Δt for high and average water temperatures were very small, the smaller or more conservative value was used in all case runs in this reach. The other case combinations, 1-8, are self explanatory and seek to demonstrate the strength of the independent variables (flow, initial water temperature, local weather). No cool weather, high flow or abnormally low water temperature conditions were investigated for the sake of being conservative.

The critical year and average year flow cases were derived from the Corps of Engineers Study NP-7-1970-80 which was made available to the author by the North Pacific Division,

TABLE 2

Case and Nomenclature Identification

Q_C	- Flow Critical (1936-37)
Q_A	- Flow average (30 years)
T_H	- Water Temp - Upper Extreme ($T_a + 2\sigma$ - Ref 4)
T_A	- Water Temp - Average Cond. (Ref 4)
W_H	- Climatic Conditions - Upper Extreme (1958)
W_A	- Climatic Conditions - Average (30 years)
Δt_H	- Allowable Under T_H Conditions (Wash. State Std.)
Δt_A	- Allowable Under T_A Conditions (Wash. State Std.)

Lake Roosevelt Cases

<u>Case</u>	<u>Flow</u>	<u>Inlet</u>	<u>Weather</u>	<u>Δt °C</u>
1	Q_C	T_H	W_H (Spokane)	Δt_H
2	Q_A	T_H	W_H (Spokane)	Δt_H
3	Q_C	T_A	W_H (Spokane)	Δt_A
6	Q_A	T_A	W_H (Spokane)	Δt_A

Grand Coulee to Mouth of Snake

1	Q_C	T_H	W_H (Hanford)	Δt_H^*
2	Q_A	T_H	W_H	Δt_H
3	Q_C	T_A	W_H	Δt_H
4	Q_C	T_H	W_A	Δt_H
5	Q_C	T_A	W_A	Δt_H
6	Q_A	T_A	W_H	Δt_H
7	Q_A	T_H	W_A	Δt_H
8	Q_A	T_A	W_A	Δt_H

Mouth of Snake to Bonneville Dam Outlet

(As Cases Above)

Snake River Flows Follow Same Coding

* Minimum Allowable Δt Used for All Cases to Make Results Conservative.

Portland, Oregon. The critical year used in this report is a synthetic year which consists of the 12 month series used in the federal fiscal year comprising the last half of CY 1936 and the first half of 1937. This combination represents the most probable combination of the lowest flows which might be expected from the post Columbia Treaty water management plan as it stands today. The actual numerical values for points from the International Border to Bonneville Dam are listed in Appendix Tables A-1 and A-2.

Middle River Below the Snake

The case identification for the Middle River follows the same pattern as for the Upper River and for the same rationale. Data for all eight cases were actually run on the computer model although only the data from the high temperature weather (actually 1958 weather) were used. The differences between weather sets were found to be trivial when used for thermal predictions in comparison with the other independent variables of flow, water temperature upstream, and net basin supply.

Weather Data

Two sets of weather data were developed from a historical series used by Battelle on a number of Columbia River simulations. The PGE study showed the justification of the use of 1958 as the highest single year on record.⁽⁴⁾ Other studies have indicated the relationship of major weather areas in the Pacific Northwest, and accordingly, in the Lake Roosevelt simulations, Spokane weather was used for both average and 1958 conditions. Hanford 1958 weather for both the high and the average was used for all runs down to Bonneville Dam. The justification for this procedure has been previously established in a number of reports by the author.^(4,7,8)

THERMAL CAPACITY OF LAKE ROOSEVELT

The initial step in the estimation of the capacity of Lake Roosevelt was the testing of the MAXPWR version of COLHEAT using the flow regimen in Lake Roosevelt described in the Battelle report to the Office of Water Resources Research (OWRR).⁽¹¹⁾ The report determined, among a number of other facts, that the majority of the flow regimen of the Lake is confined to an upper layer of about 100 feet in depth. Using this assumption, and the homogeneous nature of the upper flowing layer, the use of the COLHEAT model was justified. In the final ten miles of the reservoir, as the effects of submerged discharge through the penstocks begin to be felt, this justification could not be used. However, since the last ten miles contributes little if anything to the heat budget of the reservoir system, it was assumed that for purposes of capacity estimation all of the surface (or upper 100 feet) would be discharged through the penstocks and no credit was taken for the mixed conditions described in detail in the OWRR report. Yearly simulations run with COLHEAT were within 1 to 2°C under these admittedly crude conditions of modeling, but the objective was to determine differential capacity rather than absolute temperatures. The test results revealed that equilibrium temperatures of the surface of Lake Roosevelt computed for monthly averages were essentially identical by the COLHEAT model as with manual methods. As indicated above, the evaluation of the differentials was the essential feature of the work and it is believed the technique used produced estimates accurate to $\pm 5\%$ for the weather and flow data available. Original computer runs used to establish this procedure are on file for inspection by those desiring additional information.

The four cases simulated are described as cases 1, 2, 3, and 6 in the case listing of Table 2.

The next step was to compute the allowable differentials under Washington State Class "AA" standards on a month-by-month basis. The computations were made using the standard formula published by the state (see Table 3 for the formula and the monthly computations resulting). Allowable differentials were computed using the synthetic Northport record generated earlier, and displayed in Figure 11 as input, and the maximum allowable temperature of 15°C as the upper maximum. Two sets of values were generated: one for the average cases and one for the high temperature prediction which was two standard deviations higher than the average set. It should be noted that under the high temperature conditions which might occur less than once in 15 years, no thermal effluent could be released to the Lake in July, and only small, impracticable amounts in August.

Using the case definitions described above and in Table 2, the four cases for Lake Roosevelt were then run and the information organized for presentation. Case 3 was dropped from the report because it did not add information which was useful since all values were within sensitivity ranges reported in Cases 1, 2 and 6. The three case outputs are plotted on a month by month basis in Figures 13, 14 and 15.

The MAXPWR routine reports two types of capacity separately and then summarizes them into an integrated total for the total reach under examination. The so-called "upstream capacity" is computed first on the basis of allowable Δt . In effect this step computes the total power which could be released under the average flow conditions to raise the stream temperature by the amount stated in Table 3. The next step is to route the warmed flow downstream allowing the water temperature to react with the atmosphere. If conditions are favorable for cooling, the stream will cool down to a point where sufficient incremental decay of the original thermal elevation occurs. A previously programmed plant size (in all cases in the study the value of 1500 MW was used) is then reinserted

FIGURE 13. Worst Case Thermal Capacities Under Existing Washington State "AA" Stream Standards

FIGURE 14. Effect of Average Weather on Capacity of Lake Roosevelt Under Existing Washington State "AA" Stream Standards

FIGURE 15. Effect of Average Flows and Weather on Capacity of Lake Roosevelt Under Existing Washington State "AA" Stream Standards

TABLE 3

Wash. State Standards - Class "AA" Stream

$$\Delta t \text{ (Allowable)} = 75/(T-22) \text{ } ^\circ\text{F}$$

	<u>Temp. International Border</u>		<u>Allowable Δt</u>	
	<u>$\bar{T}^\circ\text{C}$</u>	<u>$\bar{T}+2\sigma^\circ\text{C}$</u>	<u>Average Condition, $^\circ\text{C}$</u>	<u>Aver + $2\sigma^\circ\text{C}$</u>
Jan	5.6	5.9	2.1	2.0
Feb	4.8	5.0	2.2	2.1
Mar	5.0	5.2	2.2	2.1
Apr	7.0	7.9	1.8	1.7
May	9.6	10.8	1.5	1.4
Jun	12.4	14.0	1.3	1.2
Jul	14.0	15.6	1.2	-0-
Aug	14.3	14.9	1.2	0.1
Sep	13.8	14.2	1.2	0.8
Oct	12.3	12.6	1.3	1.3
Nov	10.4	10.8	1.5	1.4
Dec	7.9	8.3	1.7	1.7

and the decay process allowed to take place again. This decay process is repeated until the bottom of the reach is located at which point the program summarizes the remaining increment not yet decayed (see illustration next page). Two reports are then issued, one totaling the upstream, or dilution capacity under the Δt and the other the total amount of thermal heat which has been decayed in the reach under examination.

Δt = INCREMENTAL ALLOWABLE BY STANDARDS FORMULA
 ΔT_o = OUTLET CARRYOVER (NET RISE IN TABLE 4)
 $\Delta \delta$ = INCREMENTABLE INCREASE FROM 1 ADDED PLANT
 CAPACITY = INLET CAPACITY @ Δt + DECAYED INCREMENTS

The results are compiled in Table 4 on a month-by-month basis. Only two cases are illustrated, the worst and the average to illustrate the basic capacity of the reach under present Class "AA" standards. An important advantage of MAXPWR is the separation of the two thermal components into categories of decayed and undecayed additions and the ability to adjust the definition of plant size, thermal increment, or any other desirable management variable at the will of the investigator.

In summary, the data reveal a surprisingly high amount of capacity under average conditions after the Columbia Treaty dams are in full operation. Thermal elevation of the lake would be limited by the standards formula to values less than 2.0°C in winter and less than 1.0°C in summer. Despite these stringent limitations, under conditions which would be met 75% of the time, some 20 GW of thermal capacity exists as a minimum, rising to 30 GW under more favorable conditions. Under conditions which would be seen in 95% envelope, a considerable reduction would occur in July

TABLE 4

Potential Capacity of Lake Roosevelt to Absorb
Thermal Loading After Columbia Treaty Dam Completion
1975 Conditions

Case 1 (Extremes)

	Maximum Upstream <u>Input GW_{th}</u>	Local Additions <u>GW_{th}</u>	Predicted Surf. Temp. <u>At Grand Coulee Dam</u>	Net Temp* Rise °C <u>Mile 596.6</u>
Jan	19.6	11.8	4.9°C	1.8°C
Feb	15.6	14.2	7.0	2.0
Mar	12.8	13.0	9.1	2.1
Apr	16.0	13.1	11.8	1.6
May	14.9	20.9	17.3	1.2
Jun	11.6	18.4	18.8	1.0
Jul	0.0	0.0	22.4	0.0
Aug	1.1	0.7	20.1	0.1
Sep	7.9	6.0	15.9	0.5
Oct	13.2	9.1	12.7	1.0
Nov	14.6	9.7	9.0	1.4
Dec	21.8	9.6	6.7	1.7

Case 6 (Means)

Jan	23.2	12.6	4.8°C	1.8°C
Feb	22.5	15.3	6.9	2.0
Mar	23.0	13.5	8.3	2.1
Apr	27.0	15.5	10.5	1.8
May	30.1	23.8	15.4	1.6
Jun	25.7	21.1	16.8	1.3
Jul	18.3	10.5	20.4	1.2
Aug	13.8	10.6	20.2	1.1
Sep	11.9	9.6	15.7	0.9
Oct	12.7	9.6	12.5	1.0
Nov	14.7	10.2	8.6	1.4
Dec	19.6	9.9	5.9	1.8

* Net Increase Over Estimated Discharge Temperatures Figure 5

and August. It is important to point out that the Case 1 extremes may have a probability lower than 5% since they consist of three independent variables subject to individual statistical control or modification. The 15°C upper limit is especially interesting, because elevation of this value by as little as 1°C would guarantee a thermal capacity of from 15 to 20 GW thermal in the Lake Roosevelt area within a 95 to 97% probability. The data suggest that the error limits on the measurements used to monitor compliance may carry sufficient variation to permit the existence or non-existence of very large amounts of thermal capacity without measureable modification of the ambient thermal regimen outside of established mixing zones.

THERMAL CAPACITY OF THE UPPER COLUMBIA RIVER, MILES 324 to 594

Having established incremental values of the net thermal addition from the Lake Roosevelt section of the Columbia, these values were then used to adjust upwards, the expected discharge temperature below Grand Coulee after completion of the Columbia Treaty Dam system. That is, for purposes of illustration, the cases assumed that an exploration of the upper limits of full development was the principal object of the test array. Using this policy, Table 5 was prepared as a guide in assembling input information for the computation of allowable thermal increments in the next lower reach. Two sets of monthly differentials were computed for the average and maximum probable upper limit cases ($\bar{T}+2\sigma$). Because the standard criteria formula requires an iterative computation, some trial and error is involved, but the guiding principal was to determine the maximum amount of thermal addition which could be sited within present standards using 1,500 MW thermal increments.

TABLE 5

Washington State Standards - Class "A" Stream
Columbia River - Grand Coulee Dam to Washington/Oregon Border
 Mile 394 to Mile 596 Δt (Allowable) = $90/(T-15)^{\circ}\text{F}$
 Mile 280 to Mile 394 Δt (Allowable) = $110/(T-15)^{\circ}\text{F}$
 Temp. $^{\circ}\text{C}$ Grand Coulee - Post Columbia Treaty Conditions - 1979-80

	Mean Cond No Heat(1) Added	Mean Cond Heat(2) Added*	Δt (3) t Allowable Mean Cond	High Water Temps(4) $\bar{T}+2\sigma$	$\bar{T}+2\sigma$ Heat(5) Added*	Δt (6) t Allowable +2 σ Cond.	Actual(7) $\Delta t'$ incl. $\Delta t'$ †
Jan	7.2	9.0	2.0	8.3	10.1	1.7	1.7
Feb	5.3	7.3	2.1	5.9	7.9	2.0	1.8
Mar	4.6	6.7	2.1	5.0	7.1	2.0	1.8
Apr	4.8	6.6	2.1	5.2	6.8	2.0	1.8
May	6.1	7.7	1.9	7.9	9.0	1.8	1.7
Jun	8.4	9.7	1.8	10.8	11.8	1.6	1.6
Jul	10.8	12.0	1.6	14.0	14.0	1.4	1.4
Aug	12.4	13.5	1.5	15.6	15.6	1.3	1.3
Sep	13.2	14.1	1.5	15.4	15.9	1.4	1.3
Oct	13.1	14.1	1.3	14.7	15.7	1.2	1.3
Nov	12.0	13.4	1.4	12.6	14.0	1.3	1.4
Dec	10.0	11.8	1.6	10.8	13.5	1.4	1.4

* See Table 4 for Thermal Additions in Lake Roosevelt

† Upstream Heat Increment

The output of the eight cases was plotted on a composite diagram. The data used in the development of the analog plots are listed in Tables 6 and 7. Inspection of the original analogue plot of the eight cases revealed a number of significant observations. The principal findings were as follows:

- The resulting data plots grouped into two families of curves which were principally flow-dependent. The four cases using critical flows showed very early thermal

TABLE 6

Summary of Thermal Inputs and Temperatures
Upper Columbia

Average Flow Conditions Cases 2 - 6 - 7 - 8

		Case 2				Case 6				Case 7				Case 8			
		Upstream Input GW _{th}	Local Add'ns GW _{th}	Temp M324.3 °C	Net Incr.* °C	Upstream Input GW _{th}	Local Add'ns GW _{th}	Temp M324.3 °C	Net Incr.* °C	Upstream Input GW _{th}	Local Add'ns GW _{th}	Temp M324.3 °C	Net Incr.* °C	Upstream Input GW _{th}	Local Add'ns GW _{th}	Temp M324.3 °C	Net Incr.* °C
Jan	a	20.3	9.5	8.8	1.5	20.3	9.2	8.2	1.5	20.3	8.5	7.8	1.5	20.3	8.3	7.1	1.5
	b	20.3	9.5	8.8	1.5	20.3	9.2	8.2	1.5	20.3	8.5	7.8	1.5	20.3	8.3	7.1	1.5
Feb	a	25.8	10.9	9.8	1.7	25.7	10.8	9.4	1.7	25.7	9.0	8.5	1.6	25.7	8.8	8.1	1.6
	b	25.8	10.9	9.8	1.7	25.7	10.8	9.4	1.7	25.7	9.0	8.5	1.6	25.7	8.8	8.1	1.6
Mar	a	26.3	10.8	9.9	1.7	26.3	10.8	9.6	1.7	26.3	9.9	9.9	1.6	26.3	9.8	9.6	1.6
	b	26.3	10.8	9.9	1.7	26.3	10.8	9.6	1.7	26.3	9.9	9.9	1.6	26.3	9.8	9.6	1.6
Apr	a	23.4	12.7	10.5	1.6	23.4	12.7	10.3	1.6	23.4	11.1	12.4	1.7	23.4	11.1	12.2	1.7
	b	23.4	12.7	10.5	1.6	23.4	12.7	10.3	1.6	23.4	11.1	12.4	1.7	23.4	11.1	12.2	1.7
May	a	25.0	12.7	16.4	1.5	25.1	12.3	15.6	1.5	25.1	11.4	15.2	1.6	25.1	11.1	14.4	1.6
	b	25.0	12.7	16.4	1.5	25.1	12.3	15.6	1.5	25.1	11.4	15.2	1.6	25.1	11.1	14.4	1.6
Jun	a	20.7	15.0	19.6	1.4	20.7	14.4	18.6	1.5	20.7	11.7	18.7	1.4	20.7	11.2	17.6	1.5
	b	20.7	15.0	19.6	1.4	20.7	14.4	18.6	1.5	20.7	11.7	18.7	1.4	20.7	11.2	17.6	1.5
Jul	a	18.9	13.9	21.4	1.3	18.8	13.3	19.9	1.1	18.8	10.9	20.6	1.3	18.8	10.1	19.3	1.1
	b	18.9	6.4	19.6	1.3	18.8	13.3	19.9	1.1	18.8	6.4	19.5	1.1	18.8	10.1	19.3	1.1
Aug	a	13.7	12.9	21.6	1.0	13.7	12.6	20.8	1.0	13.6	9.2	21.1	1.0	13.6	8.7	19.9	1.1
	b	13.7	3.2	19.8	1.0	13.7	6.4	19.9	1.0	13.6	3.2	19.8	1.1	13.6	8.7	19.9	1.1
Sep	a	12.7	12.6	17.5	1.0	12.7	12.4	17.1	1.0	12.7	7.9	18.8	1.1	12.7	7.7	18.1	1.2
	b	12.7	12.6	17.5	1.0	12.7	12.4	17.1	1.0	12.7	7.9	18.8	1.1	12.7	7.7	18.1	1.2
Oct	a	12.9	9.0	15.4	1.0	12.9	8.8	14.7	1.1	12.9	7.5	15.1	1.2	12.9	7.2	14.3	1.2
	b	12.9	9.0	15.4	1.0	12.9	8.8	14.7	1.1	12.9	7.5	15.1	1.2	12.9	7.2	14.3	1.2
Nov	a	13.6	10.3	10.0	1.3	13.7	9.8	9.5	1.1	13.7	6.6	11.2	1.0	13.7	6.5	10.9	1.1
	b	13.6	10.3	10.0	1.3	13.7	9.8	9.5	1.1	13.7	6.6	11.2	1.0	13.7	6.5	10.9	1.1
Dec	a	18.2	8.1	9.7	1.3	18.2	8.0	9.3	1.3	18.2	6.6	9.9	1.1	18.2	6.5	9.6	1.2
	b	18.2	8.1	9.7	1.3	18.2	8.0	9.3	1.3	18.2	6.6	9.9	1.1	18.2	6.5	9.6	1.2

a Without 20° Limit

b With 20° Limit

* Net Increase over Unheated Reach

TABLE 7

Summary of Thermal Inputs and River Temperatures
Upper Columbia
 Critical Flow Conditions Cases 1 - 3 - 4 - 5

		Case 1				Case 3				Case 4				Case 5			
		Upstream Input GW _{th}	Local Add'ns GW _{th}	Temp M324.3 °C	Net Incr.* °C	Upstream Input GW _{th}	Local Add'ns GW _{th}	Temp M324.3 °C	Net Incr.* °C	Upstream Input GW _{th}	Local Add'ns GW _{th}	Temp M324.3 °C	Net Incr.* °C	Upstream Input GW _{th}	Local Add'ns GW _{th}	Temp M324.3 °C	Net Incr.* °C
Jan	a	22.2	9.5	9.0	1.5	22.2	9.3	8.4	1.5	22.2	8.6	8.1	1.5	22.2	8.4	7.4	1.6
	b	22.2	9.5	9.0	1.5	22.2	9.3	8.4	1.5	22.2	8.6	8.1	1.5	22.2	8.4	7.4	1.6
Feb	a	19.4	10.8	9.8	1.7	19.4	10.6	9.5	1.7	19.4	8.7	8.2	1.6	19.4	8.7	7.8	1.6
	b	19.4	10.8	9.8	1.7	19.4	10.6	9.5	1.7	19.4	8.7	8.2	1.6	19.4	8.7	7.8	1.6
Mar	a	18.7	10.7	10.2	1.7	18.6	10.5	9.9	1.7	18.6	9.7	10.1	1.5	18.6	9.6	9.9	1.5
	b	18.7	10.7	10.2	1.7	18.6	10.5	9.9	1.7	18.6	9.7	10.1	1.5	18.6	9.6	9.9	1.5
Apr	a	13.4	12.3	11.3	1.4	13.4	12.2	11.2	1.4	13.4	10.9	14.2	1.6	13.4	9.7	7.8	1.4
	b	13.4	12.3	11.3	1.4	13.4	12.2	11.2	1.4	13.4	10.9	14.2	1.6	13.4	9.7	7.8	1.4
May	a	10.1	12.5	20.5	1.2	10.1	12.3	20.2	1.2	10.1	11.2	18.7	1.4	10.1	10.5	18.5	1.6
	b	10.1	6.4	19.3	1.2	10.1	9.6	19.8	1.2	10.1	11.2	18.7	1.4	10.1	10.5	18.5	1.6
Jun	a	9.6	14.6	22.5	1.3	9.6	14.2	22.2	1.4	9.6	11.4	21.8	1.3	9.6	10.6	21.4	1.4
	b	9.6	3.2	19.4	1.1	9.6	6.4	19.9	1.3	9.6	4.8	19.9	1.0	9.6	8.0	19.9	1.4
Jul	a	12.8	13.9	22.9	1.3	12.8	13.2	22.1	1.0	12.8	10.5	22.1	1.3	12.8	10.0	21.1	1.0
	b	12.8	3.2	19.9	1.2	12.8	8.0	19.9	1.3	12.8	4.8	19.9	1.0	12.8	8.0	19.9	1.3
Aug	a	13.4	12.9	21.6	0.9	13.4	12.4	20.8	1.0	13.4	9.2	21.1	1.0	13.4	8.7	20.0	1.1
	b	13.4	3.2	19.9	1.3	13.4	6.4	19.9	1.3	13.4	4.8	19.9	1.1	13.4	8.7	20.0	1.1
Sep	a	12.6	12.6	17.5	1.0	12.6	12.4	17.0	1.0	12.6	7.9	18.8	1.2	12.6	7.6	18.2	1.2
	b	12.6	12.6	17.5	1.0	12.6	12.4	17.0	1.0	12.6	7.9	18.8	1.2	12.6	7.6	18.2	1.2
Oct	a	13.2	9.1	15.4	1.0	13.2	8.8	14.7	1.1	13.2	7.5	15.2	1.2	13.2	7.2	14.3	1.2
	b	13.2	9.1	15.4	1.0	13.2	8.8	14.7	1.1	13.2	7.5	15.2	1.2	13.2	7.2	14.3	1.2
Nov	a	14.8	10.4	10.3	1.3	14.7	10.3	10.0	1.3	14.7	6.7	11.5	1.1	14.8	6.6	11.1	1.1
	b	14.8	10.4	10.3	1.3	14.7	10.3	10.0	1.3	14.7	6.7	11.5	1.1	14.8	6.6	11.1	1.1
Dec	a	18.0	8.1	9.7	1.3	18.0	7.9	9.2	1.3	18.0	6.6	9.9	1.2	18.0	6.5	9.5	1.1
	b	18.0	8.1	9.7	1.3	18.0	7.9	9.2	1.3	18.0	6.6	9.9	1.2	18.0	6.5	9.5	1.1

a Without 20° Limit

b With 20° Limit

* Net Increase over Unheated Reach

peaking, close to the solar cycle thus indicating a very high degree of coupling of the water temperature to seasonal factors when flows are drastically reduced. The average flow cases grouped into a somewhat lower temperature group with late temperature peaks, essentially the same as exists today. The data suggest that flow manipulations resulting from the Treaty operations will have major effects on the timing of seasonal peaks.

- During the August through December period, all eight cases were grouped into a common set which was within a standard deviation of the data used to make the comparisons. This suggests that fall season water management practices will have little or no effect on the thermal capacity or the absolute temperatures of the Upper Columbia.
- The relatively narrow width of the bands (on the order of 1.5°C) also shows the relatively low degree of coupling of the system to weather and upstream water temperature below Grand Coulee Dam. The data developed also indicate that there exists a high degree of predictability for the development of a thermal management plan which could operate to the best interests of both power and fisheries.
- Lastly, Figure 16 indicates the extent to which the 20°C upper limit constitutes an effective barrier to the managed development of the Columbia for once-through cooling purposes, and the critical relationship of that limit to the net basin supply management practices resulting from the Columbia Treaty. The results show an effective comparison of the relative impact of from 10 to 30 GW of thermal additions in relationship to other modifications of the natural regimen.

A number of other illustrations and tables have been prepared to illustrate the sensitivity of the system to the various parameters under consideration. In Figure 17 the capacity of

FIGURE 16. Predicted Temperature at Columbia River Mile 324.9 (Mouth of Snake River). Maximum Allowable Heat Added rising Δt_h Without Limiting to 20°C.

FIGURE 17. Post Columbia Treaty Upstream Capacity Comparison of Critical Flow (1937)/Hot Weather (1958)/High Water Temperature ($\bar{T}+2\sigma$) and Average Flow/Average Weather/Average Water Temperature. (20°C Upper Limit and Using Formula Δt only.)

the Upper Columbia to dilute waste heat is estimated on a monthly basis without taking into account any cooling which might take place. This constitutes a minimum basis capacity. Since cooling takes place constantly, the values shown could be used as baseline minimums for planning purposes.

In Figures 18 and 19, the analysis concentrates entirely on the incremental capacity which can be absorbed without a net incremental increase in down river temperatures. The so-called Local Capacity is the amount of thermal dissipation which could be expected for thermal increments of the sizes shown. This assumes proper spacing of the plants by 1500 MW steps and may not be practicable for real cases. As an illustration of the separation of variables, Figure 18 and 19 contain valuable information previously not identified. These two figures reveal that within the presently written water quality criteria, a great deal of heat dissipative capacity exists, probably averaging 10 GW on an annual basis. A number of specific points are also illustrated, namely:

- Weather has an insignificant effect on the capacity of the system once flow quantities and basin supply management plans are set for a given seasonal operation. The variation in capacity computed is less than 1 GW for weather difference between average and the 1958 high, generally considered as having a probability of occurrence of less than 2%.
- The temperature of the water resulting from upstream development for thermal power and the result of queing of the supply in the Columbia Treaty system have significant effects on the capacity of the reach. Since evaporation is the principal method of equilibrating streams, the higher the average stream temperature, the higher the evaporative capacity. This is demonstrated by the capacity increases for the higher water temperature cases illustrated in Figure 18 and 19.

FIGURE 18. Post Columbia Treaty Local Capacity Summary, Upper Columbia River, Average Flow Cases

FIGURE 19. Post Columbia Treaty Local Capacity Summary, Upper Columbia River, Critical Flow Cases.

- Finally, these two figures illustrate the fact that flow volumes per se have no significant effect on the local or evaporative capacity of the stream as viewed as a separated variable. This does not mean that flow does not effect water temperature, but does illustrate that water management practice is the predominate independent variable.

Having investigated the net effect of thermal additions to the reach on both a conservative and non-conservative basis, the effects of net basin supply and management practices and weather influences on these effects, it seemed like a reasonable next step to investigate the effect of management practices alone on the thermal regime of the Upper Columbia. Accordingly, the COLHEAT program was used to examine the effects of routing post Columbia Treaty flows under average and critical conditions. Temperatures generated by the study of the effects of the Columbia Treaty dams which are summarized in Figures 11 and 12 were used as input information. Again, the flows obtained from Corps study NP-7-1979-80 were used for net basin supply and the average and 1958 weather interacted with these flows. The results are diagramed in Figures 20 and 21. In all cases the highest potentially possible water temperatures ($\bar{T}+2\sigma$) were used as inputs. The figures illustrate a number of very significant factors:

- Critical year flow management practices will move temperature maximums upwards by about 1.0 to 1.2°C and will move thermal peaking periods significantly in time ranging between July 1 and September 1. This indicates that temperature sensitive species will have no automatic or natural mechanism which can be counted on for intuitive guidance in seeking optimum conditions.
- Naturally occurring temperatures in the Columbia, independent of thermal plant heat loading, will be significantly lower in September than those currently observed. These

FIGURE 20. Post Columbia Treaty Effect of Local Weather on Natural Columbia River Temperatures. Average Flow Upper Columbia Reach.

FIGURE 21. *Post Columbia Treaty Effect of Local Weather on Natural Columbia River Temperatures. Critical Flow Upper Columbia Reach.*

will contrast with much higher temperatures expected in the Snake River such that differentials of from 5 to 7°C will be observed routinely during the late summer to early fall.

- Lastly, Figures 20 and 21 reveal that under critical flow conditions temperature could exceed 20°C and these could occur as early as July 1. Comparison of the values shown for natural conditions with the temperatures for fully loaded conditons involving gross thermal additions of from 20 to 25 GW illustrated in Figure 16 reveal that within the thermal differential of the state water quality criteria a great deal of thermal capacity exists in a 2°C band between natural post Columbia Treaty temperatures and fully developed conditions using a maximum of thermal inputs. The data suggest that the value of a 2°C differential is the key consideration in determining the benefit cost factors which are needed to judge the impact of thermal effluent additions to the Upper Columbia River system.

THERMAL CAPACITY OF THE SNAKE RIVER BASIN

Consideration of the Snake River as a cooling source for thermal plants is a difficult and complex problem for a number of reasons. The principal reasons appear as follows:

- The net basin supply is essentially fully appropriated or will soon be so that the designation of any water quantity which might be consumptively used becomes a question of property and law rather than technology.
- Existing authorized dams on the Snake have greatly increased the evaporation of that river. Since a thermal plant cooled by cooling towers requires 22,000 acre feet/GW/year of electrical capacity or alternatively 9,000 acre feet/GW_e/year using ponds or reservoirs as cooling ponds, off stream cooling is no ready answer to the question in the Snake River Basin area.

- The impoundment of the Lower Snake from Lewiston to the mouth can be expected to produce material increases in the August and September water temperatures. In general, impounded water of the Lower Snake will reach full equilibrium. On this basis, with equilibrium temperatures on the order of 23 to 24°C, there does not appear to be a satisfactory basis for the use of large once-through cooled power plants anywhere in the Snake system except in conjunction with irrigation development activities where extremely complex water rights issues are involved.

In order to support order of magnitude estimates of the impact of the use of the Snake River for once-through cooling, a simulation of the anticipated net basin supply, management of water flow, and weather was made using the COLHEAT model for the river reach between Lewiston and the mouth at Burbank, Washington. The results of the simulation are summarized in Figure 22.

Three data plots for the critical months of June, July, August, and September are shown. The water quality criteria against which this information needs to be examined are similar to those of the Columbia with a cut-off temperature for heat additions at 20°C. Since the average temperature of the Snake below Lewiston is expected to be above 22°C during 2 years out of 3 for 2 to 3 months, the practicability of once-through cooling appears very doubtful.

Figure 21 compares the temperatures at Burbank, Washington at the mouth for two conditions. These are

1. Average flows, average weather, and addition of 7.5 GW of thermal effluent at Lewiston
2. Critically low flows, 1958 weather, and no thermal additions anywhere on the river.

FIGURE 22. Snake River Temperature at Burbank, Cool Weather (1964), High Flow (1959) 7.5 MWTH Added at Lewiston Compared with Hot Weather (1948), Low Flow (1937). No added thermal plants: Both with Four Dams Complete.

The resulting comparison clearly indicates that thermal plant additions would produce conditions comparable to critical year, high temperature conditions and are difficult to defend.

Opportunities for dual purpose, or "helper" type cooling systems which operate in conjunction with irrigation offer considerable promise. However, as indicated above, the question of the regional water budget is involved and raises water rights issues beyond the scope of this report.

The study of the Snake suggest that, below Lewiston, there is no single purpose once-through cooling capacity under the present state water quality criteria. Above Lewiston, for locations on the impoundments of the upstream reservoirs, the question of water rights predominates over water quality considerations and appears to need additional study in depth.

THERMAL CAPACITY OF THE MIDDLE COLUMBIA RIVER, MILES 140 to 324

Under presently published state water temperature criteria, it is not at all certain that any thermal capacity exists below the mouth of the Snake River. This is true for the following reason:

- The Middle Columbia will in 2 years out of 3 exceed 20°C at Bonneville Dam as a result of greatly extended travel times in the John Day reservoir, higher Snake River temperatures, and the expected use of the river for peaking operations which tends to cause temperature pulses in the normal temperature record as a result of alternate wetting and drying of the shoreline areas. The detailed reasons for this have been documented in previous studies for PGE and for the Richland Operations Office, USAEC.^(4,5)

However, because of the general interest in the subject and the possibility that dual purpose cooling-irrigation systems might prove financially feasible, the decision was made to compute the capacity on a month by month basis in order to determine the thermal capacity on a fall-winter spring basis using the existing criteria. This was justified on the basis that the separation of essential variables had never been previously demonstrated, and that both potential developers and regulatory agencies might gain valuable insight into how the variable affect the river water temperatures under a variety of combined and separate circumstances.

Therefore for purposes of computation, the thermal capacity was estimated using the assumption that the Δt under state quality criteria would be calculated at the upstream end in order to establish a limiting value of the thermal increment without the 20°C upper limit. The values were also estimated using

the 20°C limit. The resulting information would give a clear illustration of the sensitivity of the 20°C limit in relation to the thermal capacity of the reach as well as the sensitivity of the water temperatures to the other three principal variables in this study, namely net basin supply, upstream water management practices, and weather.

In order to initiate computations, Table 8 was prepared using the Washington State water quality criteria. It should be noted that in most months the allowable increments exceed the 1.1°C limit imposed by Oregon criteria and also the values suggested for inter-state waters by the Water Quality Office of EPA. However, as stated above, the principal object of the study was to demonstrate the sensitivity of the various actions which might be taken to evaluate alternative actions in water quality management. Under critical conditions of flow, and using the fully developed incremental additions of thermal effluent developed for the Lake Roosevelt and Upper Columbia reaches as inputs, the expected monthly average water temperatures at the confluence with the Snake were used to compute the thermal differentials for the Washington State formula.

The thermal history for the Snake River at Ice Harbor Dam was used as input, the 1966 year being a relatively high year and readily available to the investigators from previous studies.⁽⁴⁾ See Appendix Table A-5 for justification of this choice.

Other side-streams such as the John Day River were considered as iso-thermal and were admitted to the simulation on an iso-thermal basis. Since the total side-stream input between the Snake and Bonneville Dam is on the order of 10% or less of the total flow, this procedure was considered justified.

TABLE 8

Washington State Standards - Class "A" StreamBasis: Δt (Allowable) = $110/(T-15)$ °FData Used for Predictions - Columbia River at Pasco
To Bonneville Dam, R.M. 146.5

	Critical Flow Conditions			Average Flow Conditions		
	Temp Above Snake- $\bar{T}+2\sigma$ Natural-°C	Temp Above Snake- $\bar{T}+2\sigma$ Heat*-°C	Δt For Critical Flow-°C	Temp Above Snake- $\bar{T}$ Natural-°C	Temp Above Snake- $\bar{T}$ Heat*-°C	Δt For Average Flow-°C
Jan	7.6	8.8	1.7	5.5	7.1	1.8
Feb	8.2	9.7	1.6	6.5	8.1	1.7
Mar	8.5	10.0	1.6	8.0	9.6	1.6
Apr	9.9	11.3	1.5	10.6	12.2	1.5
May	19.3	20.4	0	12.8	14.4	1.4
Jun	21.1	21.7	0	16.1	17.6	1.2
Jul	21.7	22.9	0	18.2	19.3	0.6
Aug	20.6	20.6	0	18.8	19.9	0.1
Sep	16.4	18.6	1.2	16.9	18.1	1.1
Oct	14.4	15.7	1.3	13.1	14.3	1.3
Nov	9.0	11.5	1.6	9.8	10.9	1.6
Dec	8.4	9.5	1.6	8.4	9.6	1.7

* 20° Limit Observed at Last Injection Point
Increases Above 20°C Due to Equilibration

By way of comparison with the results obtained, Figure 23 is presented to show the expected temperatures at Bonneville Dam after the Columbia Treaty Dams are operable. As noted above, temperatures above 20°C are expected in 2 out of 3 years even though the average temperature in summer will be about 1°C lower than before the Columbia Treaty operation.⁽⁴⁾

MAXPWR was then used to compute the integrated total of plants and related thermal effects within the constraints of Table 8. Inspection of the computer output revealed that the differences between the average weather cases and the high temperature weather cases (1958 weather) were trivial. In general the differences induced by local weather were less than the known accuracy of the simulation system and the input data (approximate error is 0.30°C). The results of the four high temperature weather cases were then examined for sensitivity to the other significant parameters. Table 9 lists the various capacity factors with and without the 20°C upper limit for the reach.

As a method of evaluating the effect of the water quality criteria formula on the potential for siting, Figure 24 was prepared. It illustrates the conservative capacity of the reach on a month by month basis without any credit for cooling within the reach. While it is obvious from inspection of Table 8 that little or no capacity exists for extended periods of time, as defined in this study and the water quality criteria, Figure 24 shows the dramatic effect of slight modifications of the criteria. For example, if the 20°C upper limit did not exist, and the capacity of the river were judged by a Δt only computed under the water quality criteria formula, to the point where a 1.1°C (2.0°F) differential were permitted, some 12 to 15 GW of thermal capacity might be sited and still stay upper temperatures down to 22°C under critical conditions. Again no allowance for cooling of these increment additions has been made.

FIGURE 23. Predicted Temperature Envelope at Bonneville Dam (Post Columbia Treaty Dams) Upstream Thermal Additions, 10 GW Above Pasco, WA. From Reference 4.

TABLE 9
Summary of Thermal Inputs and Temperatures
Middle Columbia

		Case 1				Case 2				Case 3				Case 6			
		Upstream Input GW _{th}	Local Add'ns GW _{th}	Temp M146.5 °C	Net Incr.* °C	Upstream Input GW _{th}	Local Add'ns GW _{th}	Temp M146.5 °C	Net Incr.* °C	Upstream Input GW _{th}	Local Add'ns GW _{th}	Temp M146.5 °C	Net Incr.* °C	Upstream Input GW _{th}	Local Add'ns GW _{th}	Temp M146.5 °C	Net Incr.* °C
Jan	a	28.0	15.6	7.7	1.6	29.8	15.6	7.9	1.6	29.7	16.1	6.9	1.6	31.5	16.2	7.1	1.6
	b	28.0	15.6	7.7	1.6	29.8	15.6	7.9	1.6	29.7	16.1	6.9	1.6	31.5	16.2	7.1	1.6
Feb	a	25.1	16.7	10.4	1.4	32.3	17.0	10.6	1.4	26.7	17.2	9.6	1.4	34.3	17.4	9.6	1.5
	b	25.1	16.7	10.4	1.4	32.3	17.0	10.6	1.4	26.7	17.2	9.6	1.4	34.3	17.4	9.6	1.5
Mar	a	24.2	17.0	11.3	1.3	35.7	17.3	11.4	1.4	24.3	16.9	11.2	1.3	35.7	17.2	11.3	1.4
	b	24.2	17.0	11.3	1.3	35.7	17.3	11.4	1.4	24.3	16.9	11.2	1.3	35.7	17.2	11.3	1.4
Apr	a	21.2	19.5	12.6	1.3	35.3	19.9	12.7	1.3	21.3	19.4	12.5	1.3	35.3	19.8	12.5	1.3
	b	21.2	19.5	12.6	1.3	35.3	19.9	12.7	1.3	21.3	19.4	12.5	1.3	35.3	19.8	12.5	1.3
May	a	0	0	21.2	0	0	0	20.8	0	19.2	20.1	20.7	1.1	38.8	19.9	18.9	1.3
	b	0	0	21.2	0	0	0	20.8	0	19.2	13.7	19.8	1.3	38.8	19.9	18.9	1.3
Jun	a	0	0	22.6	0	0	0	22.5	0	18.5	20.1	22.3	0.9	32.1	27.3	21.3	1.0
	b	0	0	22.6	0	0	0	22.5	0	18.5	8.2	19.9	1.1	32.1	10.7	19.9	1.2
Jul	a	0	0	23.9	0	0	0	23.7	0	7.7	8.8	22.9	0.4	12.0	9.7	21.3	0.4
	b	0	0	23.9	0	0	0	23.7	0	7.7	5.8	19.8	0.4	12.0	6.7	19.8	0.5
Aug	a	0	0	22.6	0	0	0	22.5	0	1.3	1.1	22.2	0.1	1.3	1.1	22.1	0.2
	b	0	0	22.6	0	0	0	22.5	0	1.3	0	20.0	0	1.3	0	20.0	0
Sep	a	15.8	20.1	18.0	0.8	16.1	20.9	18.0	0.8	14.5	19.4	18.1	0.8	14.8	19.5	18.1	0.8
	b	15.8	20.1	18.0	0.8	16.1	20.9	18.0	0.8	14.5	19.4	18.1	0.8	14.8	19.5	18.1	0.8
Oct	a	17.7	15.6	15.3	1.1	18.1	15.6	15.3	1.1	17.7	15.6	15.2	1.1	18.1	15.6	15.3	1.1
	b	17.7	15.6	15.3	1.1	18.1	15.6	15.3	1.1	17.7	15.6	15.2	1.1	18.1	15.6	15.3	1.1
Nov	a	23.4	19.6	8.6	1.4	24.0	19.6	8.7	1.4	23.4	19.4	8.4	1.4	24.0	19.5	8.5	1.4
	b	23.4	19.6	8.6	1.4	24.0	19.6	8.7	1.4	23.4	19.4	8.4	1.4	24.0	19.5	8.5	1.4
Dec	a	26.4	14.9	7.3	1.5	29.3	15.0	7.6	1.5	28.0	15.8	7.3	1.5	31.1	15.9	7.6	1.5
	b	26.4	14.9	7.3	1.5	29.3	15.0	7.6	1.5	28.0	15.8	7.3	1.5	31.1	15.9	7.6	1.5

a Without 20° Limit
b With 20° Limit
*Net Increase over Unheated Reach

FIGURE 24. *Post Columbia Treaty Upstream Comparison
Middle Columbia*

If local cooling is considered, even higher capacities may exist, although as stated above, the discussion is exploratory for purposes of understanding the physics of the numerical relationships of the principal variables. In Figure 25, the capacities for the two cases which have consistently shown the lowest relative capacity are compared in relation to the potential management policies which might reflect operational use of the water quality criteria.

The capacities are plotted for Cases 3 and 6 (see Table 2) with the additional option of halting further additions when 20°C was reached. The input temperatures are based on Table 6 and 7 information and assume that the river above the mouth of the Snake has been fully loaded within the intent of the discussion pertinent to the upper reaches. Generally this means that the river is about 1.0 to 1.3°C warmer than would exist under "natural" post Columbia Treaty conditions.

Figure 25 reveals one of the vital findings of the entire study, and places the question of thermal additions in perspective in a definite way. The data plotted there shows the following:

- Very minor changes in the management policy associated with water quality criteria can make very large differences in the numerical capacity of the Middle Columbia River. The dip in the curve during June and July represents a very small thermal increment, probably less than the permissible Δt of 1.1°C proposed for the Columbia by the Water Quality Office.
- If the existing standards were followed to the letter, and the maximum allowable quantities of thermal additions ranging from 20 to 30 GW made upstream on a suitable spaced basis, and if all additions were curtailed at Mile 289 in response to the numerical 20°C limit under these criteria, and critical flows were in existence,

FIGURE 25. Post Columbia Treaty Distributed Capacity Middle Columbia

the temperature of the Columbia would continue to rise as a result of equilibration to about 22.5°C. Figure 25 shows the predicted river temperatures at River Mile 289 (above McNary Dam) and the downstream temperatures at Bonneville Dam. During July, when the criteria formula and the Oregon standards would permit some thermal loading under Δt consideration, some 6 to 8 GW of loading would produce less than 0.5°C differential in river temperature between the 20°C limit and the Δt limit imposed at the Washington/Oregon border.

- . The integrated sum of thermal capacity which might exist could range widely depending on interpretation of the meaning of the water quality criteria. However, under the assumptions stated for this study, the difference imposed on the Middle Columbia temperatures from upstream loadings running as high as 30 GW would be less than 0.5°C at Bonneville Dam, well within the measurement error of current monitoring systems. This substantiates the computations made in Reference 4 in which energy increments ranging up to 19.3 GW for the combined effect of the Hanford plant and the natural annual thermal increments in the Hanford reach were predicted to affect Bonneville temperatures by less than 0.5°C.

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The author wishes to acknowledge the assistance of D. E. Peterson, Westinghouse Hanford Company, Richland, Washington for the loan of the computer code MAXPWR which was developed for the purpose of thermal capacity predictions. The code and its parent COLHEAT are the state of the art in regional systems planning for thermal siting and represent the product of long years of thoughtful and intensive cooperation between Mr. Peterson and the author and others such as J. L. Spurgeon of Computer Sciences Corporation who have made this type of analysis possible. It is hoped that the analyses in this report will serve to inspire others to further refine the conclusions reached and the methods used in an effort to resolve the growing crisis between our need to protect the environment and our needs of societal development involving energy.⁽¹²⁾

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APPENDIX A

DATA AND
SUPPORTING INFORMATION

TABLE A-1

Flow Data From Corps of Engineers
Study NP-7 - 1979-80

30 Yr Average Flows - Regulated (KCFS)												
	<u>Jan</u>	<u>Feb</u>	<u>Mar</u>	<u>Apr</u>	<u>May</u>	<u>Jun</u>	<u>Jul</u>	<u>Aug</u>	<u>Sep</u>	<u>Oct</u>	<u>Nov</u>	<u>Dec</u>
Kootenay River	24.99	24.36	23.32	27.74	40.22	45.13	33.98	16.48	15.67	18.66	21.24	30.32
Pend Oreille	20.67	22.71	23.69	27.62	48.52	53.14	27.62	9.68	11.42	20.64	24.06	20.96
Columbia												
Arrow Dam	36.04	30.94	25.12	23.95	25.94	36.45	51.66	67.95	51.38	37.39	29.82	50.11
Intl. Border	81.70	78.01	72.13	79.31	114.68	134.72	113.26	44.11	78.47	76.69	75.12	81.39
Grand Coulee	100.56	120.79	123.31	109.73	124.36	109.06	113.61	88.60	82.25	83.89	82.34	109.72
Priest Rapids	107.40	127.83	129.97	118.76	140.03	133.83	130.08	96.32	89.35	89.30	90.01	116.85
McNary	147.43	176.92	188.23	198.95	233.83	225.32	168.51	117.59	113.25	117.92	126.82	154.57
Bonneville	163.46	195.54	209.31	221.09	249.13	234.02	176.03	122.63	120.50	129.24	138.54	170.34
Snake												
Lewiston	26.66	31.17	44.99	94.99	117.07	96.71	35.29	17.73	19.24	22.47	25.30	27.97
Ice Harbor	35.52	42.94	52.29	81.96	93.43	87.52	35.58	19.19	21.03	25.25	31.39	32.01

TABLE A-2

Flow Data From Corps of EngineersStudy NP-7 - 1979-80Critical Year Flows - Regulated (KCFS)

	<u>Jan*</u>	<u>Feb*</u>	<u>Mar*</u>	<u>Apr*</u>	<u>May*</u>	<u>Jun*</u>	<u>Jul⁺</u>	<u>Aug⁺</u>	<u>Sep⁺</u>	<u>Oct⁺</u>	<u>Nov⁺</u>	<u>Dec⁺</u>
Kootenay River	21.82	19.92	17.48	21.70	28.03	29.81	21.38	11.86	12.31	12.95	21.88	23.58
Pend Oreille	17.16	20.34	17.10	16.69	24.65	31.17	12.54	7.24	8.40	16.17	19.43	16.97
Columbia												
Arrow Dam	59.45	14.54	7.60	13.50	5.59	5.00	42.12	72.76	58.20	51.84	42.29	63.12
Intl. Border	78.43	54.80	42.18	51.89	58.28	65.98	76.04	91.86	78.91	80.96	83.60	103.76
Grand Coulee	110.40	90.95	87.49	62.94	50.07	50.83	76.90	86.70	81.86	85.79	89.13	108.19
Priest Rapids	115.27	95.50	91.07	65.06	55.15	76.14	81.75	90.50	87.19	90.43	93.53	112.67
McNary	138.97	132.62	128.04	120.03	116.24	129.53	108.74	111.14	111.01	115.07	123.53	139.17
Bonneville	146.72	144.27	147.92	143.88	131.45	137.30	115.99	116.53	118.33	125.29	131.95	198.81
Snake												
Lewiston	21.51	31.67	31.52	51.19	65.21	49.23	21.38	16.83	19.77	21.54	25.30	22.68
Ice Harbor	33.09	39.09	32.53	50.89	62.48	48.08	23.08	17.70	20.50	21.79	26.02	23.20

+ 1936

* 1937

TABLE A-3

Summary of Weather Factors at Hanford

Temperature					Solar Radiation					
Year	Function (°F)		Day T _{max}	Rank Low High	Function (Langley)		Day S.R. _{max}	Rank Low High	(r' - r'')	(F ₁ ' - F ₂ ' ²)
1955	51.68 + 23.07	SIN(0.0172d + 4.39)	201	3	360.5 + 275.9	SIN(0.0172d + 4.79)	178	3	0	0
1956	53.74 + 24.06	SIN(0.0172d + 4.43)	199	13	354.7 + 290.4	SIN(0.0168d + 4.90)	176	4	9	81
1957	53.23 + 23.80	SIN(0.0172d + 4.43)	199	9	388.5 + 288.3	SIN(0.0177d + 4.71)	177	16	-7	49
1958	57.29 + 23.03	SIN(0.0172d + 4.45)	197	16	370.7 + 299.3	SIN(0.0168d + 4.86)	178	12	4	16
1959	53.46 + 21.32	SIN(0.0172d + 4.48)	196	4	376.7 + 281.6	SIN(0.0172d + 4.89)	173	11	-7	49
1960	53.77 + 23.89	SIN(0.0172d + 4.40)	201	12	381.7 + 292.8	SIN(0.0171d + 4.85)	175	14	-2	4
1961	55.98 + 22.52	SIN(0.0172d + 4.51)	194	15	381.1 + 293.4	SIN(0.0174d + 4.71)	180	13	+2	4
1962	54.43 + 20.26	SIN(0.0172d + 4.35)	203	2	361.9 + 293.3	SIN(0.0168d + 4.92)	169	10	-8	64
1963	54.60 + 22.60	SIN(0.0172d + 4.36)	203	10	370.6 + 278.8	SIN(0.0179d + 4.63)	180	6	+4	16
1964	52.87 + 20.63	SIN(0.0172d + 4.40)	200	1	365.1 + 283.8	SIN(0.0168d + 4.91)	175	5	-4	16
1965	54.68 + 21.12	SIN(0.0172d + 4.40)	200	7	367.1 + 284.2	SIN(0.0167d + 5.01)	170	7	0	0
1966	55.83 + 18.92	SIN(0.0172d + 4.38)	199	5	341.7 + 288.0	SIN(0.0161d + 5.09)	171	2	3	9
1967	57.21 + 20.79	SIN(0.0172d + 4.29)	206	14	366.6 + 259.8	SIN(0.0178d + 4.66)	179	1	13	169
1968	54.3 + 20.70	SIN(0.0172d + 4.51)	194	6	370.0 + 283.0	SIN(0.0172d + 4.87)	178	8	-2	4
1969	52.6 + 25.0	SIN(0.0172d + 4.48)	196	11	377.0 + 298	SIN(0.0172d + 4.83)	175	15	-4	16
1970	53.3 + 22.9	SIN(0.0172d + 4.50)	195	8	372.0 + 282	SIN(0.0172d + 4.52)	176	9	-1	1

Means 1955-70

$$\text{Spearman Rank Coefficient} = 1 - \frac{6 \sum (x-y)^2}{M(M^2-1)} = 0.113$$

Weak Correlation of Solar Rad. & Temp Max

TABLE A-4
Monthly Mean Air Temperatures
Trinidad, Washington

Year	June Temp °F	Rank Low High	July Temp °F	Rank Low High	August Temp °F	Rank Low High	September Temp °F	Rank Low High
1933	62.0	8	68.5	6	68.3	15	55.5	2
1934	64.5	20	68.8	8	69.6	23	56.1	3
1935	62.0	9	68.6	7	65.8	5	62.3	20
1936	64.6	22	70.8	19	69.3	19	59.2	5
1937	63.7	17	71.0	22	65.3	2	62.0	17
1938	66.2	24	72.0	24	65.4	3	65.6	25
1939	61.2	7	70.2	14	69.3	20	60.5	11
1940	66.1	23	70.5	15	68.0	12	63.2	22
1941	63.0	12	72.6	25	67.2	10	55.0	1
1942	60.2	4	69.6	10	70.0	24	61.1	12
1943	59.8	3	69.6	11	66.3	6	61.5	14
1944	64.5	21	70.7	16	67.1	9	62.0	18
1945	62.0	10	70.7	17	69.3	21	57.3	4
1946	60.8	6	69.3	9	68.5	17	59.3	6
1947	62.7	11	69.8	12	67.0	8	61.1	13
1948	68.1	25	68.3	5	66.4	7	62.0	16
1949	63.2	13	70.0	13	68.3	16	61.6	15
1950	63.4	14	70.9	21	70.2	25	62.3	21
1951	63.6	16	70.8	20	68.8	18	60.2	10
1952	63.5	15	70.7	18	69.3	22	64.0	24
1953	58.5	2	68.2	4	67.8	11	62.0	19
1954	58.0	1	67.3	2	65.0	1	59.3	7
1955	64.1	19	67.2	1	68.1	13	60.1	9
1956	60.7	5	71.3	23	68.2	14	59.8	8
1957	64.0	18	68.0	3	65.7	4	63.2	23

From Reference 4

TABLE A-5
Correlation Between Snake River Temperatures
At Ice Harbor Dam and Hanford Weather
(Tmax from Table A-3)

Year	Ice Harbor Temperature $T = \bar{T} + A \sin(cd + D)^\circ\text{C}$	Tmax °C	Rank Low to High	Hanford Weather Tmax °C	Rank Low to High	$R_1 - R_2$	ΔR^2
1963	$12.54 + 9.60 \sin (0.0172d + 4.05)$	22.14	8	25.1	6	2	4
1964	$11.31 + 8.53 \sin (0.0172d + 3.83)$	19.84	1	23.1	1	0	0
1965	$11.78 + 8.39 \sin (0.0172d + 3.67)$	20.17	2	24.3	3	-1	1
1966	$12.41 + 9.08 \sin (0.0172d + 4.00)$	21.49	7	24.8	5	2	4
1967	$12.37 + 9.10 \sin (0.0172d + 4.03)$	21.47	5	25.6	8	-3	9
1968	$11.77 + 8.70 \sin (0.0172d + 4.03)$	20.47	4	23.9	2	2	4
1969	$11.83 + 9.65 \sin (0.0172d + 4.16)$	21.48	6	25.4	7	-1	1
1970	$11.94 + 8.55 \sin (0.0172d + 4.04)$	20.38	3	24.6	4	-1	1

$$S = 1 - \frac{6 \sum (\Delta R^2)}{M(M^2 - 1)}$$

Spearman Rank Coeff = 0.714

Strong Correlation Indicated >75% Certain

TABLE A-6
Correlation Between Snake River Hydrology (Ice Harbor Dam)
and Columbia River Hydrology (Grand Coulee Dam)

Year	1929	1930	1931	1932	1933	1934	1935	1936	1937	1938	1939	1940	1941	1942	1943	1944	1945	1946	1947	1948	1949	1950	1951	1952	1953	1954	1955	1956	1957	
	25	29	28	7	20	26	23	9	22	13	16	17	24	21	14	27	18	12	6	4	5	15	8	3	19	10	11	2	1	May Snake (High Low)
	29	28	27	18	20	2	16	14	24	7	17	19	26	21	6	25	23	11	8	4	12	10	3	5	15	9	22	1	13	May Columbia (High Low)
	4	1	1	11	0	24	7	5	2	6	1	2	2	0	8	2	5	1	2	0	7	5	5	2	4	1	11	1	12	Difference
	16	1	1	121	0	576	49	25	4	36	1	4	4	0	64	4	25	1	4	0	49	25	25	4	16	1	121	1	144	(Difference) ²
	19	26	29	14	3	28	22	21	25	8	27	24	20	13	5	23	13	15	16	1	18	7	11	9	4	17	10	2	6	June Snake (High Low)
	29	25	21	13	3	5	19	18	28	15	17	24	27	22	14	26	23	11	9	1	20	4	6	16	7	8	12	2	10	June Columbia (High Low)
	10	1	8	1	0	23	3	3	3	7	10	0	7	9	9	3	10	4	7	0	2	3	5	7	3	9	2	0	4	Difference
	100	1	64	1	0	529	9	9	9	49	100	0	49	81	81	9	100	16	49	0	4	9	25	49	9	81	4	0	16	(Difference) ²
	18	27	29	13	12	28	23	22	25	7	24	26	19	10	1	21	16	17	15	5	20	2	9	8	3	4	6	11	14	July Snake (High Low)
	28	22	20	11	5	15	14	17	26	19	24	21	23	18	13	25	27	9	8	6	29	2	3	10	12	1	4	7	16	July Columbia (High Low)
	10	5	9	2	7	13	9	5	1	12	0	5	4	8	12	4	11	8	7	1	9	0	6	2	9	3	2	4	2	Difference
	100	25	81	4	49	169	81	25	1	144	0	25	16	64	144	16	121	64	49	1	81	0	36	4	81	9	4	16	4	(Difference) ²

Spearman Ranking Coefficients

$$r_{\text{may}} = 0.700$$

$$r_{\text{june}} = 0.644$$

$$r_{\text{july}} = 0.682$$

Values of $r_{M0} > 0.4$ for 30 Samples Indicates
 Strong Correlation

From Reference 4

TABLE A-7
Synthetic Monthly Mean Discharge Temperatures
Below Grand Coulee Dam

Year	May	High Low	Low High	June	High Low	Low High	July	High Low	Low High	Aug	High Low	Low High	Sept	High Low	Low High
1929	-2.2	27		-4.4	29		-4.8	24		-3.4	6		-5.7	24	
1930	-2.7	28		-3.5	20		-6.8	29		-5.3	22		-4.8	20	
1931	-1.8	20		-3.5	21		-5.9	28		-4.1	13		-2.8	3	
1932	-1.4	10		-3.4	18		-3.1	14		-5.7	26		-5.7	25	
1933	-1.7	18	8	-1.9	1	22	-1.5	2	24	+1.2	1	25	-3.0	5	21
1934	-1.5	15	12	-3.4	19	8	-4.8	25	3	-4.3	15	11	-5.0	21	6
1935	-1.8	21	7	-3.5	22	6	-2.8	9	16	-4.8	19	9	-4.1	15	11
1936	-2.1	25	3	-3.6	24	5	-2.9	11	15	-4.9	20	8	-5.7	26	3
1937	-1.6	16	10	-2.6	9	15	-4.0	21	6	-4.0	10	15	-4.0	14	13
1938	-1.1	4	22	-3.8	27	2	-2.4	8	18	-4.1	14	14	-4.1	16	12
1939	-1.9	22	5	-2.7	12	14	-4.2	22	5	-5.7	27	3	-5.7	27	4
1940	-1.4	11	14	-2.9	13	13	-4.9	26	1	-4.0	11	16	-5.0	22	7
1941	-1.6	17	11	-2.0	5	20	-4.6	23	4	-5.8	28	2	-3.9	12	14
1942	-1.3	9	19	-3.0	14	11	-3.2	15	11	-6.5	29	1	-5.9	28	2
1943	-1.3	8	17	-2.4	8	18	-1.7	3	22	-0.5	2	24	-4.3	17	10
1944	-3.3	29	1	-3.9	28	1	-3.9	20	7	-5.3	23	4	-3.9	13	15
1945	-1.2	5	20	-1.9	2	23	-2.8	10	17	-3.4	7	20	-3.2	7	19
1946	-1.3	7	18	-3.7	25	3	-3.8	19	8	-5.3	24	5	-4.6	18	8
1947	-1.7	19	9	-2.6	10	16	-4.9	27	2	-4.3	16	12	-4.6	19	9
1948	-1.2	6	21	-3.1	16	10	-3.0	12	13	-3.7	9	18	-2.9	4	23
1949	-1.4	12	15	-1.9	3	24	-3.3	17	10	-3.2	5	21	-7.8	29	1
1950	-1.4	13	16	-3.7	26	4	-1.7	4	23	-4.0	12	17	-3.2	8	20
1951	-1.0	3	23	-1.9	4	25	-1.9	5	20	-5.1	21	7	-3.6	11	16
1952	-0.8	2	24	-2.0	6	21	-3.0	13	14	-5.3	25	6	-5.1	23	5
1953	-2.1	26	2	-3.5	23	7	-1.9	6	21	-2.2	3	23	-3.5	10	17
1954	-1.5	14	13	-2.6	11	17	-0.8	1	25	-4.7	18	10	-2.0	2	24
1955	-1.9	23	6	-3.3	17	9	-3.6	18	9	-4.3	17	13	-3.0	6	22
1956	-0.7	1	25	-3.0	15	12	-3.2	16	12	-3.6	8	19	-3.3	9	18
1957	-2.0	24	4	-2.1	7	19	-2.0	7	19	-2.3	4	22	-1.3	1	25

From Reference 4

APPENDIX B
COLHEAT SIMULATION MODEL

COLHEAT SIMULATION MODEL

The COHEAT simulation model has been described in previous reports and publications, and has been extensively used both on the Columbia River and other tributary systems for the operational analysis of the effects of industrial development. The computational system operates on the assumption that most streams will be turbulent or supercritical in hydraulic characteristics and that, within this assumption, the non-dimensional distribution of velocity within the stream is similar regardless of the stream dimensions. Based on this concept originally described by Nikuradse the model sets up a series of difference equations derived from the heat budget method and iteratively computes the downstream temperatures as a function of the input parameters in the following manner:

$$T_{i+1,j+1} = (1-B) \left(T_{i,j} + \Delta T_{i,j}^{(1)} + \Delta T_{i,j}^{(2)} \right) + B \left(T_{i,j-1} + \Delta T_{i,j-1}^{(1)} + \Delta T_{i,j-1}^{(2)} \right)$$

where $T_{i,0}$ = average temperature of water entering the system during the i^{th} time interval, °C.

$T_{i,j}$ = average water temperature of the beginning of the j^{th} flow increment at the end of the i^{th} time increment (flow day) °C

$\Delta T_{i,j}^{(1)}$ = the temperature change during the first half of the i^{th} time interval in the j^{th} flow increment as determined from surface heat exchange plus advected energy (heat budget) in °C

$\Delta T_{i,j}^{(2)}$ = same as above except for the second half of the i^{th} time interval, in °C

B = the fractional part of the water in the inner fast moving trough.

A flow day of water is approximately the mean daily flow of all the water in the system.

In the simulation model the water system is composed of an inner and outer trough with relative volumes B and (1-B), respectively (see Figure B-1). If A is the number of mean flow days, then the number of outer trough flow days is the largest integer, NJ, in

$$(1 + B) \cdot \Delta + 0.5.$$

The system is then divided into NJ equal volume nodes which are also referred to as flow days or flow volumes.

Note that the above definitions have analogous meanings for time increments other than a day; for example, flow-hour.

The following data are required for operation of the temperature model:

- Water temperature at the inlet end (time increment appropriate) flow discharge at the outlet end
- Water temperature at the outlet end (optional, for statistical comparison where available)
- Meteorological data (wind velocity for time period, mean air temperature, dew point, sky cover in tenths, short wave radiation)
- River or reservoir dimensions reduced to equivalent non-parallel trapezoidal cross sections (volume, surface or bottom areas are derived)
- Advected heat quantities (megawatts per time incrementation)

The model permits the advection of heat into any of the input defined troughs. The flow day(s) of water corresponding to the advected heat trough are adjusted in temperature to simulate the addition of the heat. A more detailed description of the simulation system is available in documents listed at the end of this appendix.

MODEL OF CHANNEL FLOW AT A TRANSLATIONAL INSTANT

l VARIES AS RESERVOIR GEOMETRY AND FLOW
AND REPRESENT A RESERVOIR LENGTH FOR THAT REGION
ONE FLOW DAY IN LENGTH

Neg. No. 0695295-2

FIGURE B-1. Representation of Model of Channel Flow at a Translational Instant

THE MAXPWR VERSION

This version of COLHEAT originally developed by Peterson and Spurgeon and fully described in publication BNWL 1405, Potential Thermal Effects of an Expanding Power Industry: Upper Mississippi Basin, uses the basic heat budget and stream operator system to admit thermal loadings at intervals determined by the program under control criteria. Fixed thermal differentials for both individual reaches and sidestreams can be selected in response to stream standards. The individual size of thermal additions is also adjustable, however for simplicity, a single value representing the largest feasible unit for the stream at a given location is used.

The program then computes the amount of thermal energy which would be entrant to the reach under examination to fully utilize the Δt at the entrant point. Then the stream is allowed to cool towards equilibrium until an amount of heat equal to the plant input quantity has been dissipated. At this point an amount of load equal to the size of the selected plant is injected and the program again moves downstream until that increment has been dissipated. When this point is reached, another increment is inserted.

The program then summarizes the input heat, the local additions, the gross and net atmospheric cooling, and reports these monthly. In addition, the natural stream temperatures without heat injection are reported for each point desired as well as other data such as evaporation, equilibration temperature and the reference and input data used in the computations.

The MAXPWR system works on the following principles:
Let P be a unit volume of water. P enters the river system at the input temperature, $T_1 = T_{IN}$, as specified by the weather card. Let V_1 (cubic feet) and S_1 (square feet) represent the volume and surface area respectively. The 1st river section, then P has S_1/V_1 (square feet) of surface area while in river section 1.

If the flow through RS_1 is F KCFS or $FLOW$, $- 3.6 \times 10^6 * F$ CFH, then the travel time for P through RS_1 is $H = V_1 / FLOW$, hours. At this point the heat budget equations are evaluated with $Q_t = BTUS(T_1) \text{ Btu/hr} * ft^2$. Now the value T_2 , the upstream end temperature of RS_2 and be determined

$$T_2 = T_1 + CONST * Q_t * S_1 / V_1 * \frac{(V_1)}{Flow_1} \quad (2)$$

Equation (2) would tend to overstep in the direction of the sign of Q_t . To dampen or eliminate this effect, several smaller steps are taken within the river section. The effect of this is that Q_t alternates in sign and becomes smaller in absolute value. Thus T_2 can be determined with a fair degree of accuracy. This procedure can be controlled by the Control Card parameter $DTLIM.(0 \text{ } ^\circ\text{C})$ where the first step cannot exceed $DTLIM$ in absolute value. See the MAXPWR diagram and diagram description for further details on this procedure, (BNWL-1405).

The procedure for determining T_{i+1} given T_i given T_1 is analagous to the above procedure. T_i denote the temperature of the water as it passes the river cross section at the upstream end of river section i .

In addition to the proceeding, the MAXPWR system also injects heat into the water and adds flow by means of sidestreams.

To satisfy the requirement that the heated river does not exceed the natural river temperature plus a prescribed limit $DTMAX (^\circ\text{C})$, the system computes both the natural river temperature TN_i and heated river temperature T_i as described earlier. When the two temperatures differ sufficiently to accept a unit of advected heat into the heated river without violating the above limit, the heat is injected at the added energy.

Additional Information About The

COLHEAT MODE

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