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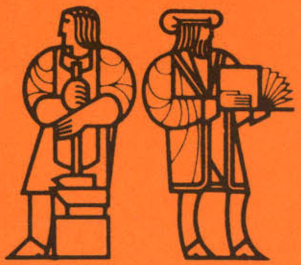

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ABSTRACT

Pollution control policies have been an outgrowth of increased awareness that measures must be taken to handle the increasing amounts of wastes and by-products of human activity. A particular problem in the policies is how to address wastes that have large natural variations due to natural sources and changing environmental conditions. This is especially true for the control of thermal discharges from steam-electric generating facilities into large bodies of water also influenced by solar heating and inflows of water from natural sources.

The basis for most pollution control policies in the United States is the set of regulations specifying ambient and effluent standards. Technology-based effluent standards have been increasingly used to provide a conservative basis for environmental protection. Ambient standards, based on impacts on humans or other life forms, however provide a viable regulatory approach for those effluents with costly treatment, particularly where large natural variability indicates the environment has a significant capacity to assimilate additional inputs. A major problem with ambient temperature standards indicated by two case studies of large thermal discharges, is the variability in induced and natural conditions which affect facility siting, design, and operation, and verification of compliance.

The Browns Ferry Nuclear Plant is an example of a large thermal discharge into a varying river environment. The final set of ambient temperature limiting standards for the site which have values near naturally occurring conditions, required the owners of the plant to redesign the heat dissipation system. The final design included the use of supplemental cooling (open, helper, or closed mode) to provide flexible plant operation under varying river flow conditions. Problems with real-time monitoring for compliance with the standards led to a study of various methods of verification. Simulation of plant operation found that adjusting the standards higher than naturally occurring values had larger effects than various monitoring strategies utilizing spatial and temporal averaging. A one-dimensional natural change in temperature model used in conjunction with real-time monitoring reduced power losses due to natural variation by about one half, but could not account for all the short-term variations in natural temperatures caused by topographic and river flow changes and density effects.

The Millstone Nuclear Power Station, located in a coastal environment is an example of a thermal discharge into an area with relatively constant long-term mixing conditions. Concerns over natural temperature variation were present throughout the site's history, although this has not affected plant operation since the ambient standards, based on biological evidence, were set to include full open-cycle operation. A natural temperature model, based on finite element circulation and dispersion models was developed as one means of addressing the natural variability issue. The model produced reasonable resolution of the horizontal tempera-

ture distribution and relative changes over a tidal cycle. The model had some limitations in those areas where solar heating significantly affects the vertical temperature distribution. If properly combined with baseline temperature monitoring, the natural temperature model provides an assessment tool for characterizing the physical environment around a thermal discharge. It also has potential in verification of compliance by combining with thermal plume monitoring and modeling efforts to define the ambient baseline conditions and the effects of natural conditions on the extent of a thermal plume.

It is recommended that ambient standards continue to be used in the control of thermal discharges to take into account the natural assimilative capacity of large bodies of water. Real-time monitoring of compliance with maximum rise temperature standards should not be used in areas of high natural variability. Natural temperature models which cannot adequately predict highly variable situations should not be used to correct real-time monitoring efforts. Therefore, flexible effluent standards which adapt to large changing conditions should be used based on modeled plant effects and potential biological impacts. Natural temperature modeling (including extensive monitoring of baseline temperature conditions) in both preoperational and operational studies should be used to provide a balance of the understanding between physical and biological characteristics in complex environments.

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I Introduction

Industrial growth, larger population, scarcity of easily recoverable natural resources, and desire for a higher standard of living all place more demands on the earth's capacity to accept or assimilate the unwanted by-products and waste materials created by human activities. The term "pollution" is used to describe wastes when they impact the air, water, or land resources important to man. Policies to control pollution often limit the level of the pollutant measured in the environment (ambient standards). This is done to protect the environment and to allow for "disposal" of the waste material. In cases where there are large natural sources, adding relatively small amounts of a substance to background levels is often not considered harmful. The environment also assimilates or breaks down many waste products that are natural substances. Controlling pollution in this fashion poses several practical problems. The long term effects of low levels of pollutant concentrations on the environment for example are often hard to determine. Another problem is the difficulty of monitoring pollutants in the environment. Many of the wastes produced by human activities have natural origins making the separation of man-made pollutants from natural sources difficult. Changing natural conditions affect the transport and dispersal of a pollutant also causing problems in determining representative levels.

Newer approaches to pollution control have, for the most part, used effluent standards to limit discharge of pollutants at the source. Since the limits are normally fixed, these standards do not take into account the environment's ability to assimilate some pollutants. The effluent standards also must consider the variable nature of waste discharges.

Policies for the control of waste heat from steam-electric generating facilities are difficult to establish due to the above problems. Most thermal effluents are discharged into large bodies of water which can often dissipate the heat effectively without significant environmental damage. Water temperatures are not only influenced by the discharges but also by solar heating and inflows of water from natural sources. Separating the effects of the facility from natural conditions, representative monitoring and the use of effluent standards are therefore important issues in controlling waste heat discharges.

This thesis explores the problem caused by natural temperature variations on the control of waste heat. Specific examples of large thermal discharges are studied to determine how various control policies are affected by natural temperature conditions. The background of general pollution control policies is first considered as a means of placing thermal pollution control in perspective. The main goal of the next two sections is to identify parts of pollution control policies concerned with the variability of natural conditions and discharges.

1.1 Basic Environmental Regulations

The most important part of pollution control policies is the set of regulations governing waste discharges. The following section explores the two main forms of environmental regulations; ambient and effluent standards which have become the mainstays of current control policies in the United States.

To control the impacts of pollution on the environment, man has resorted to legal constraints, using private remedies (court suits) or the development of statutory law (laws and regulations) to prevent indiscriminant release of wastes. Private remedies based on common law and the court system were important in early pollution control efforts but in recent times have taken a back seat to statutory law. This is due to the limitations of the judicial system, the size of the control problem, and the need for planning to prevent unwanted environmental impacts. Nevertheless, the courts have played a major role in the control of pollution through judicial interpretation of statutory legislation and judicial review of administrative actions by governmental agencies.

The easiest statutory approach to pollution control is to set laws and regulations which prevent any pollutant discharges into the environmental at the source. The magnitude of the wastes, the lack of ultimate disposal, and the economic constraints of such a task have made it necessary to take a more lenient approach to pollution control. The present statutory pollution control is based on two requirements: ambient standards which specify the maximum level of a pollutant in the environment or effluent standards which set the amount of pollutant that can be discharged at the source.

Ambient and effluent standards are characterized as being health-based or technology-based. A health-based standard sets a maximum level of exposure to a pollutant which will not have an impact on human or other life forms. Ambient standards fall into this category. These standards are normally based on dose versus health effect information and often do not specifically consider economic factors. Ambient air quality standards have been set for general diffuse pollutants with multiple sources and are based on health effects to humans. Ambient water quality standards have been set for the protection of fish and other aquatic organisms. Effluent standards are normally categorized as technology-based. These standards are based on the maximum level of control provided at the source. Economics are frequently considered but effluent standards can include "technology forcing", that is, setting a more stringent standard based on industry's ability to achieve such control in a reasonable period. An effluent standard may also be health-based in the case of a toxic substance where little or no discharge is warranted. However, this is often translated into a technology-based standard determined by the level of control that can actually be achieved.

The form, the degree of harmfulness or toxicity of the pollutant, the assimilative capacity of the environment, and the economic costs of preventing the discharge, all determine which standard will be used. The choice of using an ambient standard or effluent standard is often precluded by the hazardous or toxic nature of the waste material making an effluent standard (often as strict as zero discharge) the only possible recourse. Fortunately, many wastes of human activities are not hazardous and can be broken down by the environment. Many of the wastes produced by man also have natural origins as is the case with some air pollutants. Sulfur dioxide, a major waste from the burning of fossil fuels, is produced in large amounts by the oxidation of hydrogen sulfide resulting from biological decay. Man-made hydrocarbons released as unburned fuels result in only about one-tenth the amount created by bacterial decomposition and vegetation. Aerosols from volcanic eruptions, forest and grass fires, dust storms, and sea spray account for 90% of the particulates found in the atmosphere (Williamson, 1973). Heat also has a substantial natural origin caused by the sun which produces far more heating of surface waters than the total heating produced by man. In some cases the earth as a whole can cope with the additional load of waste substances without a significant change in the total environment. Local pollution, however, is much harder to cope with and regulations must consider both the local effects of pollutants and existing natural conditions.

In cases where the earth can assimilate the waste (or where sources will not add appreciably to natural background levels), ambient standards are often used as an economical way of controlling the impact of a pollutant. Early statutory pollution control consisted mainly of ambient standards when it was thought that "dilution is the solution to pollution." More evidence of health impacts from low levels of pollution, larger amounts of discharged wastes and a growing concern for protection of the environment,all forced greater use of effluent standards to halt further deleterious impact. The present statutory control structure relies heavily on both forms of standards to achieve a desired environmental quality.

Ambient and effluent standards both have advantages and disadvantages. Effluent standards are ideally suited to pollution control but do not consider the possible assimilative capacity of the environment. They are often the most costly alternative and usually transform the pollutant into a form that must still be disposed of. Setting ambient standards requires extensive information about the human, aquatic or terrestrial effects of the pollutants. Dose-response studies must be made for each pollutant on a number of species.

A common problem both ambient and effluent standards must address is variability. Variability enters control policies in many forms. A health-based standard must consider the variability of effects on different species and even different effects on individuals within each species. In effluent control, industrial processes which generate wastes are usually not constant. This must be taken into account in setting effluent standards. Ambient standards set for pollutants in the natural origins must account for the variability caused by changing natural sources. Natural factors also influence the dispersal of a pollutant causing fluctuations in levels found at any point. Therefore, pollutants with high natural variability (often controlled by ambient standards) pose especially difficult problems in pollution control policies.

1.2 Pollution Control Policies - Considering Variability

The previous section described the major approach to pollution control in the U.S., regulating pollutant discharges based on ambient or effluent standards. Changing environmental conditions, including natural sources and unsteady industrial process flow, were mentioned as occurrences to be regarded in pollution control policies. The consideration of variability enters the overall control policy for a specific pollutant in (1) the statement of the actual standards (e.g. provisions for time averaging) and (2) the method for verification to prove facility compliance with the standard (e.g. monitoring and/or modeling). A discussion of these two areas for both air and water quality standards provides the topic of the following section.

The exact language of ambient and effluent standards is dependent on the level of government responsible for establishing the standards. A major difference exists between ambient air quality standards and water quality standards since the air standards are set at the national level and must be met at all locations. Due to the vast differences in the character of bodies of water, the states are primarily responsible for water quality standards which must be approved by federal agencies. The states are also responsible for determining effluent control needed at sources of pollution which will prevent violations of both the ambient air and water quality standards. Although federally adopted effluent standards must be met, the strictest standard (effluent or ambient) overrides the lesser requirement.

1.2.1 Ambient Standards

Since ambient standards are set to prevent adverse impacts (i.e. health effects or impacts on aquatic or terrestrial life) they must take into account the period of exposures to specific concentrations. In most cases the concentration of a pollutant in the environment is variable over time, hence, the level of effort necessary to control overall exposures is often hard to determine. Three factors are considered in addressing the time variability issue: concentration, averaging time, and frequency of occurrence. Ambient standards for air and water differ in the importance placed on these factors.

The concern for impact prevention is translated into ambient standards which specify a maximum concentration of a pollutant in the environment. Concentrations are used to determine exposures by considering the time over which the concentration occurs. A hierarchy of standards can be set to prevent impacts at different exposure levels, usually to prevent acute or long-term effects. Air quality ambient standards set exposure levels which are not to be exceeded and specifically address an averaging time to determine the exposures. An example of this is the national primary air quality standards for sulfur dioxide which have an annual average limit for chronic health effects and damage to vegetation, and a higher 24-hour average limit to prevent possible change in lung function and irritating odor.

The frequency of occurrence is especially important in air quality since it is well documented that the highest ambient levels of pollution occur infrequently. Air quality standards take this into account by the use of annual averages and short-term standards which can be exceeded once a year before an actual violation of the standard is recorded.

There is little emphasis on the variable nature of pollutants in water quality standards. Although mixing is often more uniform due to the smaller volumes involved, significant variation can occur due to changing flow patterns and variations in sources and sinks. Except for coliform bacteria, most state ambient water quality standards are expressed as maximum concentrations never to be exceeded in the receiving water.

Spatial variability is also a problem that must be addressed in ambient standards. An important topic in the control of water pollutants is the "mixing zone" which allows concentrations higher than the ambient water quality standards in a small region of the receiving water. The description and delineation of the zone poses difficult regulatory problems which are normally handled on a case-by-case basis. Some general guidelines for the description of the zone usually require a zone of passage in rivers or streams to allow fish and fishfood organisms to pass. Mixing zones in lakes and coastal waters are often set using a defined radius from the discharge or a defined area. The permissible size of the mixing zone is dependent on the acceptable amount of damage that takes the physical and biological features of the receiving water into account. The definition of the zone is usually determined by monitoring and/or modeling as will be discussed later. A mixing zone provision does not specifically exist for air quality standards although the site boundary of a facility is often used as the nearest point considered.

1.2.2 Effluent Standards

Federal effluent standards are based on the best available system of effluent reduction adequately demonstrated. The final effluent standards for a discharge are normally set by the state and must be low enough to prevent violation of ambient standards. In determining whether an effluent standard is stringent enough, the worst case environmental condition is used. Effluent standards with single limits, therefore, do not take into account changing natural conditions. The strictest effluent standard is a zero discharge requirement and a standard this strict is normally used only on hazardous or toxic substances. Often such strict control is not economically or technologically feasible and standards must be more lenient as is the case for liquid discharges even though laws were written calling for zero discharge by 1985. Although current thermal effluent control laws require essentially no discharge of waste heat into the receiving water, an exemption provides the opportunity to use the water for heat dissipation.

Effluent standards must also take into account the variability of effluent flow since few industrial processes have constant outputs. This is normally accomplished by including provisions for time averaging in the statement of the standard.

1.2.3 Intermittant Control

There has been much debate over the use of intermittant control of waste discharges based on changing environmental conditions. Facilities would cut back discharges when adverse conditions prevented adequate mixing of the wastes in the air or water environments. The broadest suggested use of such controls is for air pollution. Tall stacks combined with cutbacks in power have been suggested as an alternative to costly control equipment (Montgomery et al., 1975). This operation still provides for the compliance with ambient standards. Judicial interpretation of the federal legislation held that tall stacks are not adequate control technology since the intent of air quality laws is to remove pollutants from the air, not simply dilute them (Big Rivers Electric Power Company v. EPA, 1975). The Environmental Protection Agency has never in recent years allowed use of intermittant controls for air quality control although the topic is still being debated as a means of meeting ambient air requirements. Intermittant control policies have not been used in recent years for water quality control except for discharge of waste heat.

1.3 Verification of Compliance with Standards

Ambient or effluent standards provide only part of the overall pollution control policy. Some method must be used to determine if the standards will be met before a facility discharging wastes becomes operational. Once in operation, compliance with the standards must also be verified. Both modeling and/or monitoring methods are used to demonstrate compliance. The following describes how modeling and monitoring methods specifically address the previously mentioned variability issues.

Pollutant dispersal modeling is normally used to determine the impact of new facilities on the ambient levels of pollutants in the environment. In some cases, new federal source performance effluent standards are not strong enough to meet local ambient standards. Therefore, an analysis is necessary to indicate what levels of control are needed for design bases. Procedures for the modeling of new source impacts on air and water quality differ in their consideration of variability.

The basis for most water pollutant design basis analysis is the worst case condition usually defined in terms of periods of low dilution and transport. Water movement in areas influenced by tides is normally determined by numerical circulation models. Coastal circulation models for lakes also factor in conservative assumptions to arrive at worst case conditions. In rivers and reservoirs the worst case condition is usually based on the historical record of stream flow. The lowest flow over a seven-day period which occurred once in a ten-year period is the design basis most commonly used.

The worst case condition is translated into an analysis which determines the effluent control necessary to meet the ambient standards. The resulting effluent standard is therefore deterministic and does not take into account any of the variability in natural conditions. The worst case condition is especially restrictive in rivers and reservoirs since stream flow varies a great deal.

Air quality modeling relies heavily on typical environmental conditions by utilizing a representative meteorological record for design basis. Meteorological data for at least five years is recommended, but one year is sufficient if judged representative of the area by comparison with nearby meteorological stations. Short-term air quality standards are stated in such a way that the standards shall not be violated more than once. Some leeway exists in the modeling of air pollution diffusion since the design basis is specified as the second time a violation would occur. As in water quality modeling, the resulting effluent control needed to meet the ambient standard is adopted for the entire operation of the facility.

Modeling can also be used in continuing compliance efforts once a facility becomes operational. In this case, changing environmental conditions provide input for modeling which determines if discharges meet ambient standards. This is only used for control policies allowing intermittant controls, that is, changing effluent discharge depending on environmental conditions.

Once a facility becomes operational, monitoring is usually done to determine if previous model estimates of facility design and operation were accurate. Continued monitoring may be required if the variation in environmental conditions is significant.

In general, monitoring ambient levels of pollutants in the environment is difficult because of the small concentrations involved and the variability which can occur from changes in natural conditions. Air quality monitoring requirements given in the text of the ambient standards solve these difficulties by using long sampling times (24 hours) to determine an average concentration. Annual averages are then determined from the daily values. Shorter averaging times of 8, 3, and 1 hours are also specified for some pollutants to prevent effects from higher concentrations. Unlike air quality measurements, which can separate a pollutant from the large volumes of air used in a 24-hour sample, most water quality measurements rely on grab samples of a small volume of water transported to a laboratory for analysis. The arbitrary results of grab sampling are solved for some substances by continuous monitors which can operate in the field for long periods. Composite sampling, which involves taking a small sample of water periodically and later analyzing the entire sample, has also been used. In effect this provides an averaging similar to air quality monitoring techniques. Since the state standards do not specify which techniques should be used, variations occur from state to state on the exact meaning and compliance monitoring of the water quality standards. The statement, "maximum levels never to be exceeded" in most water quality standards is, however, different than in air quality management. Since levels of pollutants in the water are usually not as variable as in the air, there is some basis for this procedure. However, in rivers, estuaries, and coastal areas having variable currents and water movement, variability may be significant.

Spatial variation is also a problem in compliance monitoring. Location of sampling devices must be based on representative areas of the environment. Sampling should be done at critical receptor points or in a geometric pattern for a more systematic evaluation. In another approach, monitors are placed at locations based on knowledge of the dispersion in air or movement in water. Monitoring of water quality parameters is normally done at the edge of the predetermined mixing zone. Spatial averaging is usually not considered since most of the standards are written to prevent impacts at any location outside of the mixing zone or the site boundary. Spatial averaging is an important topic in the control of waste heat discharges since variable natural conditions significantly influence the monitoring of water temperatures.

Monitoring to show compliance with effluent standards must also address the problem of variability. The sophistication of modern monitoring equipment has made continuous monitoring of effluent discharges possible. Such monitoring can be easily used to show compliance with maximum level requirements. Averaging the large amounts of data generally follows. Composite sampling for water effluents has also been used as a method of compliance monitoring. In fact many state and federal regulations have effluent monitoring requirements for 24-hour composite samples to be analyzed for compliance purposes. Schaeffer et al. (1979), found that this rule did not account for actual operating variability experienced even by well-run facilities and suggested that the 24-hour samples be averaged over any consecutive 30-day period. Such results already appear in some new federal source standards such as for steam-electric generating sources. A short-term maximum for each 24-hour sample usually is used to prevent acute effects. Again, the nature of the pollutant is important in determining the level of effort required in the monitoring strategy. The potential for changes in the industrial process must also be taken into account since the monitoring should be representative of the output flow.

1.4 Outline of Thesis

The introduction presented the background of how variability is considered in general pollution control policies. Regulations providing the major means of pollution control have used ambient and effluent standards to prevent impacts on the environment. The statement of the standards and methods of verifying compliance with the standards were both found to be important in the consideration of variability. Ambient standards provided a means of adapting pollutant discharges to the assimilative capacity of the environment. Effluent standards, on the other hand, usually put strict limits on effluents not accounting for natural variability since they are based on worst case conditions. Various methods of compliance verification were examined considering both monitoring and modeling approaches.

The remaining chapters explore waste heat as a specific environmental problem. "Thermal pollution" is the term given to waste heat discharges when they change the previous use of a body of water. Increased water temperature can have effects on water use due to changes in the solubility of oxygen, influences on chemical reactions, and changes in the water's ability to assimilate other waste products. Particular attention has been given to thermal effluents because of their effects on aquatic organisms. Increased temperatures can cause thermal barriers which interfere with fish movement; loss of fish population due to reproductive stresses; fish kills due to thermal shock caused by cessation of thermal discharges; increases in eutrophic conditions resulting from growth of algae and shifts to less desirable algae species; and synergistic effects with pesticides or chemical toxins which can result in a higher incidence of disease in the aquatic ecosystems (Nalesnik, 1971).

Generation of electricity by conventional fossil-fuel and nuclear power plants account for an estimated 70% of thermal pollution (Griffin and Steele, 1980). Wide use has been made of electricity since it is an easily distributed form of energy providing light, heat, and mechanical power. Hence, control of thermal pollution has been a major topic in the simultaneous achievement of energy supply and environmental goals.

Waste heat produces only one impact of electrical energy generation on the environment. Mining, transportation, and processing of the fuels all cause significant damage. In addition, air pollution is generated from the use of fossil fuels. Solid wastes from fossil fuels and radioactive wastes from nuclear fuels all must be accounted for. Improved efficiency of facilities is one way to reduce the total damage to the environment and slow down the use of finite energy sources.

The efficiency of a steam-electric generating facility using steam as medium to convert fossil or nuclear fuel to electricity is dependent on the temperature of the intake water used for cooling the condensers. Heat dissipation systems using open-cycle cooling draw intake water from a body of water and return the heated water directly back into the water. These systems have higher efficiencies than systems that recirculate the cooling water through closed-cycle systems utilizing cooling ponds or cooling towers. Open-cycle systems also have lower operating and capital costs since cooling towers or ponds are not needed. However, open-cycle systems cause the largest impacts on the aquatic environment since the total waste heat load is dissipated in the body of water. Designing heat dissipation systems that are the most efficient while not significantly damaging to the environment are of prime concern in balancing the trade-off between energy supply and environmental quality.

An important point is raised when discussing heat dissipation from steam-electric power plants. Thermal pollution is not the only impact of once-through (open-cycle) cooling systems. Suspended aquatic life can be entrained in the large volumes of water that are used for cooling. The large increase in heat kills most of the organisms passing through the plant. Larger organisms such as fish must be prevented from entering the plant by use of screens and low velocity intakes. A full discussion of these topics is not included in scope of this thesis.

Bodies of water have a natural capacity to dissipate, and eventually release to the atmosphere, the large amount of heating resulting from the absorption of solar radiation. Due to the sun's heat and the ability of the water to assimilate it, waste heat discharges have normally been controlled by ambient standards. Unlike most ambient standards which only set a maximum value of a substance, part of most ambient thermal standards are based on limiting the man-made effluent above background temperature levels. Since heating from the sun is variable and natural conditions in surface waters compound the variation of natural temperatures, separating man-made discharges from natural conditions is a difficult task. Natural heating also creates high temperatures close to ambient standards (set to protect aquatic impacts) in some bodies of water. The latest control of thermal discharges requires an effluent standard which does not allow any discharge of waste heat unless it can be shown that adverse environmental impacts will not result.

Chapter II first reviews the history of thermal effluent control, the present status of regulations affecting thermal discharges, and the general approaches used by owners of large discharges to show compliance with the regulations. Since it is difficult to generalize the various control issues, two case studies of large thermal discharges are examined. A study of the Browns Ferry Nuclear Plant in Chapter III provides an example of operating a facility on a river environment where variations in river flow affect the operation of the heat dissipation system. In Chapter IV, the Millstone Nuclear Power Station (located in a coastal environment) provides an example of natural mixing conditions which are unvarying over long periods. Both studies specifically address the role of natural temperature variations on plant operation (dependent on meeting thermal regulations). Natural temperature models are explored as one technique of separating the plant from natural effects.

The final chapter compares the results of the two case studies to show how various thermal effluent control policies consider the natural variability problem. Recommendations are also given for incorporating the results into present thermal effluent control policies.

II Thermal Effluent Control

Waste heat became a major concern along with other forms of pollution in the late 1960s and early 1970s. The history of thermal discharge regulation is long and complicated with numerous state and federal agencies playing a direct or indirect role in evaluation and regulation. Originally, ambient standards set by individual states were the applicable restrictions which gave way to stricter federally proposed limits. Recently, control has been more clearly defined with a no discharge effluent standard as the overriding requirement. Much discussion has taken place on the economics and impacts of thermal discharges, yet the no discharge rule still stands with compliance set for July 1, 1981. An important exception still exists where the discharger has the ability to do site specific studies to gain a variance from the no discharge rule. Although the studies rely heavily on biological data which is often controversial, they still offer an opportunity for adapting facilities to site-specific assimilative capacity.

The following chapter briefly reviews the history of thermal discharge regulation. Since the natural variability problem is more severe for thermal discharges due to large heat input from the sun, ambient and effluent standards presently in effect will be examined for their responsiveness to this issue. Various approaches to verifying compliance with thermal regulations will also be considered as background for the case studies discussed in later chapters.

2.1 History of Legal Control of Thermal Effluents

Legal control of thermal effluents has centered mainly on the control of waste heat from the electric power industry. Private remedies available for abating pollution under common law concepts of nuisance, property rights, trespass and negligence have only been used in minor cases in thermal effluent control. The limitations of common law and the judicial system have placed the major burden of thermal pollution on the federal and state legislatures and agencies. The review of administrative decision-making, however, is one judicial function that is still important.

Previous to 1965, the disposal of waste heat was governed mainly by economic and engineering considerations even though the Federal Water Pollution Control Act was passed by Congress in 1956. Forty-five states had some form of federally approved ambient thermal standards by 1968 after congressional passage of the 1965 Water Quality Act (Public Law 89-231 (1965)) which called for national interstate water quality standards. Many conference workshops were held between the federal government, industry, and the states to agree on an environmentally protective limit acceptable to all concerned. In 1968, a report by the National Technical Advisory Committee to the Secretary of the Interior (Water Quality Criteria) provided criteria for ambient temperature limits. These criteria (scientific judgements on the environmental effects of a level of pollution) were intended to be a guide for the states' adoption of water quality standards (legal entity governing the regulation of a body of water). The committee recognized that regional variations in climate, topography, hydrology, geology, etc. were important in establishing water quality standards in specific locations and stated that the criteria should only be used as guidelines and not as requirements (Federal Water Pollution Control Administration, 1968). Many states which had previously set their own thermal standards were encouraged by federal agencies to adopt the criteria to create a more uniform set of standards throughout the nation. Most of the states complied, and these standards are the main restrictions in effect at the present time.

Since nuclear plants were the largest sources of waste heat, thermal effluent control for these facilities was particularly important. The numerous agencies involved with the plants, however, left the thermal issue in limbo for many years. Prior to 1971, the Atomic Energy Commission (AEC), the first major federal agency licensing nuclear plants, had no clear jurisdiction over thermal effects. The failure of AEC to fully confront the thermal pollution issue in its licensing process and the states' questionable ability to provide control once the plant became licensed by AEC forced the State of New Hampshire to seek judicial review of AEC's administrative procedures (New Hampshire v. AEC, 1969). The court reaffirmed the AEC's position on thermal pollution agreeing that it only had authority to review the special hazards of radiation. In 1969 the passage of the National Environmental Policy Act required federal agencies to conduct environmental impact assessments before "major actions" were taken. The approval of a nuclear plant construction license was such an action although the AEC felt it was still only responsible for an assessment of the radiation impact.

The inability of the states to handle thermal pollution problems and the weakness of the Federal Water Pollution Control Act of 1956 led Congress to amend the act in 1970 (Federal Water Quality Improvement Act). These amendments included a provision settling the federal-state dispute since they required state certification that a proposed steam-electric generating plant would not violate applicable state water quality standards before the appropriate federal agency could license or permit construction. At this time the AEC was the federal agency licensing nuclear plants but no federal agency existed for licensing fossil-fueled plants. Enactment of the Water Quality Improvement Act of 1970 and passage of NEPA finally led the court of appeals for the District of Columbia through judicial review to conclude (Calvert Cliff's Coordinating Committee v. AEC, 1971) that the AEC had to include thermal effects in their environmental assessment for licensing nuclear power plants.

In the early 1970s a number of separate court decisions clouded the water pollution control picture forcing the passage of the Federal Water Pollution Control Act Amendments of 1972 (FWPCAA). These amendments contained the most comprehensive and complex legislative attempt to establish a viable coordinated federal-state water quality control program. The goals of the amendments were high. The most ambitious was to eliminate the discharge of pollutants to navigable waters by 1985. An interim fishable, swimmable goal for all waters was set for 1983. The set of federally approved ambient water quality standards for interstate waters established earlier remained well-rooted with a supplementary requirement for federal approval of interstate ambient standards.

The new legislation also adopted the second form of standards for pollution control - effluent standards. Federal effluent standards were to be developed for specific industrial categories including steam-electric power plants. The standards for existing sources were to be based on two levels of control technology; the best practical was required by 1977 and the best available by 1983. New sources were to meet effluent standards based on the best available demonstrated control technology. The FWPCAA included an important exception, section 316(a), which provided that the imposed thermal discharge criteria may be changed by EPA, or by the appropriate state following the introduction of evidence that less stringent limits would be sufficient to protect the aquatic life in the water receiving the discharge. Section 316(b) of the FWPCAA also had to be met which required a study showing that a proposed intake structure contained the best technology available for minimizing adverse environmental impacts.

The effluent standards and section 316(a) and (b) provisions were to be implemented through section 404(a) of the FWPCAA, the National Pollution Discharge Elimination System (NPDES) permitting process. These permits would include effluent limits and monitoring requirements for all discharges into the nation's waters. The states were given primary authority to administer the federally approved program. Applicable federal effluent standards would be the minimum permit requirement and more stringent standards would be specified as necessary to meet the state ambient water quality standards.

Applicable effluent guidelines and standards for steam-electric power generating units, effective November 4, 1974 (40 CFR 423), established recirculating (closed-cycle) cooling systems as the best available technology (existing plants) and best available demonstrated technology (new sources) for thermal effluent control. There are exceptions for existing facilities where it is physically impossible or environmentally unacceptable to install cooling towers, and no alternative means of cooling is available. The effective date for existing plants to meet this limitation is July 1, 1981, except when the electric system reliability will be compromised by compliance (under which an alternative schedule can be arranged.) Demonstrations under section 316(a) and (b) are the only other exceptions that can be used by both existing and new sources to set alternative limitations.

The final set of legal standards covering thermal discharges essentially requires the use of closed-cycle cooling for waste heat under the applicable effluent standards or ambient standards based on the favorable outcome of 316(a) and (b) demonstrations. The next subsection will examine the present situation in light of these final requirements and the ambient standards presently in force.

2.2 Present Standards Governing Thermal Discharges - Considering Natural Variability

The effluent standards adopted for the control of thermal effluents provide one of the few essentially no discharge requirements in the new performance standards for industrial facilities. In this form they allow for no variability in thermal effluent discharge. Demonstrations under sections 316(a) and (b) of the Federal Water Pollution Control Act Amendments of 1972 (FWPCAA) offer the only exception to the requirement provided the applicant can prove a well-balanced aquatic community will be maintained and that the best intake design will be used. Electric power plants granted variances under these demonstrations would still have to meet applicable state water quality standards, unless it is demonstrated that the state standards are also too stringent in certain cases.

The following discussion examines the requirements for 316(a) demonstrations. Present water quality standards are reviewed as they apply to the variability issue. The current federal criteria for temperatures in water are also examined since they may be adopted as standards by the states.

The language of section 316(a) of the FWPCAA is important in discussing the alternative to the no discharge standard:

> "With respect to any point source otherwise subject to the provisions of section 301 or section 306 of this Act, whenever the owner or operator of any such source, after opportunity for public hearing, can demonstrate to the satisfaction of the Administrator (or, if appropriate, the State) control of the thermal component of any discharge from such source will require effluent limitations more stringent than necessary to assure the projection [sic] and propagation of a balanced, indigenous population of shellfish, fish and wildlife in and on the body of water into which the discharge is to be made, the Administrator (or, if appropriate, the State) may impose an effluent limitation under such sections on such plant, with respect to the thermal component of such discharge (taking into account the interaction of such thermal component with other pollutants), that will assure the protection and propagation of a balanced indigenous population of shellfish, fish and wildlife in and on that body of water."

The basis for an exemption is the use of data, studies, experiments and other information on the potential thermal effects on the biological community. The emphasis is mainly biological; requiring an evaluation of the important species. Although never officially published, technical guidance for these demonstrations requires extensive plant operation, hydrologic, and predicted thermal plume characteristics. This data is then used to prove compliance with applicable thermal standards set at levels to protect the aquatic community. The state standards for the protection of the aquatic environment are based on suggested federal criteria which contain the latest knowledge on the effects of temperature on aquatic organisms.

Since the 1968 version of Water Quality Criteria mentioned in Section 2.1, two sets of criteria have been published. The 1972 version of Water Quality Criteria (National Academy of Sciences - National Academy of Engineering, 1972) was substantially different than the 1968 version. This contained the same temperature criteria that were published in the latest criteria, Quality Criteria for Water (United States Environmental Protection Agency, 1976). It is worthwhile to briefly review the 1968 temperature criteria since they form the requirements adopted by most states and are still the governing requirements for most thermal discharges.

The 1968 Water Quality Criteria have normally translated into two standards for receiving waters (streams or lakes): a maximum rise in temperature above "ambient" and a maximum temperature. The maximum rise in temperature criteria for streams was 5°F,based on the expected minimum daily flow for the month. Maximum rises in lakes were set at 3°F based on monthly average of the maximum daily temperature. Maximum temperatures not to be exceeded for streams and lakes were given,based on the important species of fish present in the area.

The criteria also contained a recommendation that:

> "The normal daily and seasonal temperature variations that were present before the addition of heat due to other than natural causes should be maintained."

Although such language usually appears in various states' standards, strict limitations are not given to meet this recommendation. Some states have set separate maximum temperatures for different months of the year to meet the concern for seasonal temperature variation.

Most of the above ambient standards, expressed as strict maximum limitations, fail to take into account natural variability. One exception is the maximum temperature rise in rivers and streams which is based on the expected minimum daily flow for the month. This requirement offers flexibility over the seven-day, ten-year low flow design basis used for other water pollutants. The major concern is the limitation for the maximum temperatures and maximum rise in temperatures in the bodies of water which are specifically not expressed as time averages. As will be seen in the next chapter, a case study of a river environment shows that natural temperatures exhibit a highly fluctuating nature, making compliance with the strict limits difficult.

The 1968 criteria for marine and estuarine environments have been adopted without revision as standards by most coastal states. The standards define a maximum rise in temperature for the fall, winter and spring months to be not more than 4°F or more than 1.5°F in the summer months. The basis for the rise standards are the monthly means of maximum daily temperatures recorded at the site before the addition of heat. The rate of temperature change is limited and should not exceed 1°F per hour except from natural phenomena. As with the freshwater criteria, no time averaging is specified.

Both the freshwater, estuarine and marine criteria are to prevail outside an established mixing zone which leads to the issue of spatial variability. The choice of mixing zone is somewhat arbitrary but becomes important (especially with thermal effluents) since natural conditions may cause higher temperatures thought to be caused by the effluent. This situation is evident in both case studies of actual conditions at thermal discharges as will be seen in Chapters III and IV.

The latest water quality criteria (published in 1976 but using the procedure of the 1972 version) contain an entirely different approach to the temperature criteria which, for the most part, have not been translated into state standards. (States are required to review their standards every three years and may be pressured into adopting the new criteria in the future.) The new criteria for the protection of freshwater aquatic life are specified as two upper limiting temperatures for a location based on the important species present. One is a maximum temperature for short-term time dependent exposures. The second value is a limit on the weekly average temperature which is seasonally dependent on the prevention of cold shock in the cooler months, the prevention of upper limit thermal effects in the warmer months, and the prevention of reproductive effects during reproductive seasons. A site-specific limit may also be set to preserve diversity of species or prevent the appearance of nuisance organisms. Noticeably absent is a criteria for maximum rise in temperature. Season variations have been written directly into the criteria and the maintenance of a daily cycle is not specified. The resulting criteria are surprisingly similar to the ambient air quality criteria discussed in Chapter I since they define both acute and long-term criteria. They also contain averaging times, specified directly in the short-term standard since it is time dependent, and a weekly average for the maximum temperature.

The new criteria would solve some of the previous problems that occur due to natural variability since they include time averaging. The short-term criteria may still be slightly inflexible since they would be based on the extent of plume and travel time through it. Travel time would have to be based on a worst case situation posing the question of restricting operation by the design basis condition discussed earlier. Flexibility could be provided through the use of real-time monitoring of ambient temperatures, discharge temperatures and flow conditions which would be used to calculate travel time and compliance with the standard. An example of this will be given in Section 3.4.

Criteria for marine aquatic life are stated as summer thermal maxima based on upper thermal limits for aquatic communities in the discharge area, a maximum acceptable increase in the weekly average temperature of 1°C (1.8°F) and a requirement for the maintenance of daily temperature cycle characteristics (both frequency and amplitude). Baseline thermal conditions are to be measured at a site that has reasonable proximity and similar hydrography to the discharge area where there is no unnatural thermal addition from any source.

The new criteria are again substantially different from the 1968 criteria. The maximum temperature increase above ambient and short-term maximum rate of temperature change criteria have been replaced by summer maximum temperature limits and a weekly averaged maximum increase in temperature. Suprisingly, the requirement to remain below the summer thermal maxima does not specify the weekly averaging contained in the other parts of the new criteria. Regional limits are suggested including short-term maximums and a maximum 24-hour average. There is also the requirement for maintenance of daily temperature cycle characteristics which was not contained in the new freshwater criteria. The changes from the old criteria are numerous in terms of variability. The weekly averaging of the maximum temperature increase is the most obvious change which provides far more flexibility than the non-averaged criteria. The value of the allowable limit has changed from a winter 4°F (22°C), summer 1.5°F (.8°C), to a year round 1.8°F (1°C) representing the need to limit increases equally during all seasons. The suggestion of a 24-hour averaged maximum temperature limit with short-term limit is more compatible with other short- and long-term standards mentioned elsewhere, yet the long-term limit is not averaged for as long as the other requirements.

The next section provides a general background of how the standards are applied to the actual control of thermal discharges.

2.3 Compliance with Thermal Standards

The owner of a facility with a large thermal discharge must resolve how compliance with the thermal standards will be verified with the pollution control agency. If the owner cannot prove there will be little harm to the aquatic environment, closed-cycle cooling systems will almost surely be required with essentially no discharge of heat allowed. If studies show the facility can use open-cycle operation or a combination of open-cycle and other cooling modes without harm to the aquatic community, the owner must decide how to determine compliance with limits (normally ambient standards) set to assure that adverse impacts will not result.

Extensive preoperational studies of thermal discharges are required. Various physical or numerical approaches must be used to predict the extent and magnitude of the discharge, after which the results are used to determine effects on the aquatic environment based on the applicable ambient water quality standards. In cases where preoperational studies have shown potential for impacts during specific natural conditions (as low river flows), the owner may choose flexible operation to adjust to changing conditions. In areas where the natural variation in mixing conditions over long periods is small (as ocean sites), flexible operation may not be needed. The final design and operation of the facility is then determined before the facility becomes operational. Requirements or limits on discharge are set to assure that adverse impacts on the receiving water will not happen. These limits may take the form of ambient standards in the receiving water or effluent standards at the source of the discharge.

Once the facility becomes operational, proof must be given that effluent or ambient standards are not being violated. Compliance with effluent standards can be easily verified since monitoring is done at the point of discharge. Compliance with ambient standards is more difficult since monitoring must happen in the receiving water with its large spatial and temporal variations in temperatures. In situations where the natural mixing conditions are not variable, short-term studies (which characterize the variability that does exist), may be used to confirm the preoperational estimates of the extent and magnitude of the discharge. If the actual discharge is found to meet the ambient standards, further measurements in the receiving water may not be required. In this case, regulations take the form of effluent standards based on the discharge values used in modeling the extent of the discharge. In cases where there is more variability in the receiving water's ability to handle the waste heat, more extensive monitoring may be necessary to confirm the preoperational studies. When facility operation is flexible (dependent on changing natural conditions), some method of proving continuing compliance with the thermal limitations is often required. Continuing compliance verification can take the form of real-time monitoring (monitoring at frequent intervals such as every hour) or monitoring at longer specified intervals characterizing changing natural conditions. The operators of flexible facilities often use predetermined model results or real-time modeling to determine the amount of waste heat discharge staying within the ambient standards for the natural conditions present. If the predicted model results can be shown to represent actuality, monitoring to show compliance with the ambient standards may be changed to effluent monitoring.

The previous discussion included various methods used by operators of large thermal discharges to show compliance with applicable water quality standards. This is not an inclusive list but it does point out general approaches to using real-time monitoring, or short-term studies verifying modeling results to solve the compliance issue. Although the general approaches may seem clear, a variety of issues often makes thermal control practices difficult at specific sites. It is difficult to discuss the problems without evaluating actual instances of thermal effluent control. Two case studies are presented in the following chapters to gain a better understanding of the complexity of the issues involved. The individual sites are placed in the historical context of thermal effluent control given in Section 2.1 and the applicable standards are reviewed. Finally, the effect of natural variability is addressed since it presents a major problem in verifying compliance with thermal regulations. Several approaches considering natural variability in predicting the extent of the thermal discharge and verifying compliance with applicable standards are evaluated in addressing the variability issue in thermal control policies.

III Thermal Effects in a River or Reservoir Environment

The operation of the Browns Ferry Nuclear Plant provides an interesting example of thermal effluent control in a river environment. The plant, operated by the Tennessee Valley Authority, has undergone a complicated history of thermal regulation which is still unsettled due to a recent 316(a) demonstration submittal. The Browns Ferry experience is particularly valuable since it is one of the few plants that can use a mixed-mode cooling (a combination of open-cycle and closed-cycle) system offering economic benefits over a fully-closed system. One problem that has plagued operation of the plant is the use of real-time monitoring of instream temperatures to show compliance with ambient thermal standards. The difficulties in compliance monitoring of the thermal discharge pose important questions about the handling of natural temperature variation and the use of spatial and temporal averaging in monitoring such a discharge.

The following chapter studies the thermal discharge problem by examining the role of natural variability in the compliance monitoring and operation of the plant. A summary of the background and legal history of the plant follows with details on the impetus for the thermal effluent control standards that have been used. A natural temperature modeling effort is reviewed as one approach to natural variability in both compliance monitoring and operation of the plant. Various alternate strategies for the monitoring of the discharge are examined which employ temporal and spatial averaging. The present situation at Browns Ferry is considered since it combines all of the questions on thermal effluent control which must be faced by the use of ambient standards instead of a no discharge rule. The possible adoption of new temperature criteria is viewed in its potential for changing plant operation. Finally, the importance of monitoring, modeling, and regulating is examined to determine thermal effluent control policies which consider natural variability.

3.1 Background on the Browns Ferry Nuclear Plant (BFNP)

The Tennessee Valley Authority (TVA) is a federal agency whose mission is in part to assure an ample supply of power for the Tennessee River Valley region at the lowest possible cost. When the economics of nuclear power revealed an advantage over fossil fuel in the 1960's, TVA decided to build its first nuclear plant. Because of the large need for cooling water, the plant was located on the north bank of Wheeler Reservoir at Tennessee River Mile (TRM) 294, in Limestone County, Alabama (see Figure 3.1-1) at a site known as Browns Ferry.

The hydraulic structure of the reservoir is controlled by the operation of two TVA owned dams: Guntersville Dam, located upstream of the plant site at TRM 349 and Wheeler Dam, located downstream at TRM 274.9. These dams also have hydroelectric power factored into their operation as well as flow control. The long-term mean flow at Wheeler Dam is 49,000 cubic feet per second (ft^3/s) with average stream flows 40 miles above the site for the years 1960-64 ranging from 32,000 ft^3/s during the summer months and 76,000 ft^3/s during the winter months. Channel velocities at the Browns Ferry site are about .7 feet per second (ft/s) in winter and .3 ft/s in summer.

Figure 3.1-2 shows a more detailed view of the plant site. The cross section of the river at the site consists of a navigation channel dredged to about a 30 foot depth and approximately 1800 feet in width. Although

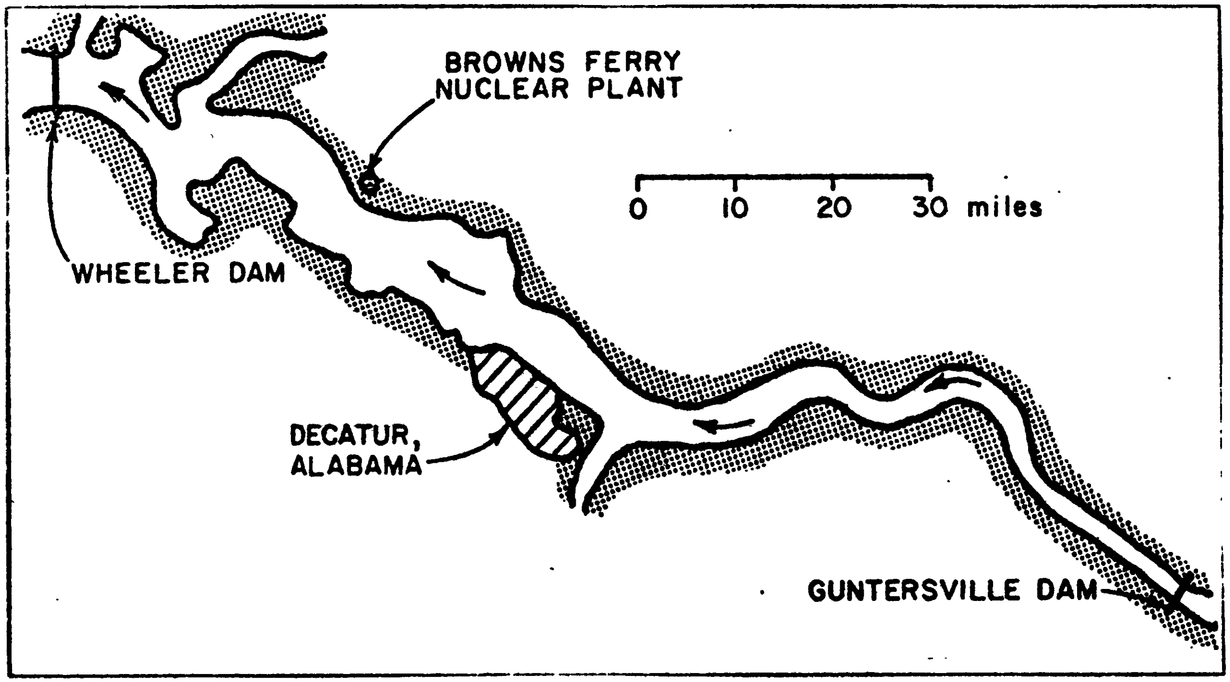


Figure 3.1-1 Location of the Browns Ferry Nuclear Plant on Wheeler Reservoir

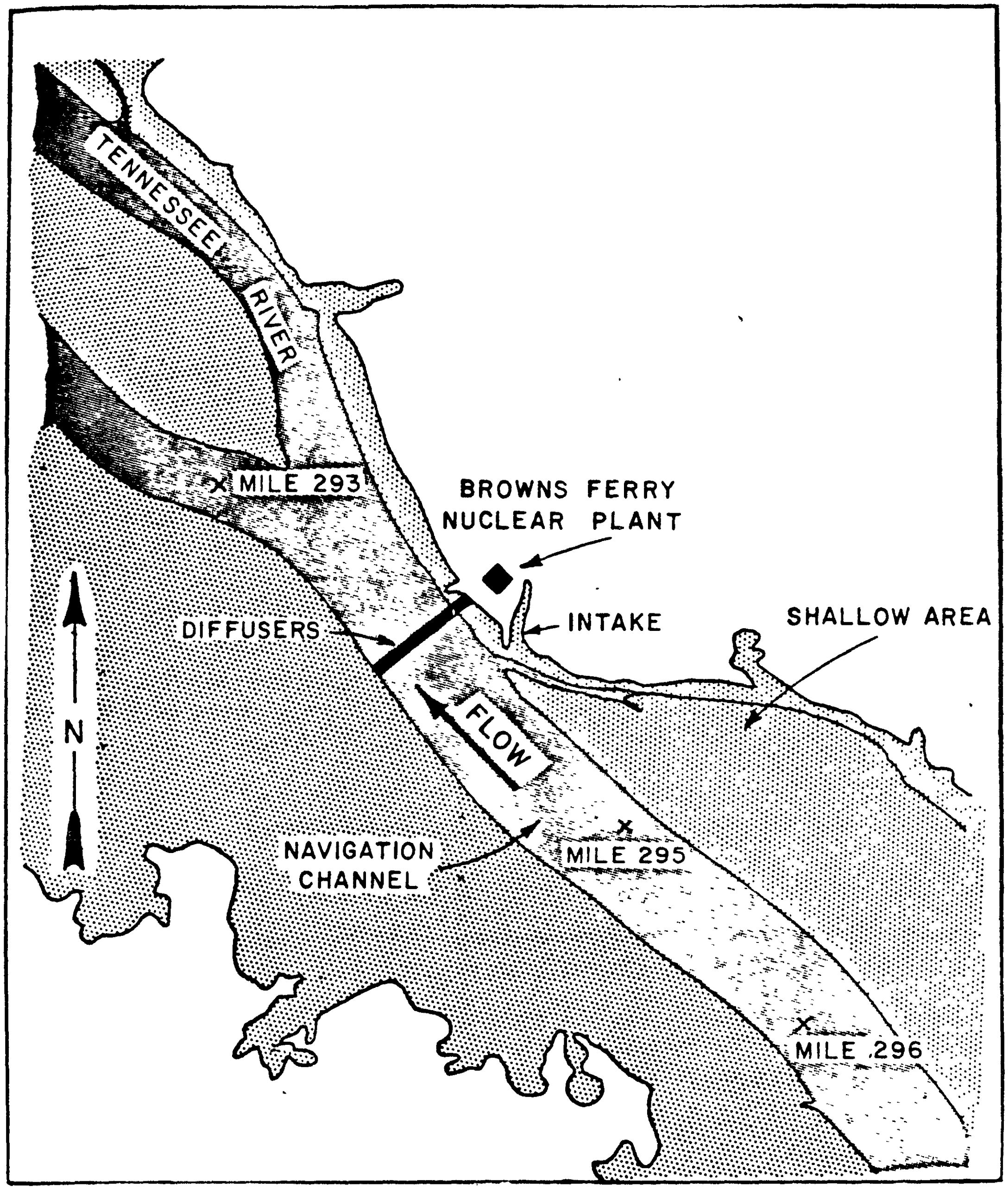


Figure 3.1-2 Detail of Wheeler Reservoir Near Browns Ferry Nuclear Plant

the main channel at this point contains only one-third of the total river width, 65% of the flow passes through it (TVA, 1971).

The BFNP consists of three identical boiling water reactors each with a net rating of 1067 MWe. The original plant design contained open-cycle cooling for heat dissipation. Water would be taken from Wheeler Reservoir at a rate of 4410 ft^3/s for three unit operation to provide condenser cooling and would be put back into the reservoir (approximately 25°F hotter than the intake water) through a multiport diffuser. The diffuser was designed to mix the heated condenser water with as much unheated river water as possible to prevent discharge into the surface strata and possible stratification of the reservoir. Stratification was undesirable since it would prevent mixing of the oxygenated surface layer with lower depths potentially causing dissolved oxygen problems in the lower reservoir.

Two major areas of concern were important in heat dissipation system design besides the stratification problem. The first was to prevent the heated discharge from moving upstream during low river flow periods. Physical laboratory studies of diffuser performance with three units in operation at full power revealed that a river flow of 40,000 ft^3/s would be needed to prevent an upstream wedge of heated water from affecting the intake water temperature and decreasing plant efficiency. The second criteria was the ambient thermal standards applicable to the Wheeler Reservoir site. The original heat dissipation system was designed to prevent a maximum river temperature of greater than 93°F outside a reasonable mixing zone with the change in temperature from upstream of the plant to downstream not to exceed 10°F. The minimum total river flow required to meet the allowable temperature rise was determined to be 17,000 ft^3/s (TVA, 1972).

In addition to the original diffuser design, the following operation procedures were agreed upon to prevent the upstream wedge and to meet the thermal standards: streamflow at the Browns Ferry site would be regulated using the upstream and downstream dam releases or power production by the plant would be decreased. Either procedure or a combination of both could be used to operate the plant within the context of TVA's total reservoir and power system. This, however, proved not to be the final design or operating procedure for the plant due to a revision in the ambient water quality standards. This revision began a lengthy regulatory process which has still not been finalized.

It is useful to briefly fit the Browns Ferry plant into the regulatory climate described in Chapter II. The case is extremely important since it includes not only the thermal control problems of a large nuclear-fueled unit faced by an electric utility, but also the conflicting roles of state and federal agencies.

The BFNP entered the chronology of thermal effluent control described in Section 2.1 after the Water Quality Act of 1965. The Atomic Energy Commission (AEC) granted a provisional construction permit for units 1 and 2 on May 10, 1967. At this time, the State of Alabama had proposed temperature standards (as a result of meetings between TVA and the state) as follows:

Water Use	Temperature Specifications
Public Water Supply Swimming and Other Whole Body Water-Contact Sports Shellfish Harvesting Fish and Wildlife Agricultural and Industrial Water Supply	With respect to cooling water discharges only, the ambient temperature of receiving waters shall not be increased by more than 10°F by the discharge of such cooling waters, after reasonable mixing; nor shall the discharge of such cooling waters, after reasonable mixing, cause the temperature of the receiving waters to exceed 93°F.

The Federal Water Pollution Control Administration (which later became part of the Environmental Protection Agency) did not approve the proposed criteria, required under the 1965 Act. After the passage of the National Environmental Policy Act (NEPA) of 1969, TVA, under a lead agency agreement with the AEC, issued Browns Ferry Nuclear Plant Units 1,2,3 - Draft Environmental Statement (TVA, 1971). (TVA was considered the federal agency with the largest responsibility for the plant.) This contained a brief consideration of all the impacts of construction and operation of the plant. TVA considered more than just the radiological impact of the plant (until then the AEC's only concern) due to its larger responsibilities.

A few months previous to the issuance of the statement (April, 1971), a Water Quality Standards - Setting Conference for Interstate Waters of the State of Alabama was held by EPA in Montgomery, Alabama. EPA recommended that the State of Alabama adopt temperature standards for streams and reservoirs in line with the criteria suggested in the 1968 version of Water Quality Criteria. With regard to the Browns Ferry site, a maximum temperature rise (ΔT_{max}) of 5°F and maximum allowable water temperature not to exceed (T_{max}) 86°F were recommended to support smallmouth bass, sauger, and walleye since these species had been listed in TVA's documentation on important sport fish in the reservoir. Comments on TVA's Draft Environmental Statement (ES)(appearing in the final ES, TVA, 1972) showed strong disagreement among the Alabama state agencies, particularly the Alabama Department of Conservation, Game and Fish Division, who strongly disagreed with the previously proposed higher state standards. In December 1971, EPA informed TVA that they would not accept the higher standards and that the standards would be altered as follows: "Waters of the Tennessee River Basin and portions of the Tallapoosa shall not be increased more than 5°F, above the natural prevailing background temperatures, nor exceed a maximum of 86°F" (TVA, 1972). These proposed standards were published by EPA in the March 11, 1972, Federal Register. Alabama adopted these standards and EPA approved them on September 19, 1972.

The Calvert Cliff's Coordinating Committee v. AEC (1971) decision forced the AEC to take a more active role in the thermal effects issue since the courts ruled that the AEC must consider all environmental impacts when licensing a nuclear plant. Prior to this ruling the AEC did not consider plant modifications for nuclear facilities which had been granted construction permits before the effective date of NEPA. The court held that this was inconsistent with AEC's duty to fully consider action avoiding environmental degradation. Since construction permits for all three units at Browns Ferry had been issued prior to NEPA this caused a delay in the licensing process.

As a result of the potential delay in receiving an operating license for unit 1 and of the change in the water quality standards, TVA decided to redesign the heat dissipation system to further minimize the thermal impact. The new design would provide supplementary cooling for those periods when the plant exceeded the new standards. Reasonable streamflow alterations could not be used, as in the original design, to meet the allowable temperature rise standard since the minimum total river flow required to meet the 5°F ΔT_{max} standard was 33,000 ft^3/s (TVA, 1972). Mechanical draft cooling towers were chosen as the least cost heat dissipation alternative. Although construction of the new towers could not be completed before the planned startup of unit 1, an operating license for the first unit was granted since only one unit in operation could meet the 86°F T_{max} and 5°F ΔT_{max} standards.

In the revised design, the three unit plant could be operated in three different modes of cooling as shown in Figure 3.1-3. The plant would stay on open-cycle cooling, open mode, whenever they were below the standards. Depending on the severity of the natural conditions, the heated condenser water could be pumped through the towers and then released into the reservoir (helper mode) or the plant could go to full recirculation of cooling water (closed mode).

Helper and closed modes of cooling have associated operating costs that are separate from the original costs of the additional cooling system equipment. Both closed mode and helper mode require power to pump the water through the towers. Closed-mode operation cannot cool the condenser water to the point of the ambient intake water due to the performance aspects of the cooling towers. The plant, therefore, loses efficiency since the heat sink water temperature is higher. There is also an upper limit on the intake water temperature due to a safety requirement for the nuclear units which requires a cutback in power when cooling tower performance is low. These problems cause additional decreases in net power output. The potential

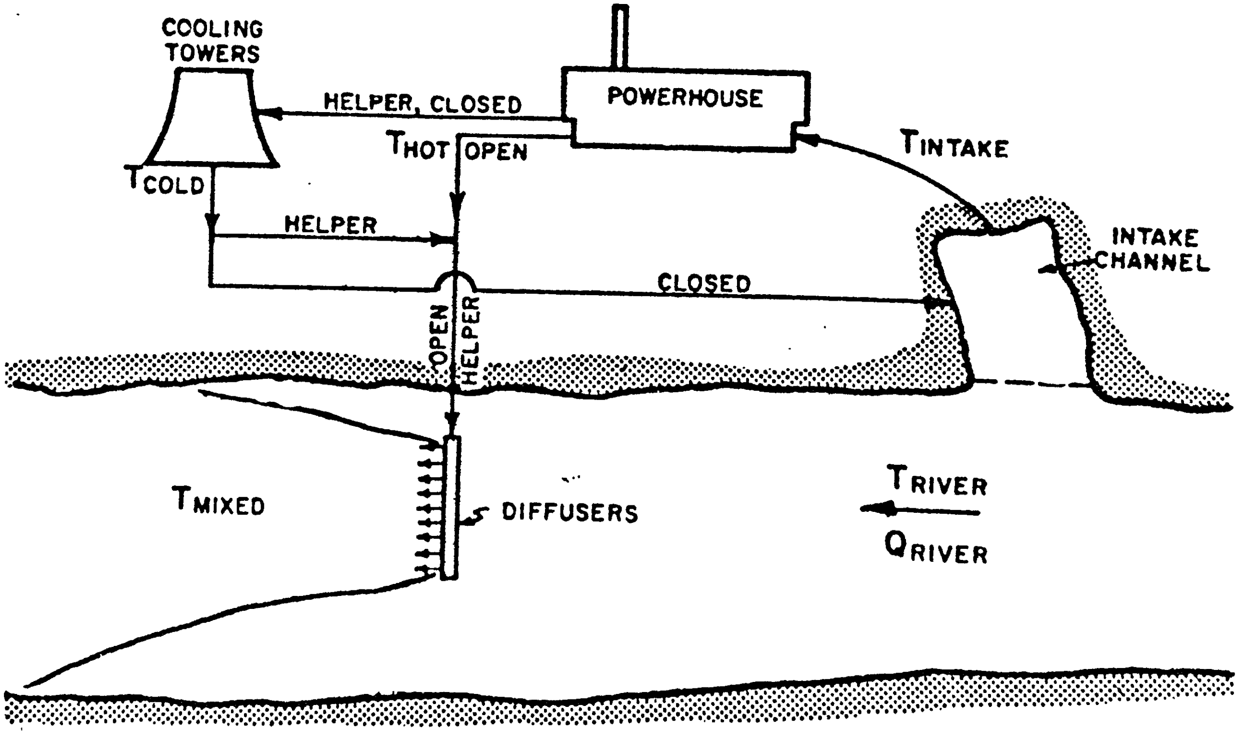


Figure 3.1-3 Schematic of Three Condenser Cooling Modes of Browns Ferry Nuclear Plant

loss of power prompted the use of the most flexible compliance with the standards so the helper or open modes could be used whenever possible.

The final operating procedure for the heat dissipation system depended on the terms of compliance with the final set of state standards. The temperature monitoring system that was used for preoperational studies was improved to continuously measure an ambient temperature upstream of the plant where it was not influenced by the thermal discharge, and also measure a temperature downstream from the diffuser induced mixing zone. Compliance with the ΔT_{max} standard was determined by comparing the difference between the mixed and ambient temperatures. Compliance with the T_{max} standard was determined by using the mixed temperature measurements. Plant operating procedures were established to determine ahead of time the optimum mode of cooling to meet the standards. A computer program utilizing projected river temperature, meteorological, river flow, and plant load data was developed to determine the temperature rise of the cooling water as it passed through the condenser (Harper and Waldrop, 1975). Analytical and empirical relationships were used in the program for plant heat rejection from the condensers, cooling tower performance, and mixing of discharge and river flows. The computer program provided an aid to the plant superintendent so he could work with the TVA personnel controlling dam releases (river flows) and select the most efficient operating mode at Browns Ferry.

Up to this point, the mixture of new regulations, new agencies, and added concerns for aquatic life had changed the design of the heat dissipation system considerably. Thermal standards and a compliance strategy finally emerged for the operation of the plant. Compliance with the standard became the next problem. TVA's in-stream monitoring, chosen to provide flexibility in plant operation, was plagued with the problem of considering the natural variability of temperatures in the vicinity of the discharge. The variability substantially influenced the determination of the measured mixed temperature and temperature difference making the results unrepresentative of the actual plant's contribution to the heating of the river. Figure 3.1-4 shows the original location of pre-operational in-stream temperature monitors used to determine compliance once the plant became operational. The original strategy for compliance with the 5°F maximum temperature rise standard used station 6 as the upstream monitor. The maximum of stations 9, 10 and 11 was used to determine the downstream temperature. The maximum of the downstream stations was also the temperature value used to determine complaince with the maximum 86°F standard. Instantaneous hourly measurements were taken at each station.

Figure 3.1-5 shows an example of the first variability problem that confronted TVA. It reveals the lateral spatial variation that occurred between the three downstream stations when the plant was in operation. Station 13 was a later replacement of the original station 9 which still demonstrates a peak well above the 5°F limit while the other station temperatures are just above 3°F and 1°F.

Short-term temporal variability also had a large effect on the definition of plant compliance. Figure 3.1-6 shows the plotted summary of water temperature differences between upstream station 4 and an average of downstream stations 10, 11 and 13 based on instantaneous 1 hour readings (TVA, 1977). Short term variations that caused temperatures above 5°F for one reading were found on September 15 and November 29.

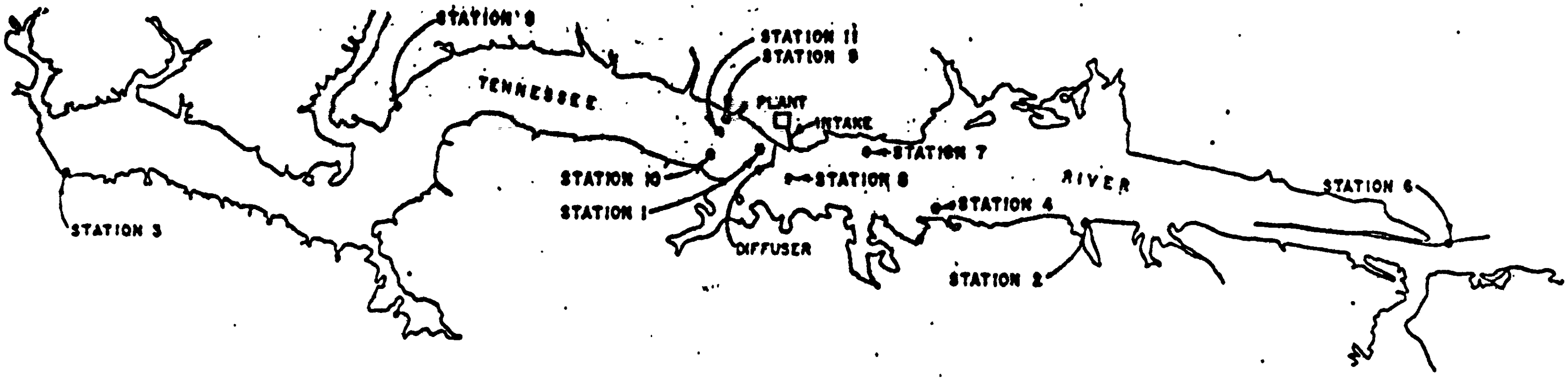


Figure 3.1-4 Browns Ferry Nuclear Power Station: Location of Original Temperature Monitors in Wheeler Reservoir

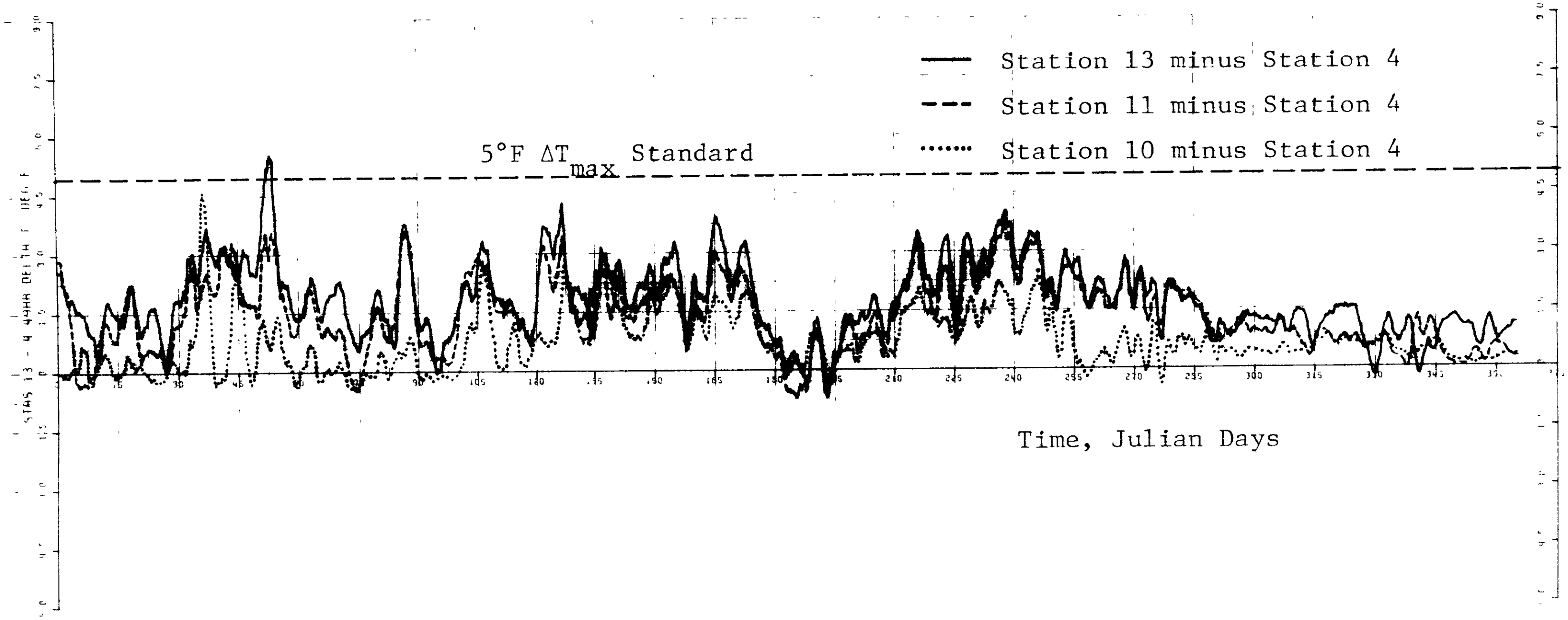


Figure 3.1-5 Individual Differences in Temperature for Various Downstream Stations and Upstream Station 4

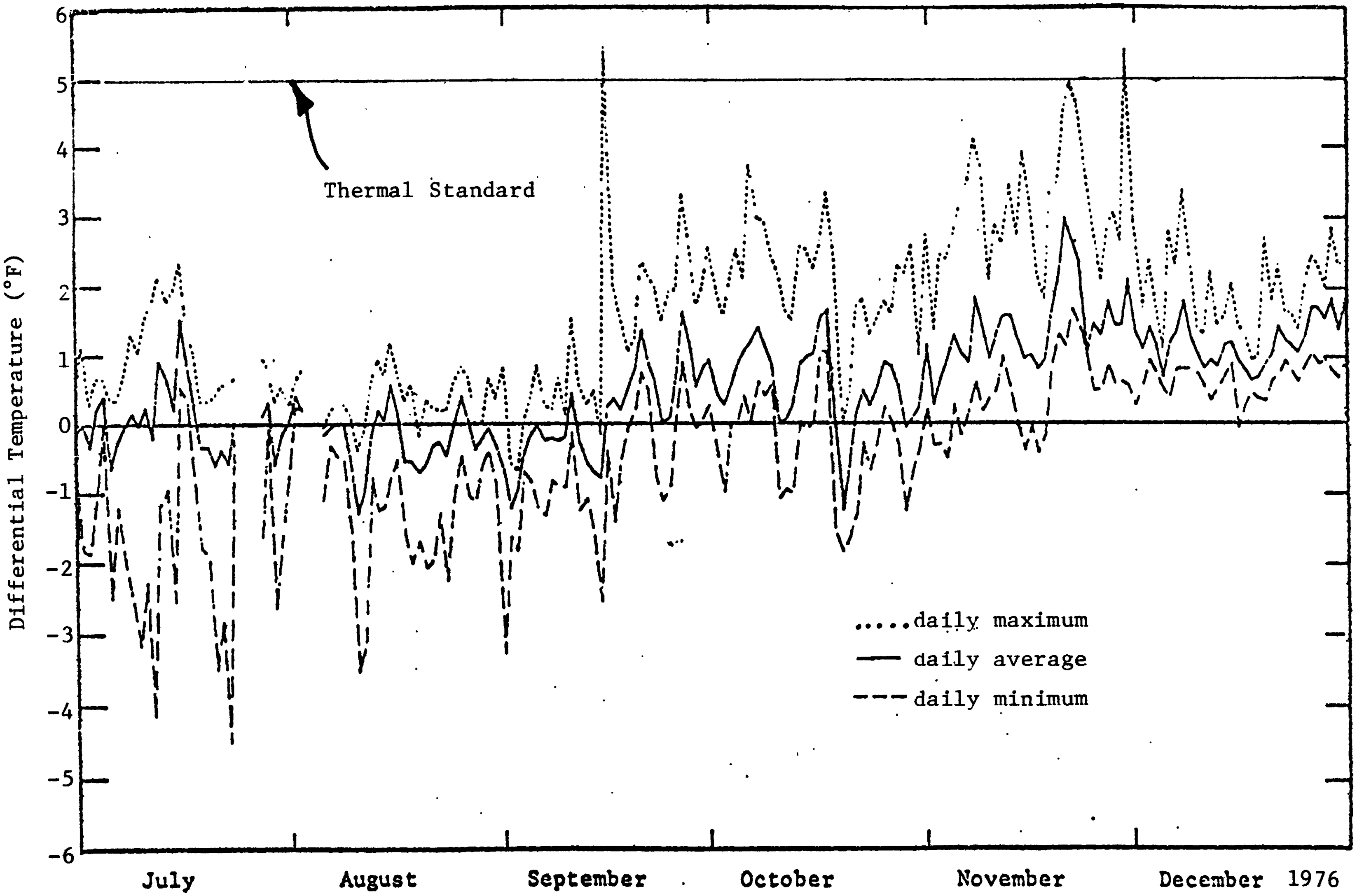


Figure 3.1-6 Hourly Instantaneous Readings at the Browns Ferry Nuclear Plant

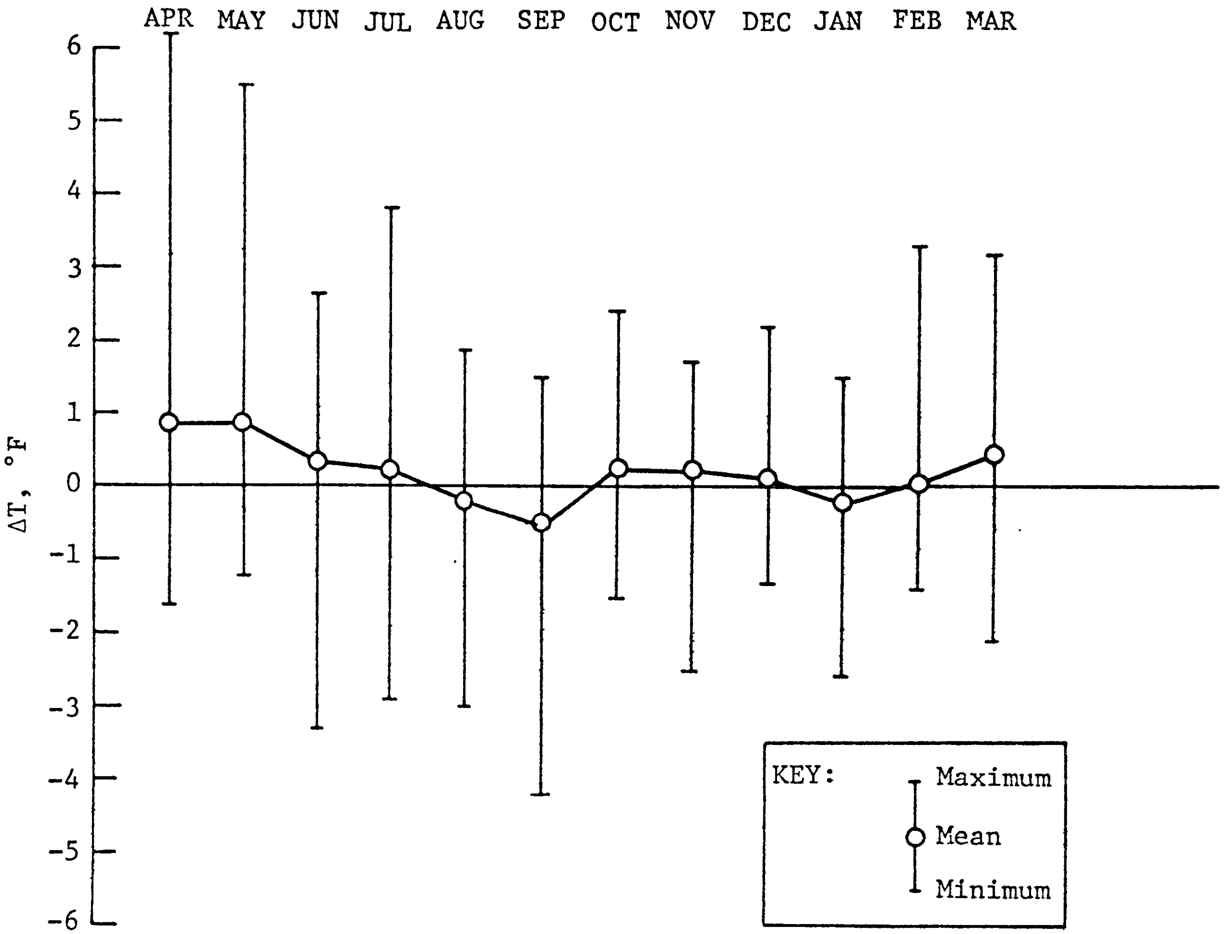


Figure 3.1-7 Monthly Average Natural ΔT and Ranges of Observed Data

Figure 3.1-7 illustrates another variability problem due to the longitudinal effects of using such a long distance between upstream and downstream stations (Freudberg, 1977). This figure shows the monthly average natural change in temperature between station 6 and station 1 (which is upstream of stations 9, 10 and 11). Although the mean values hover around zero, the range of observed data is from -4.2°F to +6.2°F without the plant in operation. The natural change in temperature caused temperature rise violations including several when the plant was not in operation (Ungate, 1978).

The above difficulties in showing compliance with the thermal standards point out the importance of spatial and temporal variability in control strategies. The next section will specifically examine the factors influencing natural temperatures in a river environment and will describe a modeling effort that could be used in better defining the actual effects of the plant on river temperatures.

3.2 Natural Temperature Variation

TVA's ability to show compliance with the Alabama thermal standards was hampered by natural temperature variations in the river. Both spatial and temporal variations caused difficulties in determining the plant induced effects. The following section briefly reviews the processes affecting temporal and spatial changes at the site revealing the major roles of meteorological conditions, topography, and river flows. The development of a one-dimensional model of natural temperature variations between upstream and downstream compliance monitors is presented as one approach to the variability problem.

3.2.1 Processes Affecting Natural River Temperatures

A natural longitudinal temperature pattern usually provides the spatial background for the temperature at any point in a river. Figure 3.2-1 shows such a longitudinal temperature pattern for the Tennessee River (TVA, 1970). The source of water for the river is high in the mountains of the northeast part of Tennessee and southwest portion of Virginia. The figure shows the large influence of the original temperature of the water source. Longitudinal effects are important for most of the river's length, especially during the warmer seasons.

Imposed on the longitudinal pattern are several temporal variations due to changing meteorological conditions. A seasonal variation in water temperature is due to changes in atmospheric conditions dependent on the position of the earth relative to the sun. Figure 3.2-2 shows the large seasonal variations in temperature at a specific monitoring location near the Browns Ferry site. Meteorological effects with smaller time scales, on the order of days to weeks, appear on Figure 3.2-2 as small humps. These effects are due to synoptic air masses settling into a region between storm fronts. Variations on the order of hours due to diurnal solar heating appear as peaks on the figure varying the river temperature as much as 5°F over the period of a day. Smaller meteorological variations such as wind speed and direction and cloud cover cause water temperature changes on the order of hours or less that are hard to identify due to the other random events occuring on small time scales. Seasonal and synoptic meteorological effects on river temperatures are essentially spatially constant over a small area of interest. Meteorological effects with time scales of a day or less can, however, produce important spatial variation

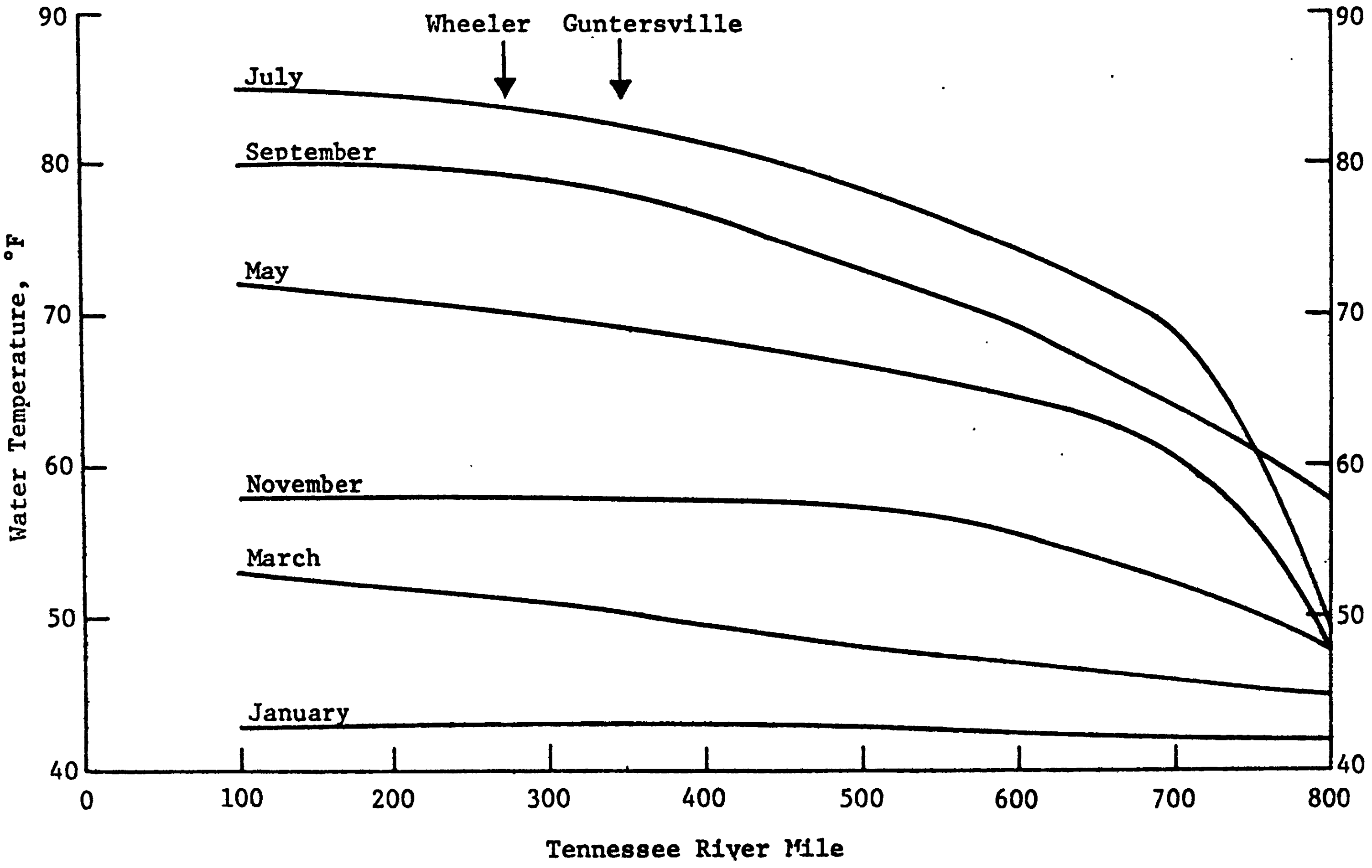


Figure 3.2-1 **Annual Variability of Longitudinal Temperature Distribution in the Tennessee River**

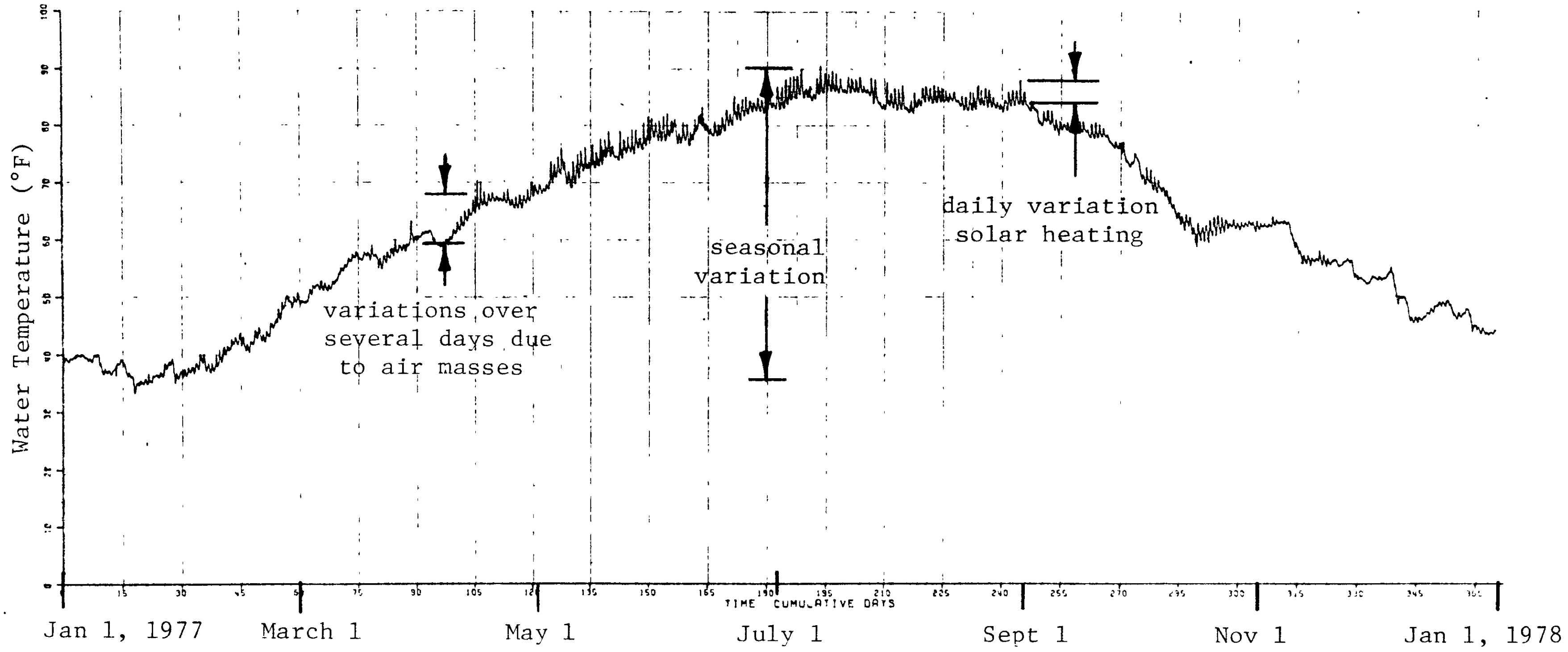


Figure 3.2-2 River Temperature Variations at 5 Foot Depths Due to Various Timescales of Meteorological Effects

(e.g. cloud cover, diurnal solar heating, etc.)

The topography of the river bottom coupled with river flows causes differences in temperatures over the spatial extent of the river. Shallow and/or stagnant flow areas will heat up or cool down considerably faster than deeper, faster flowing areas. An example of lateral spatial variation in a cross section of the river is shown in Figure 3.2-3 where the shallow area has temperatures as much as 4°F hotter than the deeper area. Complex changes in river flow due to inflows and variations in topography will also provide spatial changes as shown in Figure 3.2-4. These infrared photographs reveal spring heating and autumn cooling. Hotter temperatures, white areas, develop during the spring near the shallow areas and are advected into the deeper areas due to river flow or wind effects. The same effect is evidenced in the autumn period where patches of cooler water are present across the entire river cross section in the upper left of the picture.

In summary, river temperatures are influenced by temporal changes produced by meteorological conditions and river flows as well as the spatial changes produced by meteorological and topographic variations and river flow conditions. It is important to note that daily variations, lateral spatial variations, and longitudinal variations shown all have orders of magnitude near the specified temperature rise standard of 5°F discussed in Section 3.1.

The following discussion addresses how the longitudinal variation and some of the meteorological effects can be considered using a one-dimensional model.

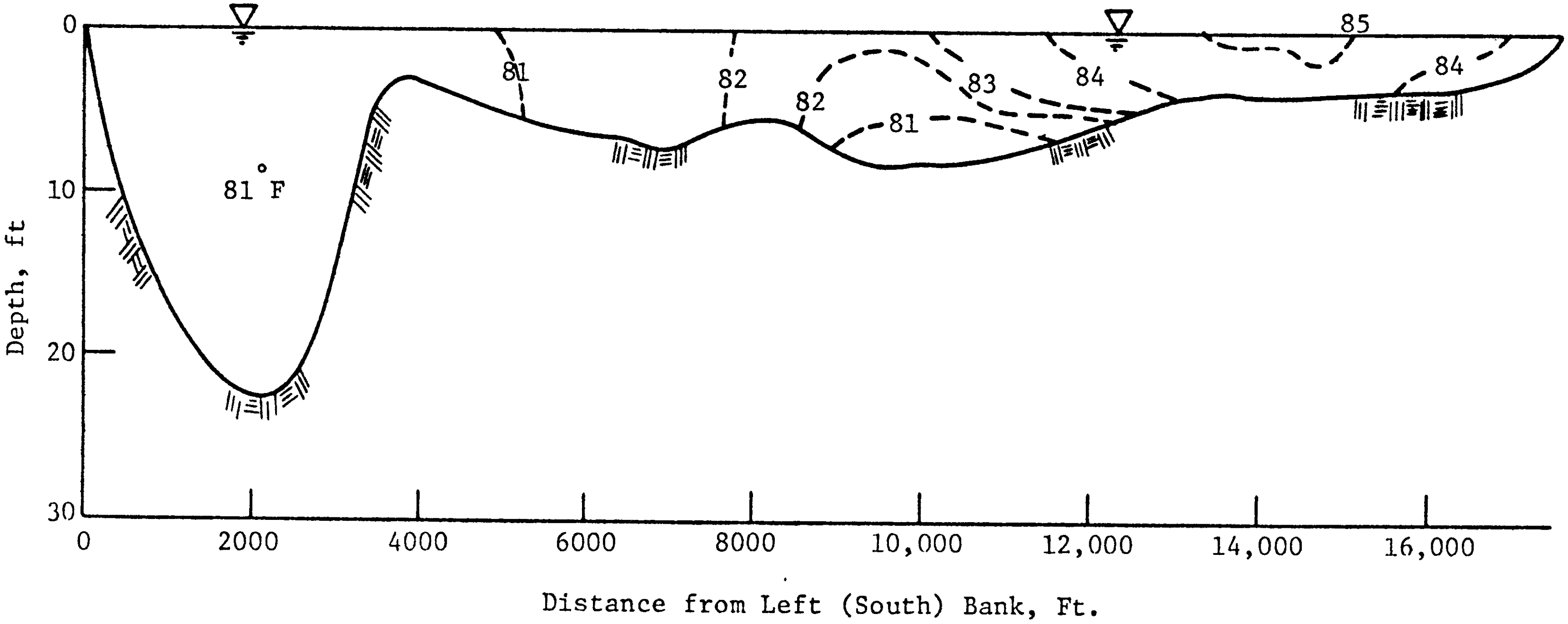
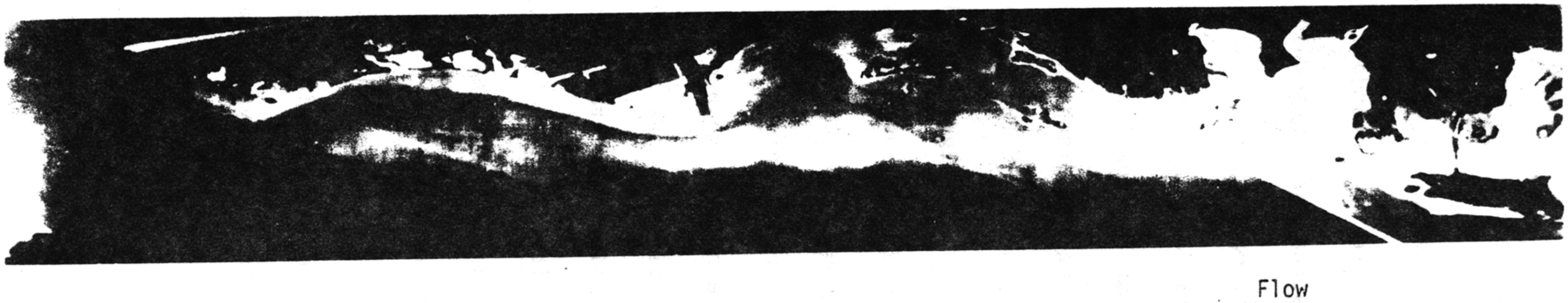


Figure 3.2-3 Cross-Sectional Temperature Measurement at TRM 301 Showing Differential Heating in Shallow Regions

Spring Heating



Autumn Cooling

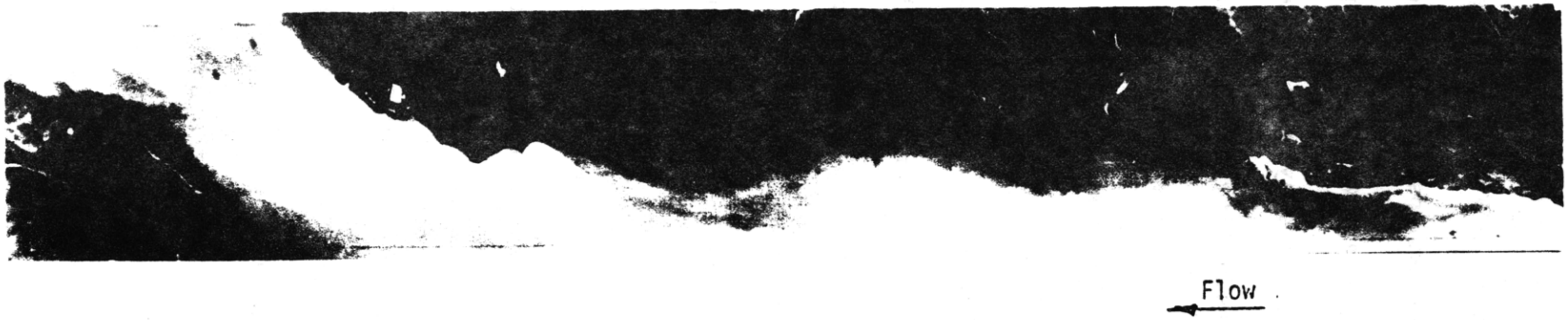


Figure 3.2-4 Infrared Photograph Illustrating Spring Heating and Autumn Cooling in Wheeler Reservoir

3.2.2 A Model for Predicting the Natural Temperature Variability at Browns Ferry

Section 3.1 revealed that one of the problems in complying with the State of Alabama's 5°F maximum temperature rise standard was the natural variability between upstream and downstream stations which often approached the temperature limit without the plant operating. Selecting the optimum cooling strategy to stay within the standard was also hampered by this issue. The possibility of smoothing out the power schedule at the dams to provide an adequate river flow for mixing the discharged water was being studied by TVA when the difficulty of separating the actual plant effects from the natural variability became evident. Figure 3.2-5 shows an example of the problem involved. The variation between an upstream and downstream monitor shows no relationship to the generation of the plant. What effect the plant had on the 5°F temperature rise standard is impossible to determine without some knowledge of the natural change in temperature between the upstream and downstream stations. This section reviews the work done by Freudberg (1977) in developing a natural change in temperature prediction model for the Browns Ferry site. In a later section an evaluation of the model's effectiveness is examined for determination of compliance with the maximum temperature rise standard.

A body of water undergoes variable heating and cooling due to a number of natural influences. Meteorological conditions (including solar heating), inflows and outflows, topographic structure, and hydrodynamics of the water all figure into the temperature distribution. Freudberg determined what portion of the natural change in temperature between two river locations at the Browns Ferry site could be modeled using a one-dimensional deterministic model based on the river flow, surface heat flux and the

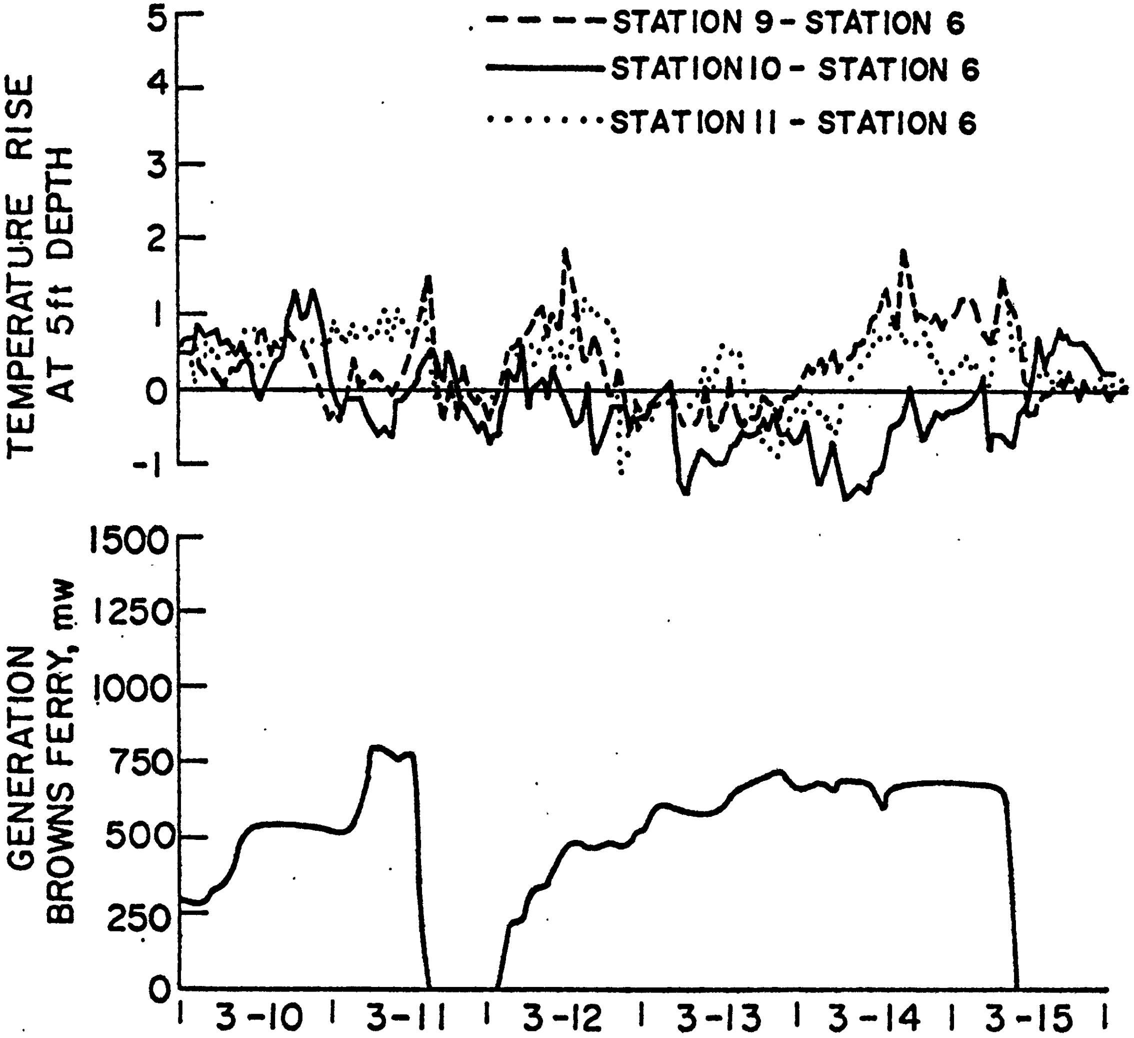


Figure 3.2-5 Measured Temperature Difference in the Tennessee River Between Upstream (Ambient) Monitor and Three Monitors Near Browns Ferry Station

known upstream temperature. Although such a model ignores such important processes as stratification, differential heating, and topographic effects, it still gives insight into a possible approach for separating plant effects from natural influences.

The basic one-dimensional convective diffusion equation provided the basis for the modeling approach:

$$\frac{\partial TA}{\partial t} + \frac{\partial (QT)}{\partial x} = \frac{\partial}{\partial x} (AE \frac{\partial T}{\partial x}) + \frac{\phi_n(t)B(x)}{\rho C} \qquad (3.2\text{-}1)$$

where:	T	is the cross-sectional average temperature
	A	is the cross-sectional area
	Q	is flow through cross section
	t	is time
	x	is the longitudinal position from the upstream station
	E	is a diffusion coefficient
	$\phi_n(t)$	is the net heat flux, a function of time
	$B(x)$	is the width, variable with distance along the river
	ρ	is the density of water, assumed constant
	C	is the heat capacity of water, assumed constant
and	h	is the average depth

Freudberg assumed a constant cross-sectional area, a constant width, and river flow as a function only of time. Dimensional analysis showed that the dispersion term could be neglected since it was unimportant relative to the other terms. The resultant equation was placed in Lagrangian coordinants to simulate the change in temperature of a parcel of water as it travels downstream, and was then integrated over time. This yields the desired one-dimensional model as follows:

$$\Delta T(t) = \frac{1}{\rho Ch} \int_{t-\Delta t}^{t} \phi_n(t)dt - [T_u(t) - T_u(t - \Delta t)] \qquad (3.2\text{-}2)$$

where: $T(t)$ is the change in temperature between the two points in the river

$T_u(t)$ is the upstream temperature

and Δt is travel time for the parcel to move between the two points in the river

Hence, the temperature difference between the two points in the river was modeled considering two effects: the net heat input over Δt and the change in temperature at the upstream point during Δt.

Many of the natural processes not considered by the one-dimensional model produce random events which have time scales on the order of hours. Since one-dimensional influences are felt over longer periods (on the order of 24 hours), the one-dimensional model was compared to a two-day running average of the measured temperatures at two of the instream monitors used for compliance purposes at the Browns Ferry site. The measured values were obtained during a period when the plant was down for repairs.

Input for Equation 3.2-2 consisted of 49-hour averages of the upstream river temperature, surface heat flux (determined from meteorological conditions and upstream river temperature), and the river flow at the site. Figure 3.2-6 shows the ability of the one-dimensional model to fit the 49-hour averaged data. The model provided a fairly good replication of the peaks and valleys of the measured change in temperature, although it is less accurate in the fall and winter. Freudberg suggested this is due to the non-homogeneous nature of the body of water during the later period

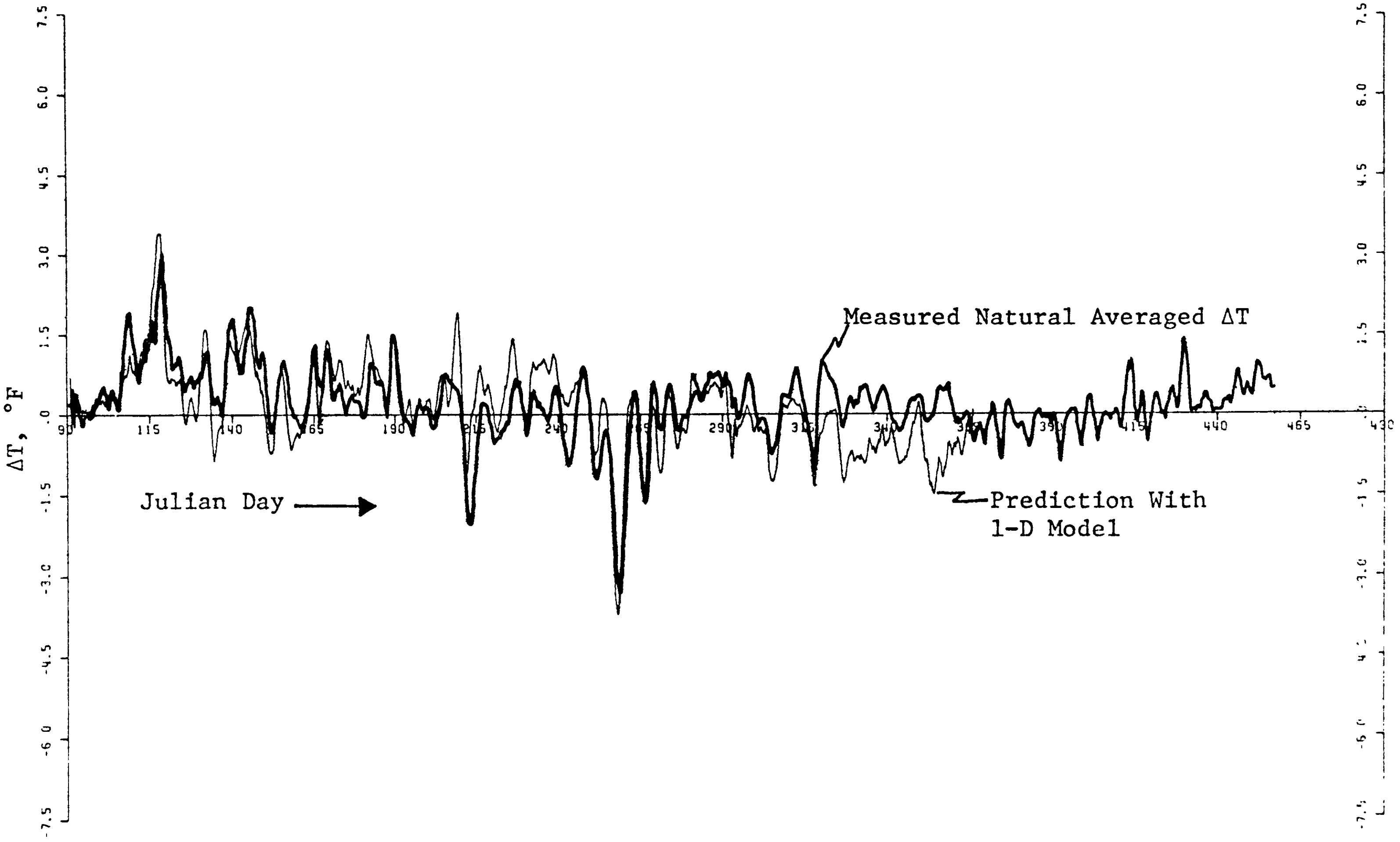


Figure 3.2-6 Comparison of Measured Hourly Averaged Natural ΔT With Prediction Using 1-D Model

when complex mixing processes take place due to the breakup of stratification. The differences in the values, however, do point out that non one-dimensional effects still play a significant role in the natural change in temperature.

Subtracting the results of the natural change in temperature prediction from the measured change in temperature provides one method of separating the plant's actual effects on river heating. A closer look at the use of this model in defining the thermal effect of the plant on the temperature rise in Wheeler Reservoir will be examined in the next section. The model will be coupled with various temporal and spatial averaging techniques to provide input to the plant operating staff so the most power can be produced while still staying within the ambient thermal standards.

3.3 Thermal Compliance Strategies

In Section 3.1, the 5°F maximum temperature rise (ΔT_{max}) standard was shown to pose difficulties in proving compliance even though the problems were most often due to natural temperature variations rather than plant effects. Section 3.2 demonstrated that longitudinal and lateral spatial variation, and short-term meteorological variations may be important contributors to the monitoring problem. The following section examines monitoring strategies aimed at obtaining maximum plant output while still meeting ambient thermal standards. Different locations of the instream monitors, the spatial and temporal averaging of the monitors as well as the use of the model described in Section 3.2 are used to separate the plant's effects from natural temperature variations. The effect of changes in heat dissipation system operation, and alternative ambient thermal standards are also discussed regarding maximizing plant output under environmental constraints. This work was done as part of a team effort and appears in detail in Stolzenbach et al.,(1979).

The power output of the plant using mixed-mode operation was simulated to test the sensitivity of varying thermal compliance strategies. A computer model was developed using river flow and the upstream water temperature as input to calculate an hourly plant induced river temperature at the downstream monitoring location. The plant induced temperature was added to actual downstream temperature measurements for a year when the plant was not in operation. If the resultant temperature violated either the maximum temperature rise, ΔT_{max}, or maximum temperature, T_{max}, standards, the model recalculated the power output of the plant based on using helper-or closed-mode cooling to meet the thermal limits. The model included diffuser and cooling tower performance based on actual computer programs used at the plant to predict needed thermal controls. Various thermal compliance strategies affecting the actual downstream temperature used by the model; the method of proving compliance with the ΔT_{max} standard; the heat dissipation system operation; or the actual numerical thermal standards could then be evaluated for their effects on power output.

Modeling results showed the power output at Browns Ferry can be significantly affected by the need for supplementary cooling (helper mode) or closed-mode operation. Figure 3.3-1 shows the power output of the plant over a year if operated the entire year in one mode, regardless of thermal standards. Open-mode operation showed decreased plant efficiency due to higher intake temperatures during the hotter seasons. Helper-mode operation had the same intake temperature, therefore the same loss of efficiency as open mode, plus an additional loss of power required for cooling towers. Closed-mode operation required the same power loss due to cooling tower

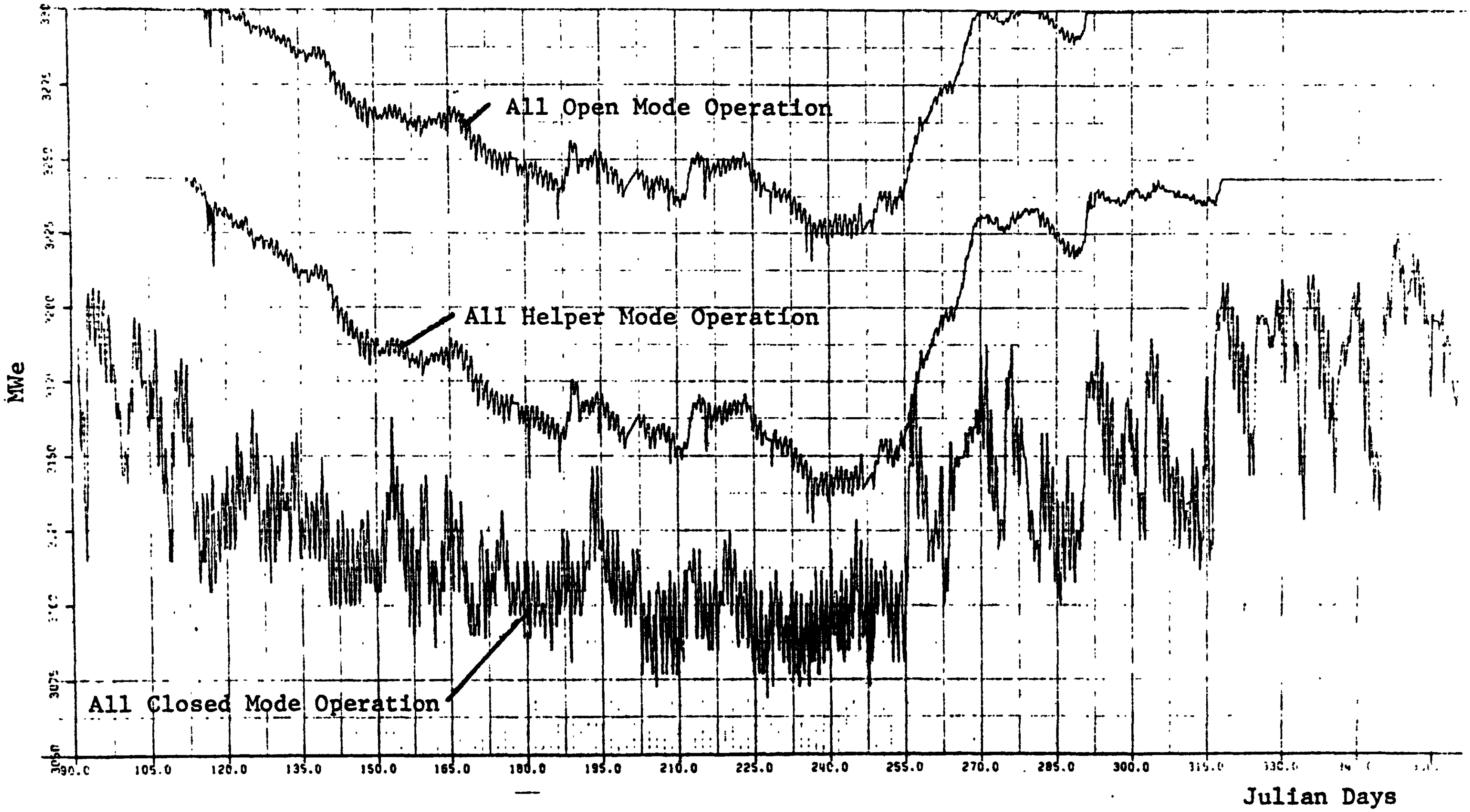


Figure 3.3-1 Power Output of Plant Under Three Separate Modes Of Operation

operation (as in helper mode) and was also heavily influenced by the cooling tower performance. This performance, based on ambient meteorology, determined the intake water temperature to the condensors, so it effected the overall plant efficiency. Each simulation of plant performance under a certain control strategy assumed that the plant can immediately switch to the desired mode of operation, (open mode) unless other modes are necessary to meet the ΔT_{max} or T_{max} standards. The plant must still burn the same amount of fuel when using the cooling towers, therefore there is decreased plant efficiency and a fuel loss associated with use of helper- or closed-mode cooling. The loss in plant capacity due to decreased efficiency also means that power must be generated elsewhere to meet the final demand. The loss in capacity is more critical since power must be purchased or more generating facilities must be planned. This combined loss will be termed power loss in the following discussion.

The simulation model of plant operation provided hourly determinations of the cooling mode needed to meet the thermal standards. If helper or closed modes were needed the resulting power loss above use of open mode was determined. These results are displayed in three forms: 1) a graph of power output of the plant in the best mode of operation (lowest power loss) which still meets the ambient standard, 2) a sorted display of hours the plant had reduced power output due to running in either helper or closed mode, and 3) the total cumulative output power loss for the period of observation. Figure 3.3-2 shows a typical evaluation result of Form 1) where power output is plotted for each hour of the observation period grouped by Julian days (cumulative days in a year with January 1 as Julian day 1). This figure can be considered a mixture of the curves shown

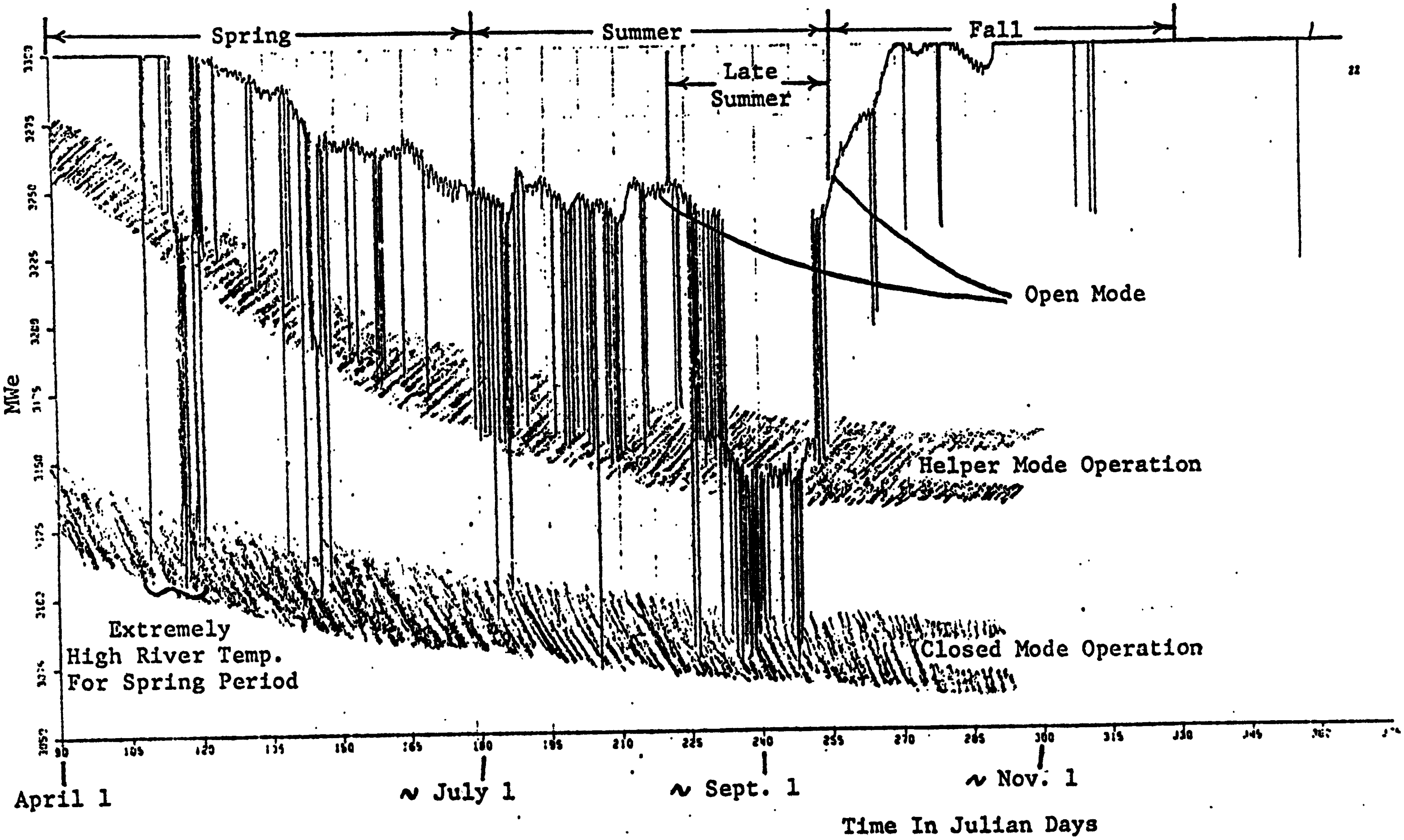


Figure 3.3-2 Typical Evaluation Result for Power Output of the Plant in Best Mode of Operation

in Figure 3.3-1 depending on which mode needed to meet the standards. The figure shows the range of each mode of operation, seasonal periods, constant open mode operations, and the spikes due to switching between various modes of operation in response to river temperatures. The power values determined from the plant output in best mode graphs were subtracted from the power of the plant if it was in open mode. These values of power loss, due to running the plant in helper or closed mode, were sorted and displayed versus the number of hours these values of power loss occurred. Figure 3.3-3 shows a typical example of a sorted power loss evaluation, Form 2), and points out the ranges of open and closed modes of operation. The power loss, due to running the plant in helper or closed mode, during the entire observation period were totaled and are reported as the cumulative hourly power lost in Megawatt hours (MWe-hr),Form 3). These values do not consider the thermal inefficiencies of running the plant in open mode. Comparing the cumulative hourly power loss provides an easy method of comparing the results of each sensitivity analysis. These values appear in brackets on the plots described as Form 2).

Two base cases are used in comparing the result of various monitoring strategies. Base Case A used the ideal case where the natural temperature was considered equal to the natural downstream temperature. In this instance all of the effect on the river temperature change between these two points was plant induced. This base case can be thought of as having the lowest possible power loss under a specified ΔT_{max} standard since the natural river temperatures only cause loss due to the thermal efficiency of the plant and not due to the temperature's effect on the determination of compliance. Available instream temperature data, when the plant was not in operation,

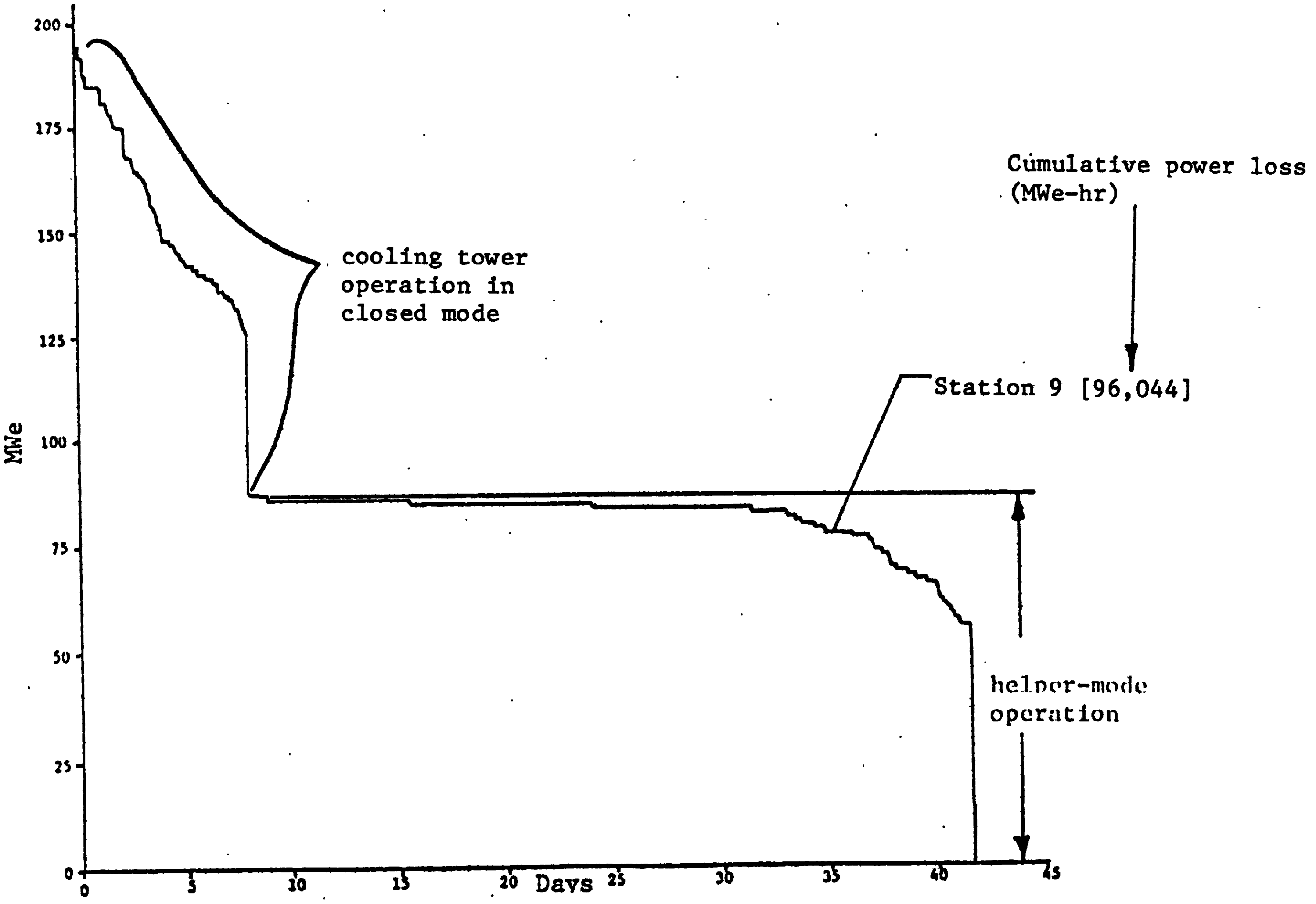


Figure 3.3-3 Typical Example of Sorted Power Loss Evaluation - Power Output Losses Shown are Those Above Open Mode Operation

consisted of readings at upstream station 6 and downstream stations 1, 9, 10, and 11 as shown in Figure 3.1-4. Evaluations of the effect of using a single downstream monitor found that station 9 produced the largest cumulative power loss for all the downstream stations. Hence this case was chosen as a basis for comparison and is referred to as Base Case B in the following discussion. The sensitivity analyses of monitoring strategies therefore have results that fall between these two base cases.

3.3.1 Spatial and Time Averaging of Compliance Monitors

The first sensitivity analyses determined the effects of location and spatial averaging of the downstream monitors on the choice of cooling mode necessary to meet the standards. The stationing of an individual monitor for a downstream reading of T_{max} and ΔT_{max} was critical as shown in Figure 3.3-4. The results show less use of both helper and closed modes progressing from station 9 to station 10 to mid-channel station 11. For example, station 11 losses were half those of station 9 if Base Case A is the ideal. An average of the three downstream stations resulted in losses near those using just station 10. This average was closer to station 11 than station 9 which suggests that station 9 may have been receiving consistantly higher temperatures, possibly due to natural heating.

Time averaging was next used as a possible method of leveling out short term variances above the standard. Natural upstream, natural downstream and calculated induced river temperatures due to the plant operation were all averaged before the mode of operation was selected. Periods of 2, 24 and 48 hours were examined using a single downstream monitor, station 9. In general, increased time averaging of river temperatures and induced temperatures decreased power losses by removing or decreasing some of the

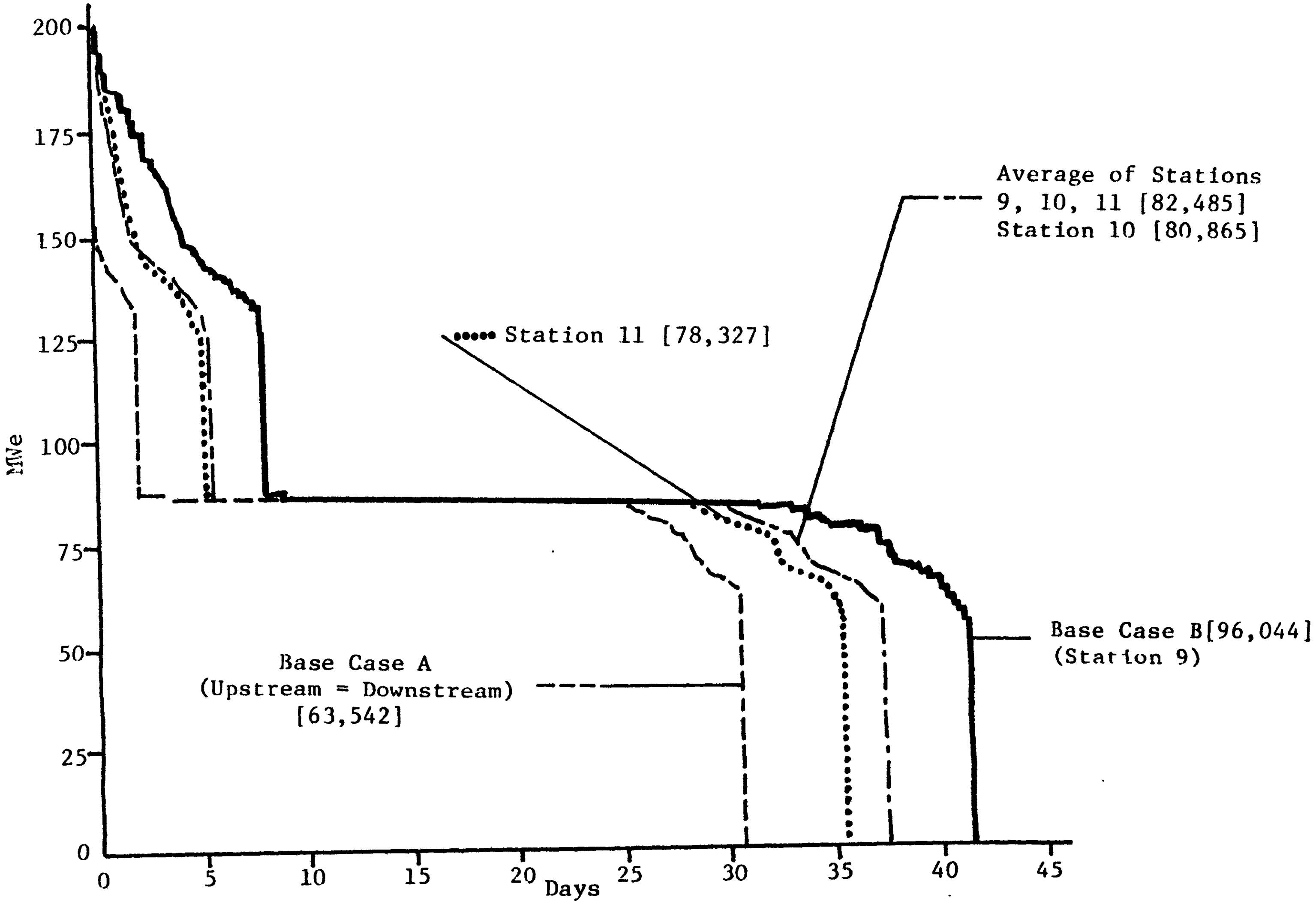


Figure 3.3-4 Comparison of Power Loss Curves for Monitor Location and Spatial Average Studies

temperature rises above the standards' limits. In decreasing this variance, short-term violations causing the plant to switch from open to helper (or helper to closed) were reduced. This was particularly true during the spring and summer periods as shown in Figures 3.3-5 and 3.3-6 which are power output plots in the best operational mode for 1- and 24-hour averaging times. The reverse occurred during the fall period where short term temperature dips (before the averaging) allowing the plant to switch from helper to open (or closed to helper) are removed by increased time averaging. This increased power loss was not as prevalent as the decreased loss during the spring leaving a yearly net decrease in power loss. Finally, the change from 2 hours to 24 hours was the only significant advantage since the 2-hour averaging was little better than no averaging Base Case B, and 48-hour averaging was not significantly better than 24 hours (see Figure 3.3-7). Therefore, the major time scales that influence the plant's compliance are between 2 hours and 24 hours. Combining the spatial averaging of downstream stations 9, 10 and 11 with a 48-hour average produced the expected decrease in power loss which showed that both spatial and temporal effects were important.

3.3.2 Use of the Natural Temperature Change Model

The one-dimensional natural temperature change (1D ΔT) model discussed in Section 3.2 was combined with the various averaging techniques presented above. The plant simulations prior to the use of the one-dimensional model used the upstream temperature as the plant intake temperature and factored the diffuser performance based on the known natural downstream temperature. Ideally, the natural downstream temperature should

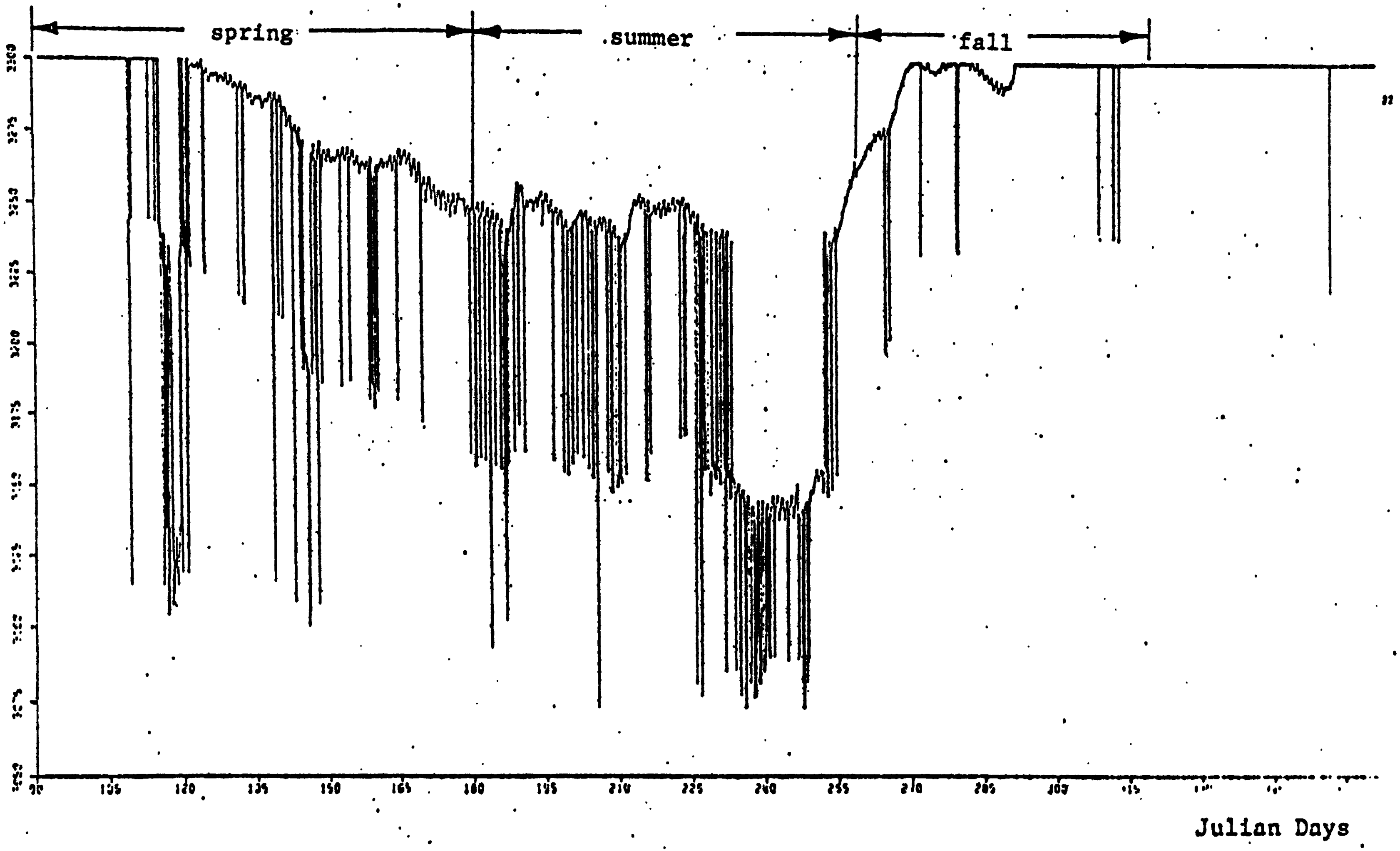


Figure 3.3-5 Base Case B Power Output in Best Mode, 1-hour Average (Downstream Station 9)

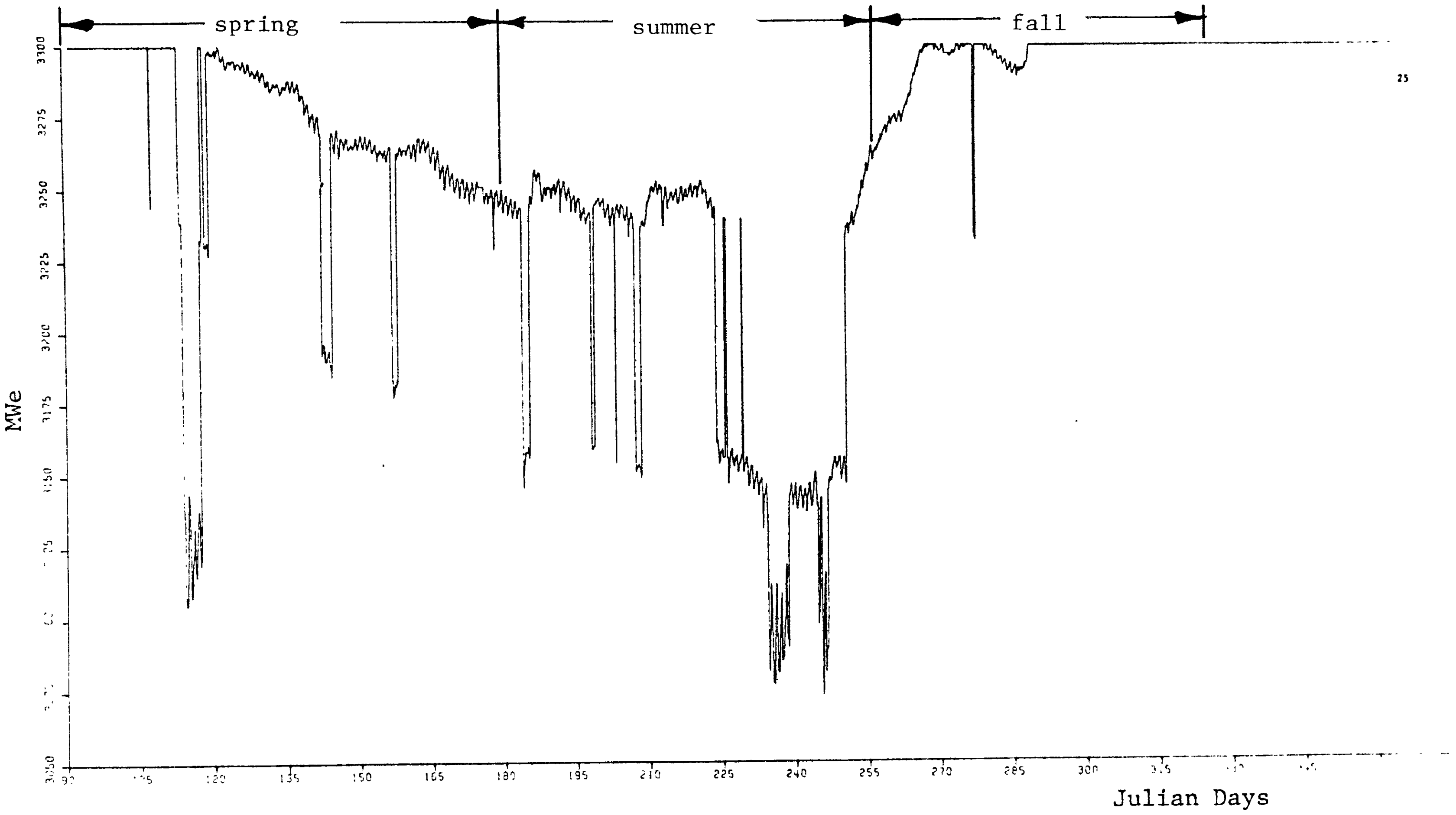


Figure 3.3-6 Twenty-Four Hour Running Time Average Power Output in Best Mode (Downstream Station 9)

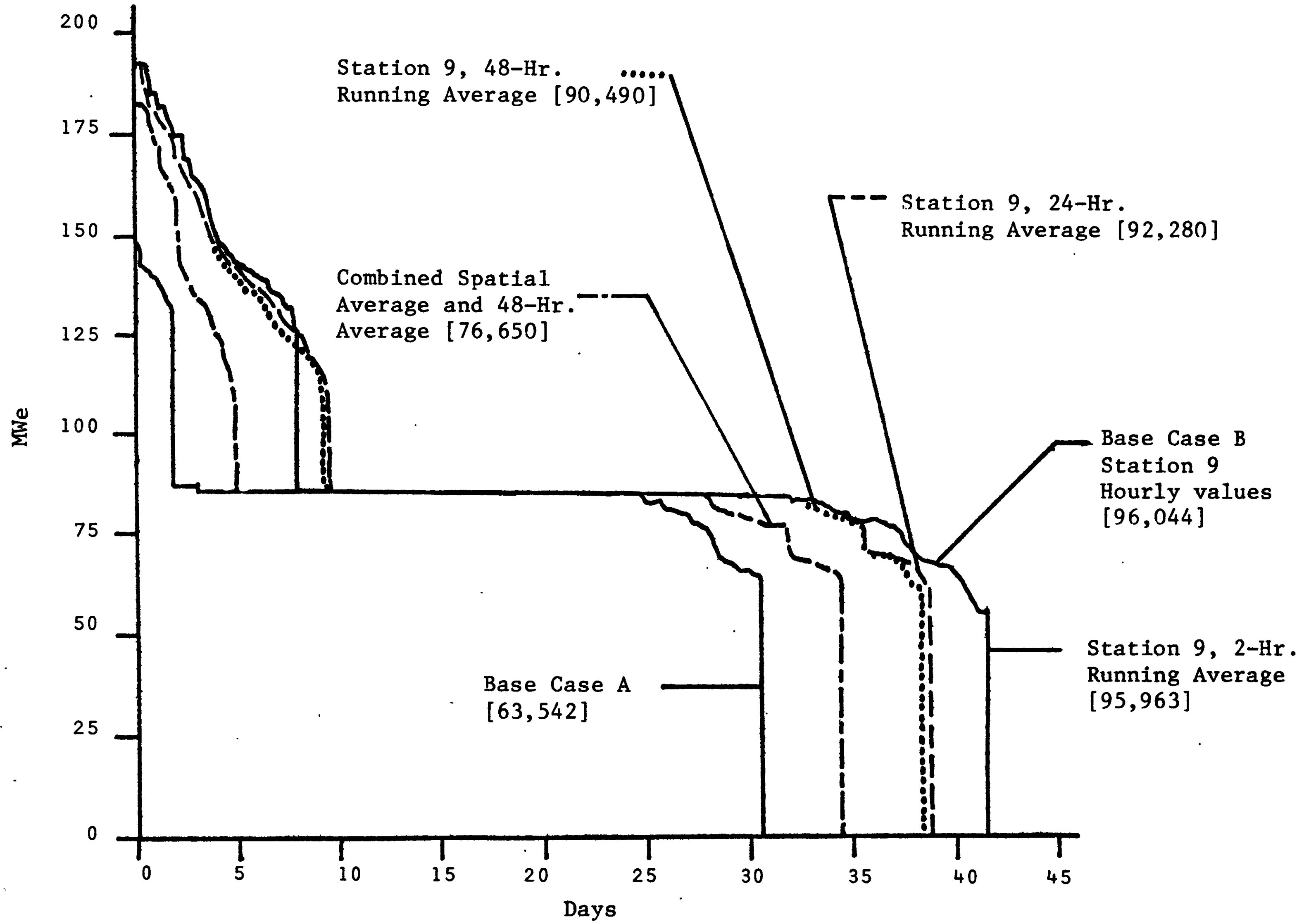


Figure 3.3-7 Comparisons of Sorted Power Loss Curves for Time Averaging Studies

be equal to the upstream temperature but this was previously proved not to be the case. The 1D ΔT model attempted to predict what the downstream temperature would be due to natural heating since while the plant is operating it is impossible to measure the natural downstream temperature. If the model result was subtracted from the downstream temperature after diffuser mixing then the outcome would be a temperature representing a truer plant induced temperature rise. Figure 3.3-8 shows the progression as the 1D ΔT model was added to station 9, the spatial average of stations 9, 10 and 11, and finally the spatial average of stations 9, 10 and 11 and the 48-hour time average. In each case the 1D ΔT model cut down on use of closed and helper modes. The cumulative power loss can be used as a quick check on exactly how well the 1D ΔT model operated. The range of power loss savings using the model was from 40% for the single downstream station 9 to 70% for the combined spatial and time averaging. The 1D ΔT model can be used to separate the natural heating from plant effects providing a more accurate determination of the ΔT_{max} standard, with resultant power savings.

3.3.3 Changes in Thermal Standards

The next set of sensitivity analyses considered how various numerical changes in the thermal standards affected power loss. Both the maximum allowable change in temperature from upstream to downstream (ΔT_{max}) plus the maximum allowable temperature (T_{max}) were considered. At the time of the study these standards were 5°F for the ΔT_{max} and 86°F for T_{max}. Figure 3.3-9 compared these standards with ΔT_{max} equal to 3°F and 10°F as well as changing T_{max} to 90°F. All the curves show reduced power loss except the ΔT_{max} = 3°F which had a large amount of loss. The difference between

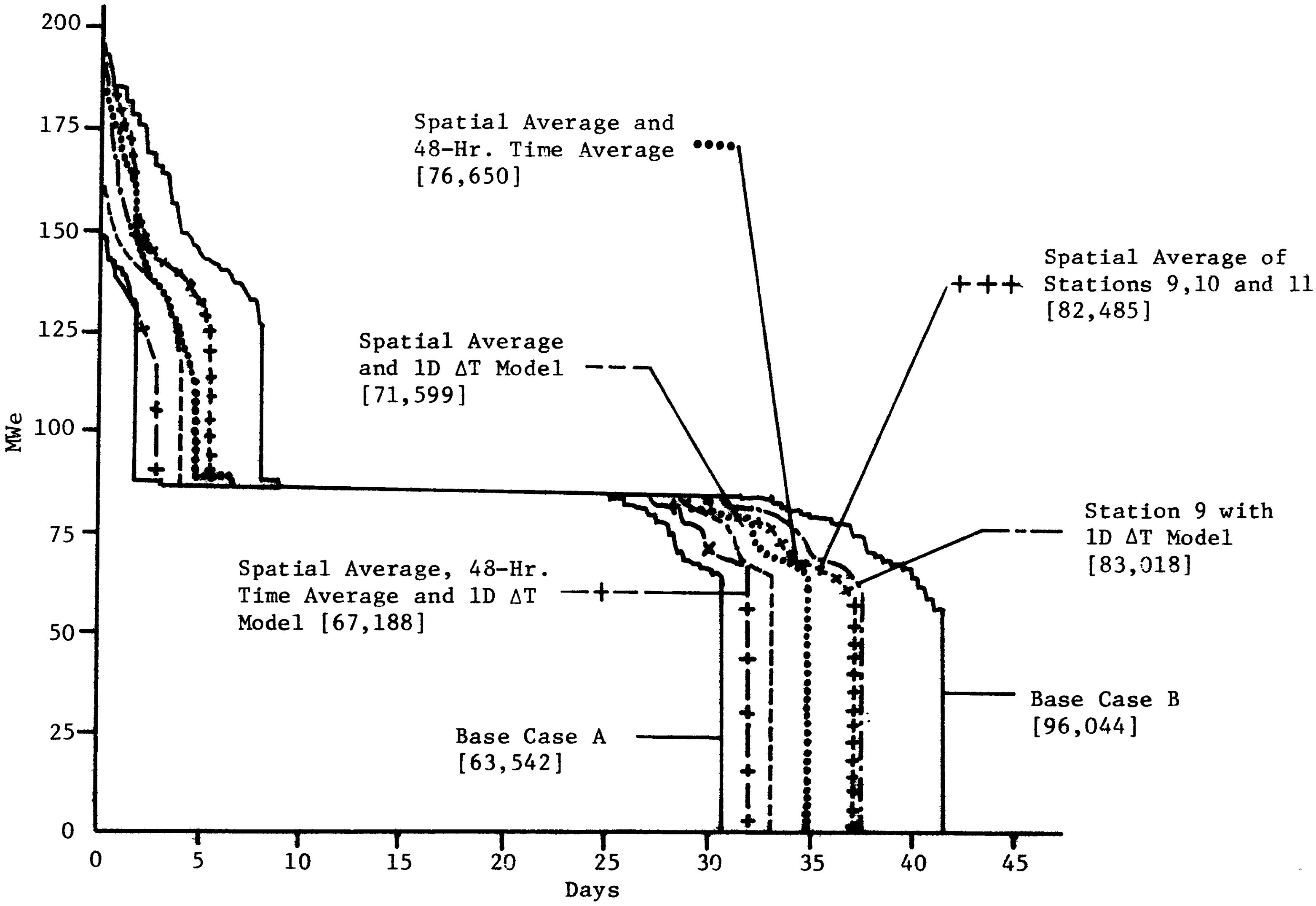


Figure 3.3-8 Comparisons of Sorted Power Loss Curves with Use of One-Dimensional Estimated Change in Temperature (1D ΔT) Model

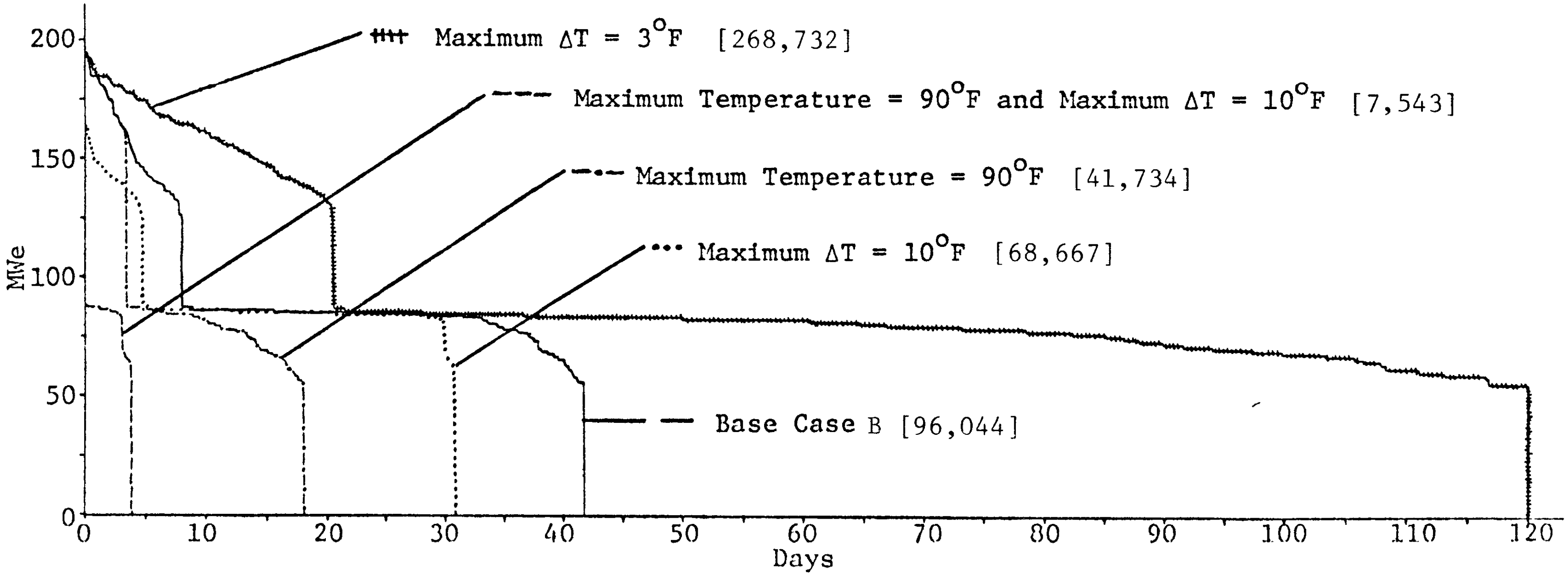


Figure 3.3-9 Comparison of Sorted Power Loss Curves for the Sensitivity of Thermal Standards Study

a T_{max} = 90°F and the ΔT_{max} of 10°F can be seen quite clearly. The T_{max} = 90°F did significantly better than the ΔT_{max} = 10°F because it allowed a sizable decrease in closed-mode operation. The power output in best mode plots show the seasonal effects of each change in standard. The ΔT_{max} = 10°F case (Figure 3.3-10) had less use of helper-and closed-mode operation in the spring period while T_{max} = 90°F evaluation (Figure 3.3-11) used no closed-mode operation in the summer period. Hence the ΔT_{max} standard was the overriding factor in the spring and T_{max} was most important in summer operation. These evaluations revealed the influences on power output due to various thermal standards. An important result was that the T_{max} standard may be more important if the utility's peak demands are in the summer, the time when the most capacity is needed. The results also showed that small changes in the standard (stricter limits) can have a large influence on plant output.

3.3.4 Changes in Plant Operation

Finally, a brief review of changes in plant operation was considered. The significance of using mixed-mode operation is shown on Table 3.3-1 where the cumulative hourly power loss is displayed for various combinations of mixed-mode operation.

Table 3.3-1

Effect of Various Cooling Modes on Power Loss

Mode	Cumulative Hourly Power Loss, MWe-hr
All Open	0
No Open	481,040
No Helper	145,664
No Open or Helper (All Closed)	911,858
Base Case B (Station 9)	96,044

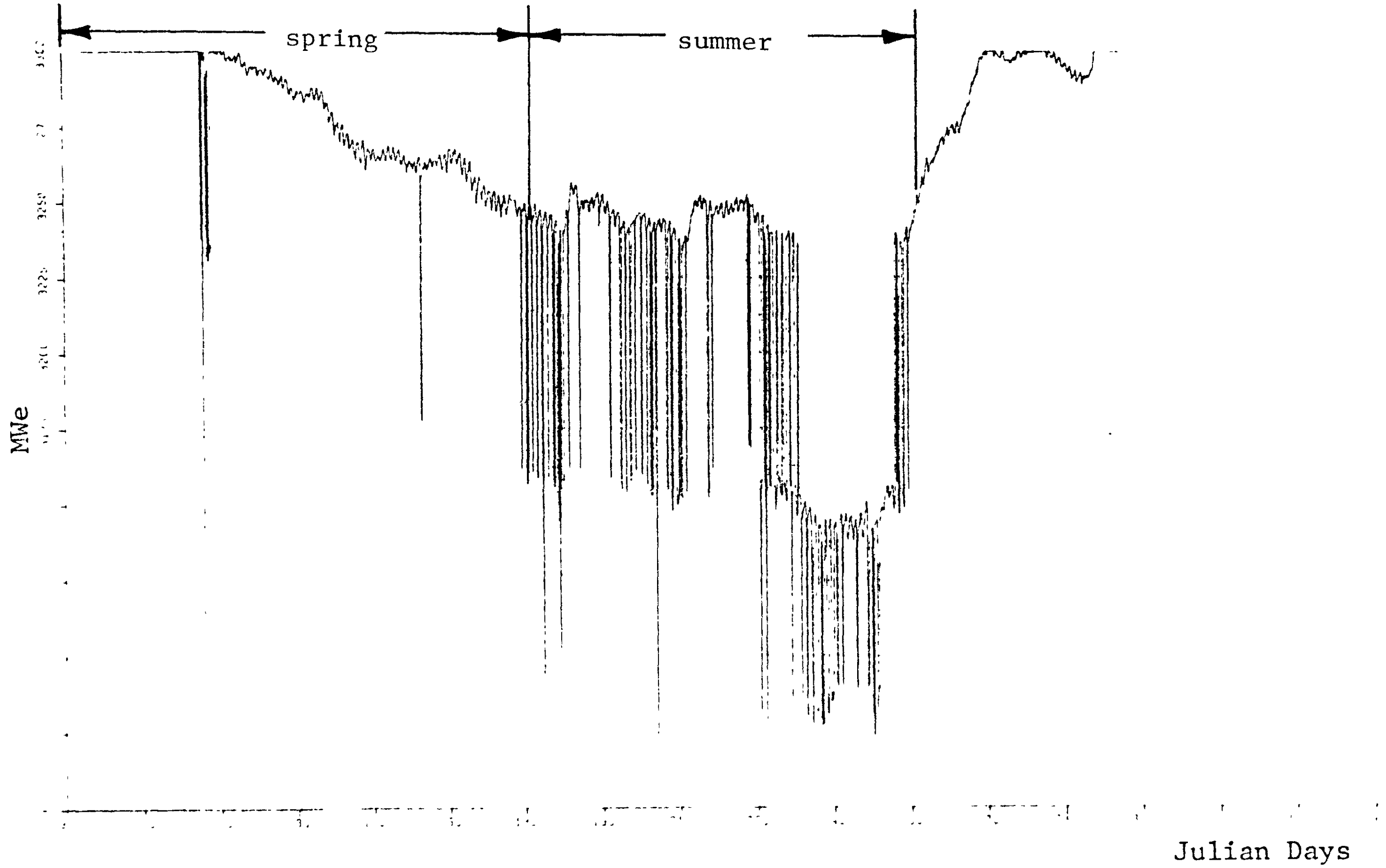


Figure 3.3-10 10°F Maximum Allowable ΔT Power Output in Best Mode

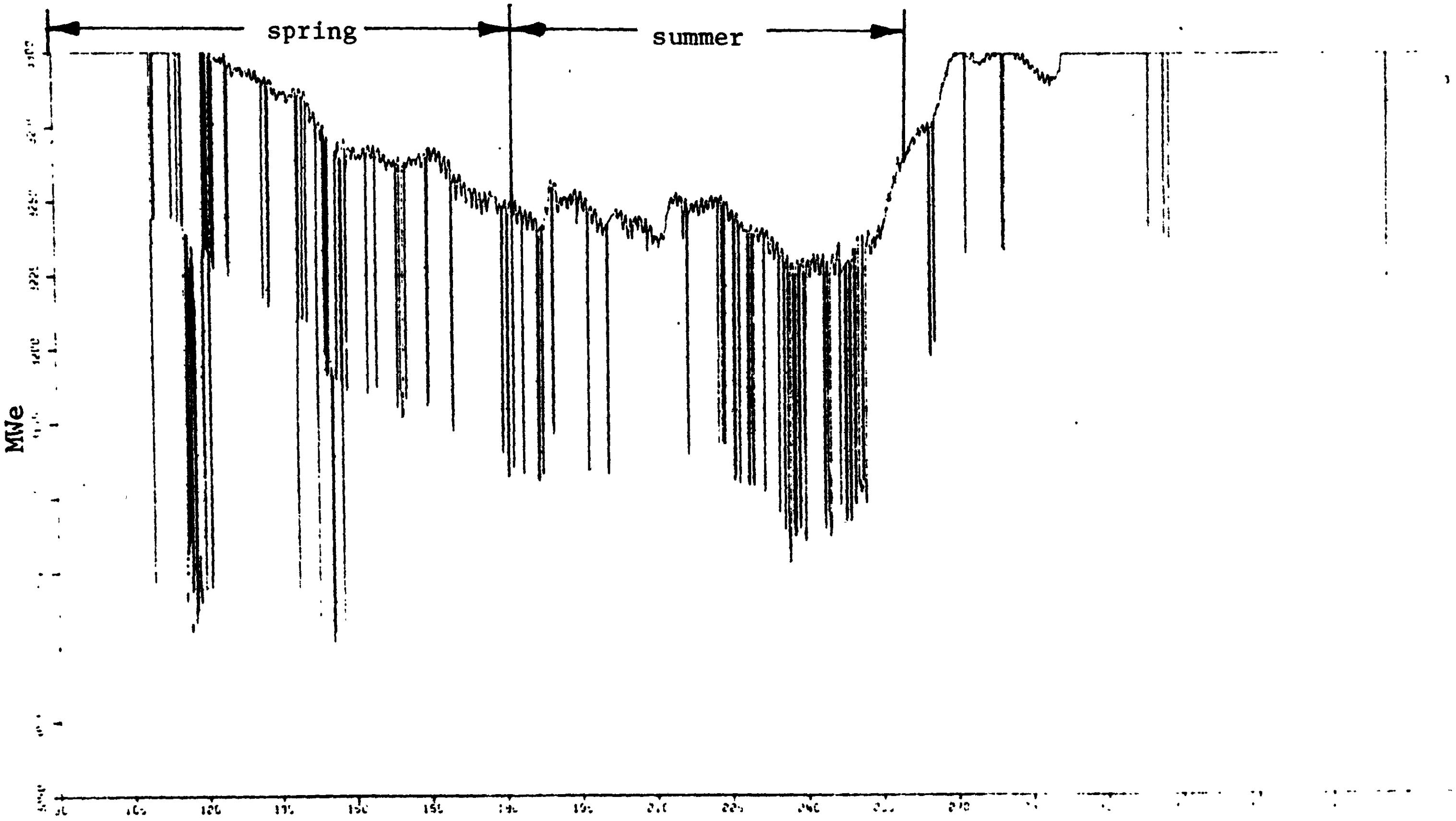


Figure 3.3-11 90°F Maximum Allowable Temperature Power Output in Best Mode

Base Case B, representing full use of open, helper, and closed modes, experienced only 10% of the power loss experienced by a totally closed system. The table also shows the advantages that three modes of operation offer such that Base Case B had significantly less power loss than no use of open or helper operation.

3.3.5 Summary

It is worthwhile to summarize the various sensitivity studies by comparing the results which had the greatest effect on power output. This is effectively accomplished using the compiled values of cumulative power loss given in Table 3.3-2. These numbers represent losses greater than the plant thermal inefficiencies experienced if the plant operated in open mode.

Base Case B (mixed-mode operation, 86°F T_{max} and 5°F ΔT_{max} standards, and downstream station 9) provides a reference point in determining strategies with adverse or advantageous effects on power output. Cases which showed more power loss were due to the non-existence of various cooling modes. The most dramatic result was that Base Case B, utilizing all three cooling modes, had only 10% of the power loss associated with all closed-mode operation. Cases without the use of open mode or without the use of helper mode also showed significantly more power loss than the completely mixed-mode operation. A small change in the ΔT_{max} standard to 3°F was the other case that showed increased power loss, almost 3 times the power loss of Base Case B.

It was found that changes in standards produced the least power loss. Revising the T_{max} standard to 90°F and the ΔT_{max} standard to 10°F in combination brought about the highest plant output. Individual changes in standards showed that the T_{max} equal to 90°F case had the next best output followed by Base Case A (only plant effects considered in the standard) and finally the $\Delta T_{max} = 10°F$ case.

Changes in monitoring or use of the natural change in temperature model had much less effect on cutting power loss as the changes in standards. Location of the downstream monitor produced the most benefit in this category. Spatial averaging of the downstream monitors and use of the model with downstream station 9 gave rise to similar power losses. The time averaging produced the least effect compared to Base Case B.

Table 3.3-2
Display of Cumulative Hourly Power Loss

Analysis	Cumulative Hourly Power Loss (MWe-hr)
Base Cases	
Base Case A, Upstream Equals Downstream	63,542
Base Case B, Downstream Station 9	96,044
Spatial and Time Averaging	
Downstream Station 10	80,865
Downstream Station 11	78,327
Spatial Average of Downstream Stations 9,10 & 11	82,485
24 Hour Running Average of Station 9	92,280
Stations 9,10 & 11 Spatial Average and 48 Hour Running Average	76,650
One-Dimensional Change in Temperature Model (1D ΔT)	
Base Case A with Estimated 1D ΔT Model	83,018
Stations 9,10 & 11 Spatial Average with Estimated 1D ΔT Model	71,599
24 Hour Running Average of Station 9 with Estimated 1D ΔT Model	78,890
Stations 9, 10 & 11 Spatial Average and 48 Hour Running Average with Estimated 1D ΔT Model	67,188
Changes in Environmental Thermal Standards	
Maximum Allowable ΔT of 3°F	268,732
Maximum Allowable ΔT of 10°F	68,667
Maximum Allowable River Temperature of 90°F	41,734
Maximum Allowable ΔT of 10°F and Maximum Allowable River Temperature of 90°F	7,543

Table 3.3-2 (cont.)

Analysis	Cumulative Hourly Power Loss (MWe-hr)
Existence of Various Modes of Operation	
All Open Mode Operation	0
No Open Model Operation	481,040
No Helper Mode Operation	145,664
All Closed Mode Operation (No Open or Helper)	911,858

The next section examines the actual compliance monitoring at Browns Ferry in light of the above discussion. In the end, a different modeling approach was used to dispence with the problem of natural variability from the upstream to downstream stations. TVA has also asked for a change in the maximum temperature standard based on biological information.

3.4 Thermal Effluent Control at Browns Ferry

The final thermal effluent control strategy at Browns Ferry Nuclear Plant centered on TVA's ability to control river flows by dam operation and to change cooling modes at the plant depending on how natural river temperatures and atmospheric conditions change the need for cooling. This operating procedure was established to meet the ambient thermal standards finally adopted by the State of Alabama. In order for the plant to operate in such a flexible manner, TVA needed to prove that the plant would not cause downstream river temperatures to exceed 86°F and would not increase river temperatures more than 5°F. TVA chose to show compliance with these standards using a real-time instream monitoring network. Section 3.1 discussed the general problems that developed in using such a compliance monitoring strategy. The following section studies the changes in the monitoring system to handle problems of temporal and spatial variability in light of the knowledge gained in Section 3.3. The continued occurrence of maximum rise violations due to natural temperature variations led TVA to recommend a new approach to compliance verification based on computer modeling and instream monitoring. This approach is examined with the current problems at the site created by inadequate cooling tower performance. Finally, the possible adoption of the federal water quality criteria as state standards is considered for its potential effect on plant operation.

The original strategy for compliance with the Alabama thermal standards used the monitors shown in Figure 3.1-4. Compliance with the ΔT_{max} standard of 5°F used station 6 as the upstream monitor. The maximum of stations 9, 10 and 11 was used to determine the downstream temperature for both the ΔT_{max} and $T_{max} = 86°F$ limitations. Instantaneous hourly measurements were taken at each station.

Three major variability problems in showing compliance were identified in Section 3.1. Lateral variations among the downstream monitors often caused single monitors to exceed the standards while the other monitors did not. TVA responded to this problem by averaging the three downstream stations in an effort to average the spatial effects of the discharge after mixing. This agrees with the results of Section 3.3 which found that averaging of the downstream monitors was an important consideration.

Short-term temperature variations picked up by the instantaneous hourly readings were the next problem. TVA solved this by changing the hourly readings to 15 minute readings averaged to a 2-hour average temperature. This 2-hour average was used as the actual temperature for compliance with the standards. The simulation studies in Section 3.3 found that the 2-hour average did not give a significant advantage over 1-hour readings. This was because the simulation model responded instantly to temperature variation, an action that cannot be accomplished at the real plant. The simulation studies showed that a 24-hour average would provide further relief from short-term temporal variations. This must be kept in mind when the newest federal thermal criteria are evaluated which have a weekly average requirement.

The final issue mentioned in Section 3.1 was the longitudinal effects of using such a long distance between upstream and downstream stations. Natural temperature rises of 5°F or more occurred without the plant operating. This prompted the TVA to change the upstream monitor from station 6 to station 4 decreasing the distance between upstream and downstream monitors from 15 miles to about 5 miles. Figure 3.4-1 shows the measured change in temperature between stations 4 and an average of stations 9, 10 and 11 for the same period given in Figure 3.2-6 which used upstream station 6. It is clearly evident that this set of monitors came closer on the average to maintaining downstream temperatures nearer to upstream values. Interestingly, most changes in temperature are to the plants advantage since the changes are negative a fair percentage of time. Although this partially solves the variability problem, peaks still exist during the spring which are over 1°F and 2.5°F causing concern for the effect of the natural change in temperature.

Other improvements in the monitoring system were carried out by TVA to provide a truer picture of the plants effect versus the natural rise in temperature. Figure 3.4-2 shows the latest set of instream monitors

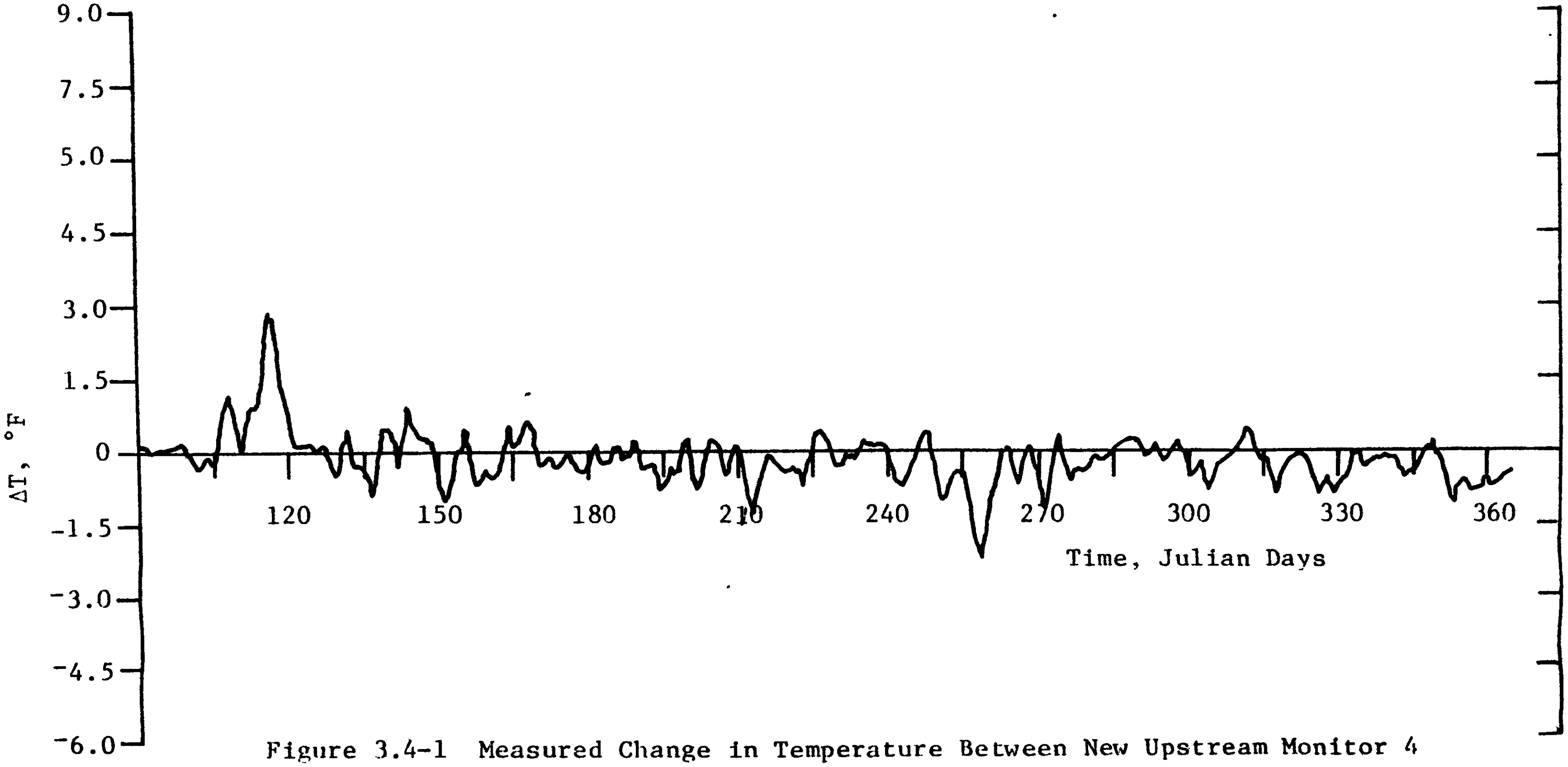


Figure 3.4-1 Measured Change in Temperature Between New Upstream Monitor 4 and Downstream Stations 9, 10 and 11

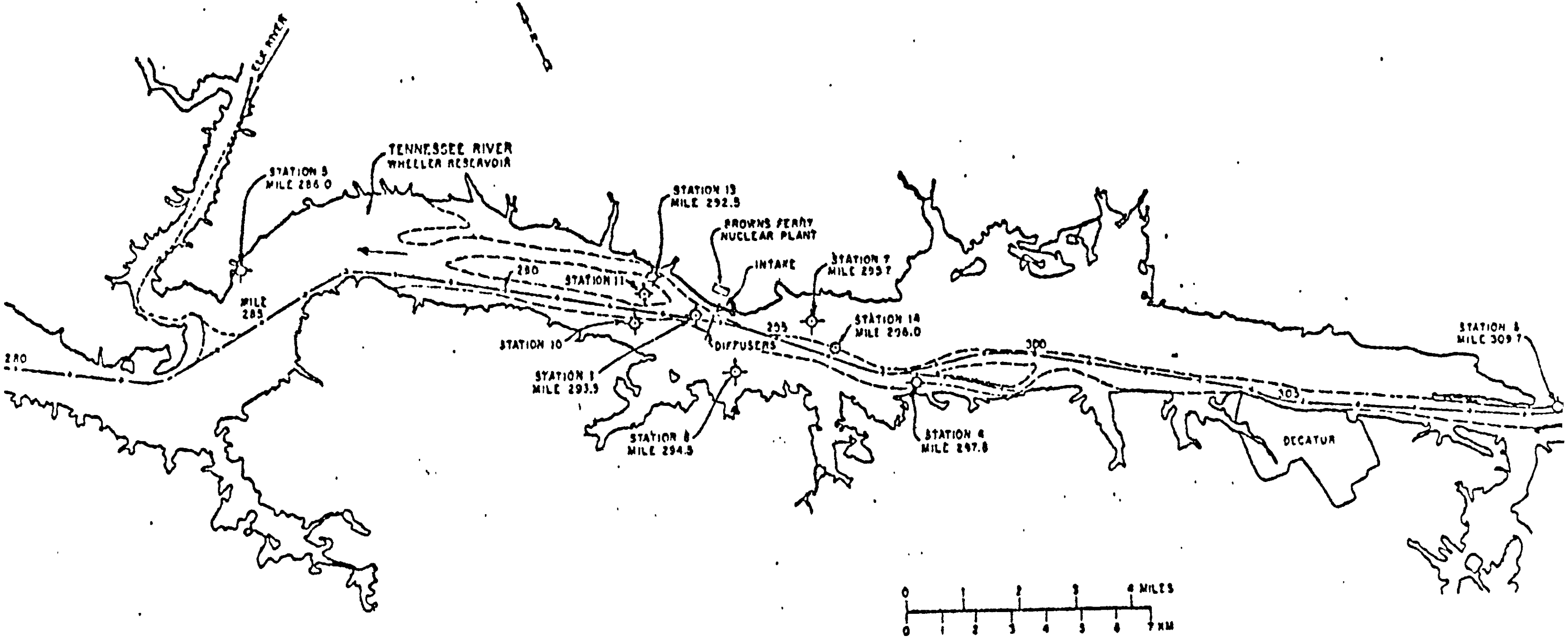


Figure 3.4-2 Revised Locations of Temperature Monitors for Browns Ferry Nuclear Plant

at the site. Station 9 was removed because it was found to be affected by natural heating near the right bank and replaced by monitor 13 located on the right side of the river channel. This was confirmed by the Section 3.3 results which showed the difference between the downstream monitors. Although Figure 3.4-1 revealed that upstream station 4 was a good choice from the plant's point of view, during some portions of the year this monitor, stationed in the main channel, did not give a true picture of upstream flow. The upstream temperature measurement was replaced by a flow weighted average of station 7 (located on the overbank), and station 4 in an effort to account for upstream lateral temperature variations (Ungate, 1978).

Maximum temperature rise violations continued to occur dispite the change in upstream monitors. This reinforced the difficulty in determining an "ambient" upstream temperature for the maximum rise determination (Ungate, 1978). Lateral, temporal, and longitudinal variations were all found to be important. Although the natural temperature model reviewed in Section 3.2 was one approach to handling this issue, the model still could not account for all the variability at the site. In response to this problem, TVA developed a compliance strategy that used a measured average downstream temperature as input to a mathematical model of the plant discharge. The model calculated the plant-induced temperature rise which was used to show compliance with the ΔT_{max} standard. This approach is similar to the system proposed by Markofsky (1976) where the "...operational monitoring is not aimed at measuring temperature rises directly but, rather at verifying that the physical parameters used in mathematical modeling of hydrothermal conditions were correctly evaluated." Adequate field measurements and diffuser performance analyses were provided to verify the use of such a monitoring strategy.

This system offers the advantage of alleviating the natural temperature variation problem while still maintaining a real-time monitoring system that detects violations due to plant effects. It offers an improvement over the modeling of the natural temperature variation because it is easier to model the plant's effect than all the random processes occurring naturally in a river environment. The new procedure actually redefines the maximum rise standard to a flexible effluent standard based on flow and temperature conditions in the reservoir. The system was approved by the state of Alabama, the regional office of the Environmental Protection Agency, and the Nuclear Regulatory Commission and entered as a National Pollutant Discharge Elimination Permit requirement. Due to problems which developed with the cooling towers this was not the end of the thermal effluent question.

Once in operation, the cooling towers never met the design requirements. This caused the plant to cut power output considerably during summer months. TVA conducted a complete study of the heat dissipation system after the structural failure of one of the towers. Considerable biological information has been taken throughout plant operation and used to determine the potential for requesting a revised maximum temperature standard based on a 316(a) demonstration. Favorable biological data and the economic consequences of further cooling tower construction led TVA to submit a 316(a) demonstration in March, 1980 (TVA, 1980) requesting a revision of the maximum temperature standard to 90°F.

The 316(a) demonstration showed no significant changes in the fish community due to plant operation. The only concern was an increase in phytoplankton which resulted in higher eutrophic conditions in the reservoir. Such conditions occurred upstream and downstream of the plant as well as during periods of no plant operation and plant operation at the 86°F standard. The data did not allow finite determination of the plant effect on phytoplankton at a 90°F limit but were significant enough to lead TVA to believe: "Hence, eutrophic conditions will probably exist whether BFNP [Browns Ferry Nuclear Plant] is granted a permanent 90°F (32.3°C) limit or not." (TVA, 1980) The TVA request should prove to be an interesting test of the extent of the section 316(a) language. As discussed in Section 2.3, the 316(a) emphasis is on proving the maintenance of a "balanced, indigenous population of shellfish, fish, and wildlife." This stresses higher aquatic life forms. TVA stressed this point by stating that the rationale followed by EPA regarding thermal sensitivity has been"...that the sensitivity to thermal increases is greater for selected fish species (in this case sauger, smallmouth bass, and walleye) than for the food producing capacity (plankton and benthos) of their environment," (TVA, 1980). Extensive studies by TVA encouraged the belief that there would be no significant effects on the important fish species of interest. To this date, the results of the 316(a) demonstration have not been acted on by the state and federal agencies responsible for the change of the thermal standard.

It is worthwhile to examine the temperature portion of the 1976 Quality Criteria for Water (US EPA, 1976) to determine what effect the adoption of such criteria might have on operation of Browns Ferry.

Sauger, walleye, and smallmouth bass were the original fish species of interest in developing thermal criteria for the Browns Ferry site. Walleye was found to be the species with the least temperature tolerance. TVA biological data on walleye showed that an upper lethal temperature (50% mortality) for walleye was 94°F (TVA, 1980). Sauger was reported to have slightly higher thermal tolerance. The upper lethal limit for smallmouth bass was greater than 95°F (TVA, 1980). The optimum temperature for smallmouth bass was 83°F (NAS-NAE, 1972). Using the data on smallmouth bass, the maximum weekly average temperature (discussed in Section 2.2) was found to be about 86°F, using an upper lethal limit of 95°F. TVA data showed that walleye were not present near the Browns Ferry site in any appreciable number. Sauger were present, although a specific value on the optimum temperature for sauger coud not be found. (It would be lower than for smallmouth bass.) Therefore, under the new criteria the maximum weekly average temperature would be lower than the 86°F standard presently in question if sauger was determined to be the critical species.

Power output during the winter period would also be affected if the thermal shock criteria were imposed. A representative winter temperature of 47°F (TVA, 1971) is plotted on Figure 3.4-3. The weekly average permissible plume temperature of approximately 72°F is exactly equal to the expected discharge temperature increase of 25°F when operating in open mode. Lower ambient river temperatures would require a lower maximum discharge rise if the thermal shock criteria were imposed.

Finally, the short-term maximum temperature criteria were evaluated using the procedure shown in the National Academy of Sciences - National

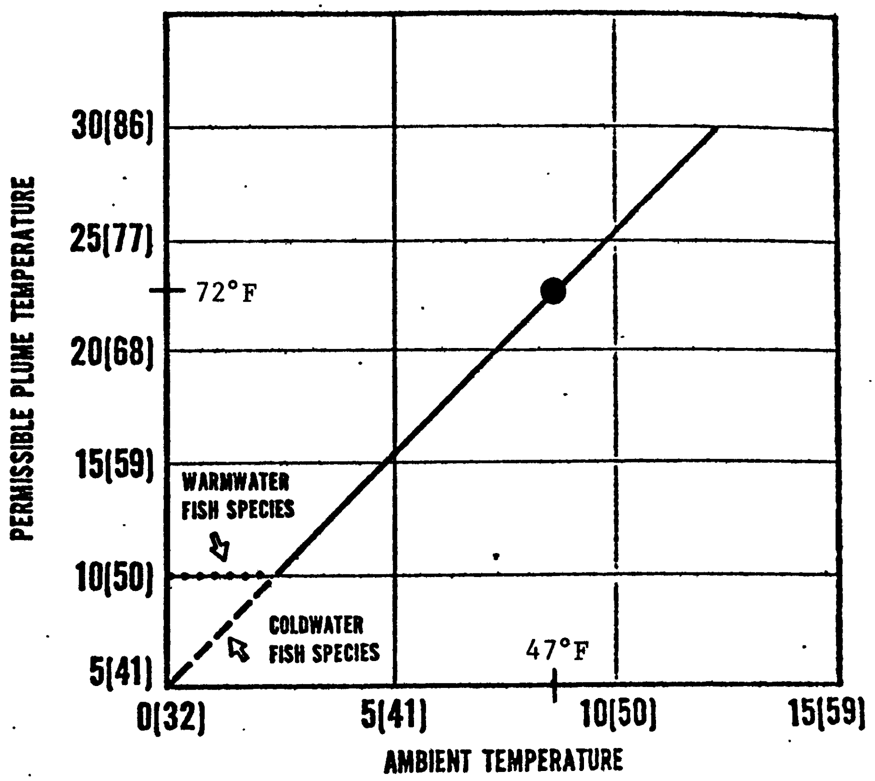


Figure 3.4-3 Graph to Estimate the Maximum Weekly Average Temperature of Plumes for Various Ambient Tempeartures, °C(°F)

(From U.S. EPA, 1976)

Academy of Engineering (NAS-NAE) Water Quality Criteria 1972. Representative acclimation temperatures could only be obtained for the largemouth bass. Although this is considered a warm water species, the following evaluation shows the effect of the short-term criteria. Acclimation temperature information at 86°F was available from the literature (Hart, 1952 cited by NAS-NAE, 1972), and was used as the upstream ambient temperature. TVA found that most of the diffuser mixing at Browns Ferry occurred within 1-2 diffuser lengths downstream of the diffuser (Ungate, 1978). One-and-a-half diffuser lengths (or 2700 feet) was used as the length necessary to achieve mixing to 5°F above the ambient temperature. A lethal threshold equal to 97.5°F (Hart, 1952 cited by NAS-NAE, 1972) minus 2°F (or 95.5°F), was used as the downstream point for ending the short-term evaluation as recommended in the NAS-NAE reference. A linear interpolation between the diffuser outlet temperature of 111°F (25°F above ambient 86°F) and the fully mixed temperature of 91°F resulted in a temperature of 95.5°F, 2100 feet downstream of the diffuser. The average temperature T_{ave} in the 2100 foot length would be 103.3°F. The following NAS-NAE formula was used:

$$1 \geq \frac{\text{Travel Time (min.)}}{10^{[a+b\ (T_{ave}(^{\circ}C)+2)]}} \qquad (3.4\text{-}1)$$

where, at an acclimation temperature of 86°F (NAS-NAE, 1972):

$a = 36.0620$

$b = -0.9055$

This resulted in a permissible travel time less than 2 seconds for open-cycle operation with high ambient river temperatures. The actual travel time for the 2100 feet with a summer velocity of .3 ft/s equals 10.5 minutes. An evaluation was done where the maximum rise at the discharge still meeting the criteria was computed for a given ambient temperature. The assumptions used were the same as the previous analysis: mixing to 5°F above ambient occurred at 2700 feet downstream of the diffuser; linear interpolation of where the 95.5°F temperature occurred; .3 ft/s velocity; average temperature in the cross section; and the same acclimation information. The discharge temperature rise was solved iteratively until the cross section average was below the maximum criteria resulting from the travel time from the diffuser to the 95.5°F temperature. The results shown in Figure 3.4-4 provide a graph similar to Figure 3.4-3 which specifies when supplementary cooling must be used at the .3 ft/s river velocity. From this analysis ambient river temperatures above approximately 73°F would require supplemental cooling to meet the standard. The assumptions did use 86°F acclimation information which may not be conservative and are for one of the warmer water species present in the reservoir. Therefore an actual criteria for the site would likely drop the allowable maximum rise at any ambient temperature.

Thermal limits also need to be developed for reproductive seasons. These would be formed similar to weekly averages or short-term maximums. These limits will not be discussed in this paper.

The form of the resulting limitations on the plant, based on the new criteria, offers advantages over the present single maximum downstream temperature, T_{max}, and maximum change in temperature in the river, ΔT_{max}, limitations in terms of handling variability. The weekly averaging of downstream temperatures would solve the problem of short-term spatial

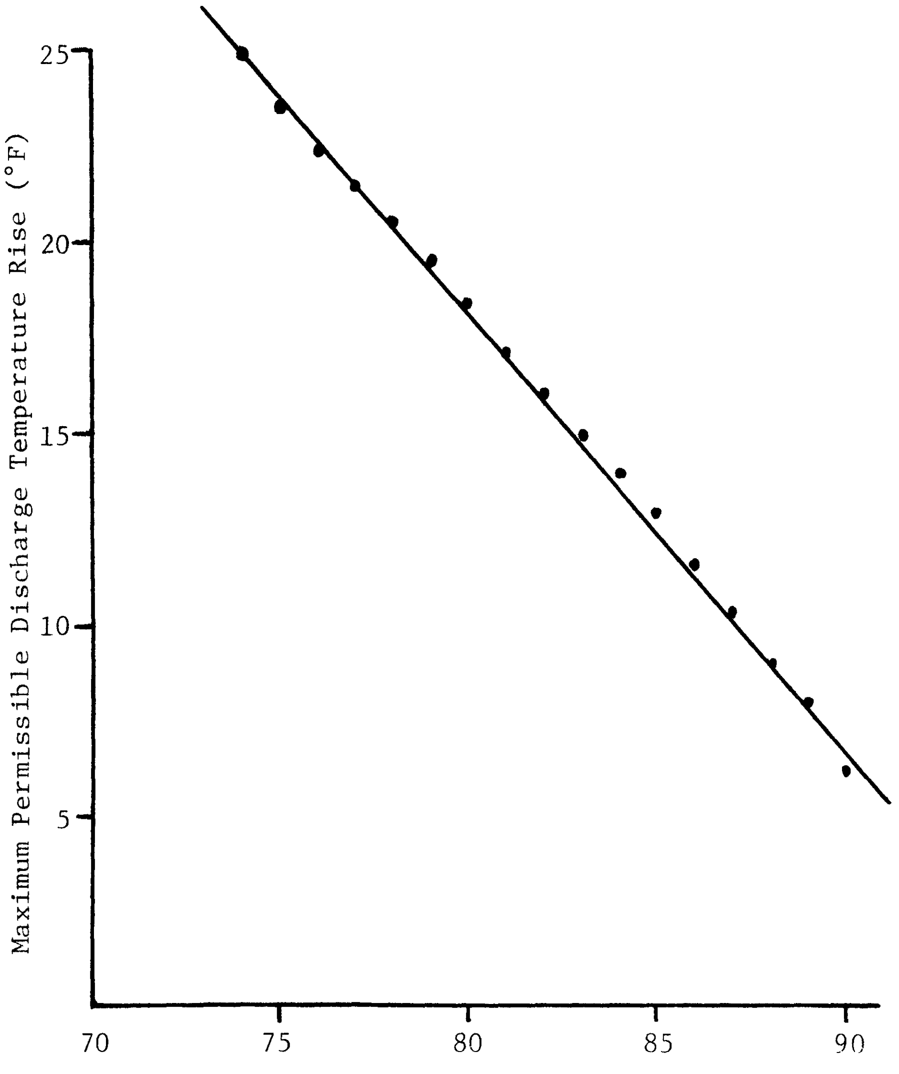


Figure 3.4-4 Short-term Criteria for Thermal Effluents at River Velocity of .3 ft/s

and temporal fluctuations. The determination of the "ambient" temperature would still present a problem since this value is necessary to determine the maximum permissible discharge rise for the short-term criteria limitation and the maximum permissible weekly average plume temperature during winter months. This would be better than the troublesome ΔT_{max} standard because the procedure would not compare an upstream and downstream reading which can be influenced by many factors as shown previously. The travel time of mixing to 95.5°F would become the important parameter computed using the available models. Hence, a combination of a computer model and instream monitors could provide real-time verification of the standards similar to present compliance strategy at the site.

Biologically, the new criteria are more sensible because they include more than one standard for the year including a requirement for the prevention of cold shock. They also agree with the theory of the ambient air quality standards since they define both short-term and long-term limits.

In reality, the adoption of the new criteria would stimulate heated debate since they would decrease the maximum allowable temperature, require supplemental cooling in the winter, and increase the use of supplemental cooling and power derating to meet the short-term limit. However, the new criteria may not be imposed if the biological data submitted for the 316(a) demonstration meets the approval of the state and federal authorities agreeing that the protection and propagation of a balanced, indigenous population has been retained.

3.5 Conclusions

The case study of the Browns Ferry Nuclear Plant revealed that several monitoring, modeling, and regulating approaches led to the final design and operation of the plant's heat dissipation system and method of compliance with the thermal standards. A breakdown of major aspects of the study important in the history of thermal effluent control follows.

Thermal standards

The final set of ambient standards adopted for the Browns Ferry site have continuously influenced the design and operation of the facility. The latest limits on maximum allowable temperature of 86°F and maximum allowable temperature rise of 5°F placed restrictions on plant output since the previous strategy of controlling river flows with small cutbacks in power output were not sufficient to meet applicable thermal requirements. Both of the standards were found to be limiting since natural conditions caused temperature distributions approaching the standards.

An evaluation of the factors affecting natural variability showed that spatial variations, both lateral and longitudinal, and daily variations all had orders of magnitude near the specified 5°F temperature rise standard. These variations caused several problems in separating plant effects from natural conditions.

Facility siting, design and operation

Operation of the Browns Ferry Nuclear Plant used large amounts of water for heat dissipation from a river with variable flows. Plant usage often approached 15% of the total flow past the site. The irregular nature of the flows had to be factored into plant design and operation.

Since TVA could control the flow past the site from upstream and downstream dams, this has been used as a method of allowing adequate flow past the site to provide maximum plant output. When newer thermal standards were adopted, other design and operation approaches were needed.

The new plant design provided a flexible operational approach that could respond to changing natural conditions, provide maximum output, and still meet the ambient standards. Cooling towers were built and the heat dissipation system was designed to use open-mode, helper-mode or closed-mode cooling. The ability to use the mixed-mode system to meet the ambient standards produced only about 10% of the power loss associated with full closed-mode operation.

Compliance with thermal standards

TVA chose to use real-time monitors to show compliance with the ambient standards. This strategy was adopted to give the plant the most flexibility in operation under specified thermal limits. However, difficulties in verifying compliance were encountered due to the natural variability in the river environment.

Several possible compliance approaches were evaluated to handle the natural variability issue while allowing the plant to operate at maximum output and still meet the ambient standards. Simulations of plant operation showed that adjusting the thermal standards away from naturally occurring values had the largest effect. Monitoring strategies involving various sampling locations, and spatial and temporal averaging had much less effect because of the persistant trends and many factors affecting variability.

A modeling approach developed by TVA to consider only the plant's effect essentially redefined the maximum temperature rise standard eliminating most of the variability problems. The resulting method of compliance changed the limiting ambient standard to a flexible effluent standard based on the results of real-time modeling of the thermal effects of the plant.

Finally, TVA also requested a change in the value of the maximum temperature standard (from 86°F to 90°F) with biological evidence to support the higher limit. The changes in both ambient standards resulted in a final compliance approach that was previously found to be the best method of dealing with the variability issue.

Modeling variability

Modeling the natural variability at the Browns Ferry site was another approach to the variability problem. A one-dimensional modeling effort characterizing the natural change in temperature in the river was evaluated. Although the model compared favorably with a long-term average of measured data, it could not account for all the variability in the river due to lateral and density effects not included in the one-dimensional formulation. In conjunction with various spatial and temporal averaging strategies, the model could come close to handling all of the natural variability. However, the real-time modeling of thermal effects compliance approach solved the variability problem.

The results of this chapter provide a background for a comparative look at how control policies affect natural variability issues (which is the subject of Chapter V). A case study of thermal effluent control in a coastal environment will be examined first to give a broader perspective of the natural variability issue.

IV Thermal Effects in a Coastal Environment

A study of the Millstone Nuclear Power Station provides a different view of thermal effluent control than was presented in the last chapter. The location of the power station in a coastal environment presents a different set of physical processes and related regulatory issues than those found in a river environment. Two major thermal control issues have been raised through most of the site history influenced by the natural temperature variations in the area. Both the extent of the thermal plume and the cause of heating in the shallower areas around the site have raised questions about the station's effects versus natural conditions.

This chapter first presents the general background of the site and the history of monitoring, modeling, and regulating the thermal effluent. Following sections describe a natural temperature prediction model for possible use in gaining a better understanding of processes affecting the coastal area. The chapter ends with a discussion of the potential for incorporating the natural temperature model into the assessment, monitoring, and regulation of the thermal discharge in an attempt to provide information on variability issues at the site.

4.1 Background of Thermal Effluent Control of the Millstone Nuclear Power Station

Millstone Nuclear Power Station is an example of a large electric generating station located in a coastal environment. Most of these coastal stations utilize the ocean for cooling water and heat dissipation through open-cycle operation. The heated effluent is discharged into the coastal water and is acted on by tidal flushing to mix it with the surrounding water. The following provides more details of the Millstone site and power station operation. A brief review of the history of thermal effluent control is also given including a description of the modeling, monitoring, and regulating efforts. This leads to a discussion of the present situation at the site with emphasis on the effect of natural temperature variability on compliance with thermal standards.

Located in Waterford, Connecticut, the Millstone Nuclear Power Station is 3.2 miles west of New London on the north shore of Long Island Sound as shown in Figure 4.1-1. The station is on a peninsula known as Millstone Point bounded on the east by Jordan Cove and on the west by Niantic Bay, which forms the entrance to the Niantic River Estuary. A more detailed map of the general site area is shown in Figure 4.1-2.

The coastal area around Millstone Point is characterized by tidal action in Long Island Sound. Normal tides are semidirunal, periods approximately 12.4 hours, with a mean range of 2.7 feet and a spring range of 3.2 feet. Water off Millstone Point was found to be well distributed vertically and horizontally due to the turbulence generated from tidal currents over the irregular bottom.

The first two units of the station are jointly owned by the Connecticut Light and Power Company, the Hartford Electric Light Company and Western Massachusetts Electric Company. The third unit is owned mainly by the above utilities with the additional support of many small utilities in the New England area. The operator of the entire station is Northeast Nuclear Energy Company (formerly Millstone Point Company). The main three owners and the operating company are all subsidiaries of Northeast Utilites, a registered public utility holding company.

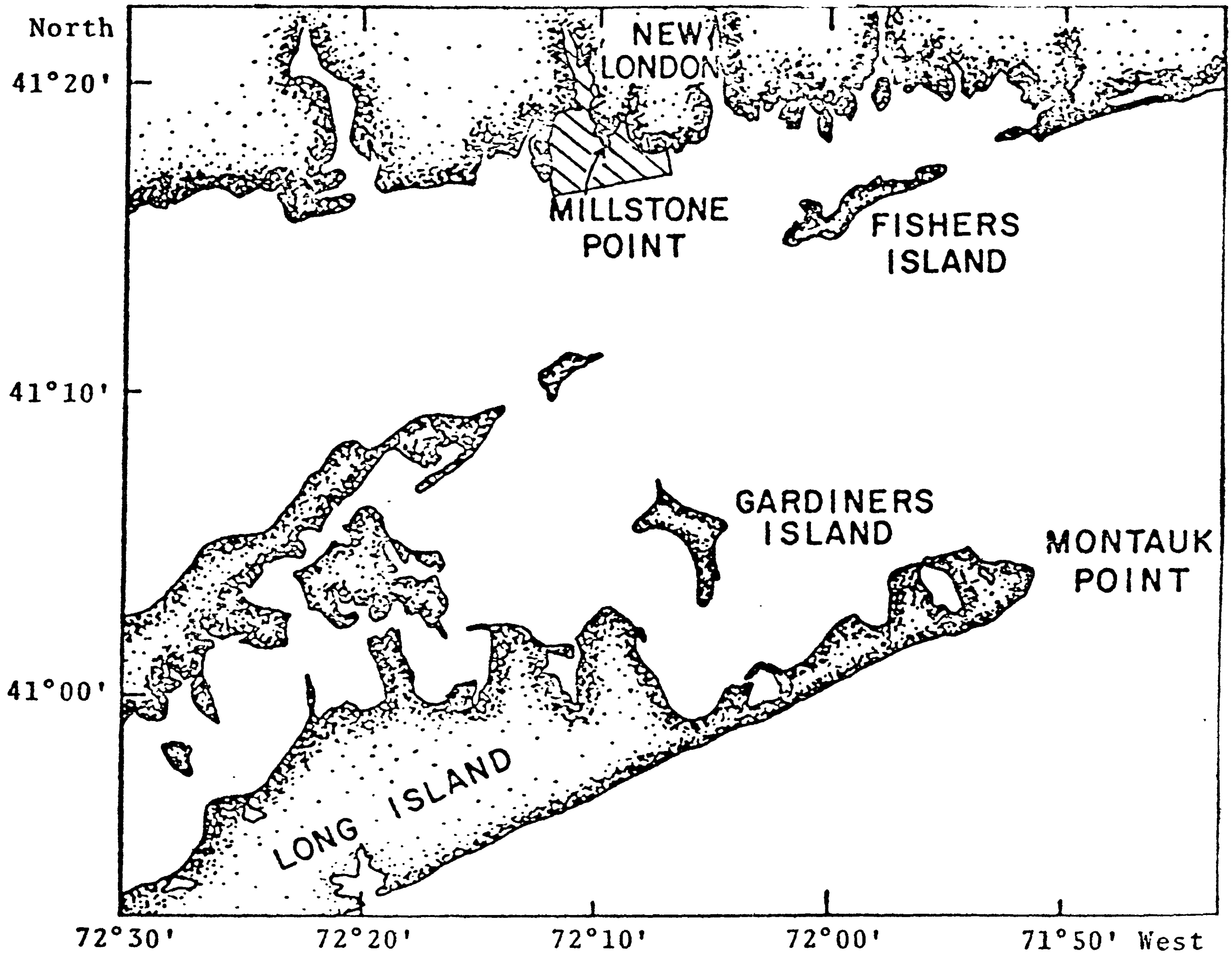


Figure 4.1-1 General Location of Millstone Nuclear Power Plant in Eastern Long Island Sound

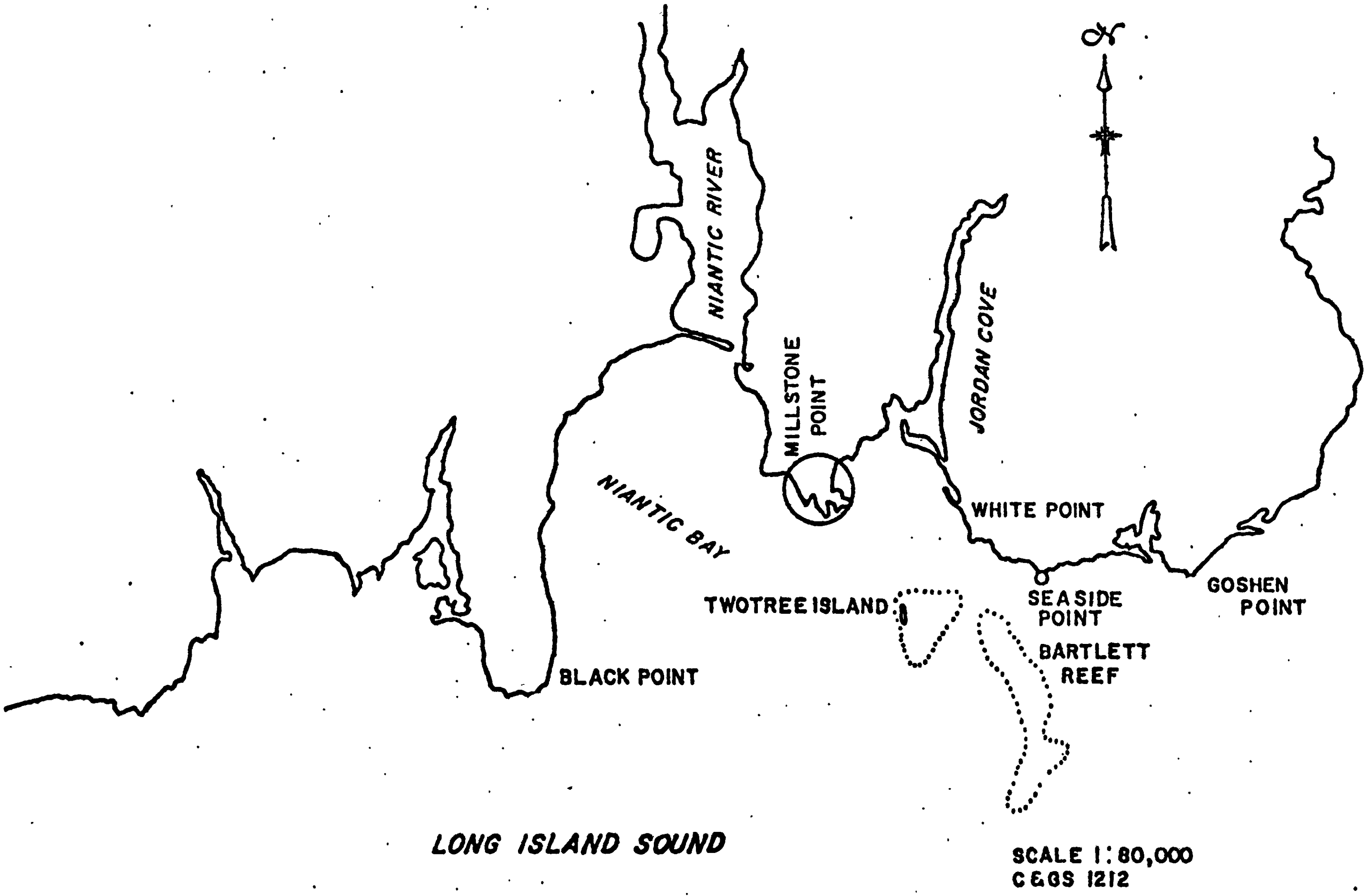


Figure 4.1-2 Specific Location of Millstone Nuclear Power Station

The power station consists of three nuclear generating units. Unit 1, a 652 MWe boiling-water reactor unit, and unit 2, an 830 MWe pressurized-water reactor unit, are presently in operation. Unit 3, an 1150 MWe pressurized-water reactor unit, is under construction and presently scheduled to begin operation in 1986 (Northeast Utilities Service Company, 1979).

The heat dissipation system is open cycle for all three units. Water is drawn from Niantic Bay through intakes on the west side of Millstone Point, passed through the condensers, and discharged into Long Island Sound. Discharge flows are 1002 ft^3/s for one unit operation and 2275 ft^3/s for two units resulting in discharge velocities of 1.5-2.0 ft/s and 3.5-4.5 ft/s, respectively. The discharge temperature rise is about 23°F for one unit and two unit operation, and 23.5°F for three unit operation (Stolzenbach and Adams, 1979).

The first set of thermal requirements applicable to the power station were the water quality standards for interstate and intrastate waters adopted by the Connecticut Water Resources Commission on November 17, 1969. Waters around Millstone Point were classified as Class SA defined as suitable "...for all water uses including shellfish harvesting for direct human consumption (approved shellfish areas), bathing and other water contact sports." The allowable temperature increase for this classification was:

> 7. Allowable temperature increase - none except where the increase will not exceed the recommended limit on the most sensitive receiving water use and in no case exceed 85°F or in any case raise the normal

> temperature of the receiving water more than 4°F.

The standards also had the provision that:

> In the discharge of...cooling water to the receiving waters, cognizance shall be given both in time and distance to allow for mixing of effluent and stream. Such distances required for complete mixing shall not affect the water usage class adopted but shall be defined and controlled by the commission. (State of Connecticut, 1969)

Several studies of the potential extent of the thermal plume from unit 1 operation were made before unit 1 became operational. A preliminary study in 1965 concluded that waters around the site had good mixing capabilities but expressed concern over natural heating in Jordan Cove and the Niantic River Estuary which might be interpreted as partly due to the station once in operation. Field data and a small scale physical model were used to provide information on local flow patterns and potential diffusion patterns due to the circulating open-cycle discharge. Tracer-dye studies were then used to estimate the actual extent of the plume. In the first study without the station operating, dye was released off of Millstone Point to simulate the movement of heated water. The resulting dye plume was followed over several tidal cycles to determine natural mixing characteristics. The results suggested that there would be negligible effects of station operation on heating in Jordan Cove. In the second set of studies, dye was injected into the circulating water system while unit 1 was in preoperational testing with the discharge at ambient temperatures. Results of the two dye studies showed that strong tidal currents near Millstone Point produced extensive dilution of the test tracer discharge before it reached the shallow areas around Niantic Bay, Jordan Cove and the Niantic River Estuary. It was concluded that the thermal discharge from unit 1 would not effect these areas (Millstone Point Company, 1971).

Based on the results of the preoperational studies, the State of Connecticut felt that operation of the plant would meet the applicable water quality standards and a state permit for the thermal discharge from unit 1 was granted on August 26, 1969. The AEC granted an operating license for unit 1 and it began commercial operation in January 1971.

The tracer-dye studies were used for estimates of the extent of the thermal plume for two unit operation. Under new federal legislation (Federal Water Quality Improvement Act of 1970) the state had to certify that the nuclear facilities did not violate any applicable water quality standards. Based on the tracer-dye studies estimates, a state certification and state permit were granted for unit 2 operation in July and August of 1970.

In response to the National Environmental Policy Act and the Calvert Cliff's court decision discussed in Section 2.3, the Atomic Energy Commission (AEC) revised their regulations to require owners of operating nuclear plants and those under construction to submit an environmental report addressing radiological and non-radiological effects on the surrounding environment. These reports were required before issuance of the construction permit or operating license for the nuclear facility. The previous hydrographic surveys were included in the operating license stage environmental report for unit 1 submitted to the AEC on November 29, 1971.

Environmental Reports for unit 2 and unit 3 construction permits and unit 2 operating license were soon to follow. The Calvert Cliff's decision also required the AEC to do an independent analysis of the environmental effects of the nuclear facilities which led to AEC reports called Environmental Statements. The Environmental Statements were required to be issued first as a draft so that interested federal, state and local authorities as well as interested parties could add comments before the final statement was issued and ensuing federal licensing actions were taken. The following discussion will not attempt to specify all the issued raised on thermal effects in the various reports. Major points will be addressed having an influence on the final assessment and control policies for the Millstone station.

The first study of the unit 1 operation was done in the summer of 1971 to determine the extent of the plume and to confirm previous predictions. Temperature survey results showed the vertical extent of the plume as expected, but the surface extent appeared to be due in large part to natural heating, solar heating or input of warmer water from nearby rivers and streams (Millstone Point Company, 1971). To separate the effects of natural heating simultaneous dye and temperature surveys were done in 1972. Measurements of dye concentrations were subtracted from the temperature measurements to determine the natural heating effects since no naturally occurring dye existed. The resulting plant-induced results were in favorable agreement with the temperatures predicted by earlier dye-tracer experiments.

Throughout the environmental report and environmental statement processes for units 1 and 2 it became evident that more emphasis was needed on the thermal effects of the station operation (US AEC, 1973). The environmental report required before the Unit 3 construction permit was granted contained a new emphasis on the thermal issue (Millstone Point Co., 1973). A new numerical modeling effort was presented which was more rigorous than the previous estimates based only on the tracer-dye studies. The new model was calibrated for site conditions using the thermal plume maps from the 1972 simultaneous dye and temperature surveys. After some discharge design changes, the final set of plume predictions for three unit operation were completed. The results showed that the 4°F isotherm (increase in temperature due to the thermal plume) would not extend more than 4000 feet from the discharge into Long Island Sound (Millstone Point Co., 1973).

On September 27, 1973, the State of Connecticut became one of the first states granted permanent authority to issue water discharge permits under the Federal Water Pollution Control Act Amendments of 1972 (FWPCAA), National Pollution Discharge Elimination System (NPDES). The requirements for thermal control at Millstone were therefore the state's responsibility. The Environmental Protection Agency (EPA) regional office still had to approve the state's determination of permit requirement based on effluent limitations, water quality standards or federal standards of performance. EPA comments on the AEC's Draft Environmental Statement for unit 3 were very critical of the State of Connecticut's handling of the thermal issue. They especially took exception to the state's ill-defined mixing zone, which relied on the evaluation of ongoing monitoring programs at the site to determine the advisability of restricting the allowable mixing zone. The EPA, seeking more uniform standards on the coastal waters, suggested revisions to the state's water quality standards to require a maximum allowable temperature of 83°F and maximum rise in temperature standards of 1.5°F, July through September, and 4°F from October through June. EPA also referenced previous documents recommending an allowable zone of passage (free from the influence of heated discharge) of 75% of cross-sectional area and/or volume of flow of stream or estuary. They also called for an evaluation of other cooling system alternatives since they anticipated federal EPA rulemaking requiring closed-cycle operation (US AEC, 1974).

The State of Connecticut changed its temperature standards for coastal and marine waters in November 1973 to:

> 8. Allowable temperature increase - None except where the increase will not exceed the recommended limit on the most sensitive receiving water use and in no case exceed 83°F or in any case raise the normal temperature of the receiving water more than 4°F. During the period including July, August, September, the normal temperature of the receiving water shall not be raised more than 1.5°F unless it can be shown that spawning and growth of indigenous organisms will not be significantly affected.
>
> (State of Connecticut, 1974)

The changes were approved by the Regional Administrator of EPA in December, 1973. The new standards contained an important phrase, "...unless it can be shown that spawning and growth of indigenous organisms will not be significnatly affected." This provided the state with an opportunity to do a case-by-case analysis of the thermal standards applicable at any site.

Further action by EPA in the thermal control area centered around proposed rulemaking establishing cooling towers as best available technology. Northeast Nuclear Energy Company, the operators of the Millstone station, requested a determination from the State of Connecticut (pursuant to Section 316(a) of the FWPCAA), that any proposed thermal effluent limitation requiring a cooling system other than the once-through system presently considered for unit 3 was more restrictive than necessary for the protection and propagation of a balanced indigenous population of shellfish, fish and wildlife in and on the receiving waters (State of Connecticut, December 1974). EPA's proposed rulemaking was issued on March 4, 1974, requiring closed-cycle cooling for all power generating units. Based on previous biological studies of station effects and thermal plume modeling, the State of Connecticut held the EPA limitations were too strong and issued an NPDES permit on December 10, 1974, allowing use of open-cycle cooling. The conditions of the NPDES permit thereby became the controlling regulations for thermal effluents at the site (State of Connecticut, December 1974).

The final requirements in the NPDES permit contained ambient standards of 4°F maximum temperature rise and 83°F maximum temperature. The requirements also set a boundary on the mixing zone not to exceed a radius of 4,000 feet from the discharge outlet. The thermal plume allowed within the permissible mixing zone was not to block zones of fish passage (State of Connecticut, December 1974). The 4,000-foot radial distance considered the results of the thermal plume modeling of three unit operation appearing in the Unit 3 environmental report.

The permit included the operation of all three units. The state, however, determined that additional evidence based on actual operating experience of the units would be desirable in order to corroborate the earlier findings. Plume studies of unit 1 and unit 2 operation and all three unit operation were required by both the state and the AEC to prove compliance with the state's ambient standards as given in permit requirements.

The effluent standards appearing in the NPDES permit were based on the design values of maximum discharge flow and temperature used in the three unit plume modeling to predict compliance with the ambient standard plus an allowance for condenser heat treatment. The effluent standards also had provisions for non-routine conditions due to pump failure, inspection or maintenance. Monitoring requirements for the thermal effluent were hourly instantaneous measurements of flow and temperature (State of Connecticut, December 1974).

The AEC requirements for station operation (technical specifications) were more strict than the NPDES permit since they also limited a maximum rate of change of discharge temperature during routine operation not to exceed 6°F/hr (US AEC, 1975).

Millstone Nuclear Power Station Unit 2 became operational in December 1975. Extensive thermal plume studies were done in July 1977 to meet the requirements of the state NPDES permit and the AEC environmental technical specifications. Measurements during two unit operation showed plumes which approached the 4,000-foot limit (for three unit operation) during slack after ebb tidal conditions, as shown in Figure 4.1-3

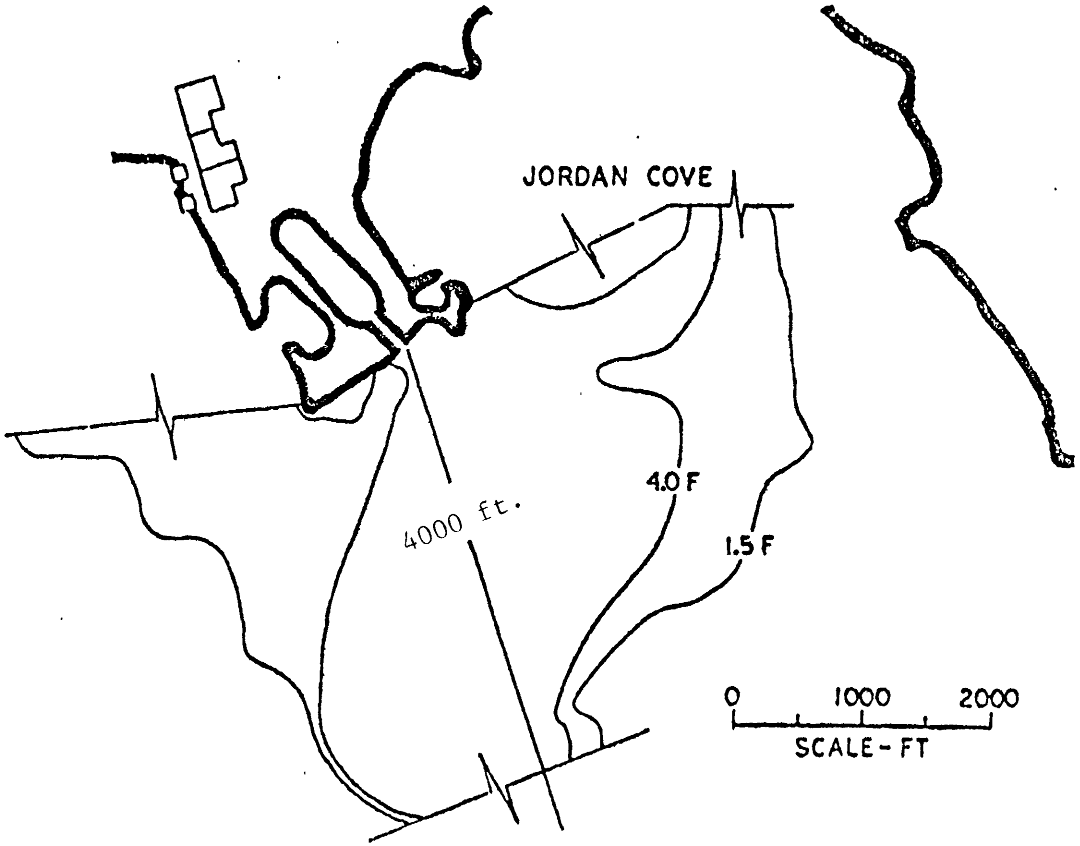


Figure 4.1-3 Measured Thermal Plume at Millstone Site - Slack After Ebb

(Northeast Utility Service Company, 1979). Simultaneous dye studies with the temperature surveys were again used to differentiate plant effects from natural heating. It was not clear that the natural heating was the cause of the previous model's underestimation of the extent of the plume. Thermal infrared surveys were also done to help define the plume's size and characterize the plume versus natural heating. Figures 4.6-22 through 24 show some of the problems in differentiating the plume from natural heating occurring in Jordan Cove (Texas Instrument Incorporated, 1978). The study also reported: "Depending on location, there is a 1° to 2°F difference in the ambient water temperature during the intensive survey period" (Northeast Utilities Service Co., 1979). The NPDES permit used the intake temperature as the ambient base temperature for the purpose of setting the maximum temperature rise effluent limits. Figure 4.6-20 shows that the intake may also be influenced by the thermal plume. New modeling studies on the extent of the thermal plume during three unit operation have been made (Stolzenbach and Adams, 1979) and were submitted to the State of Connecticut with a request for a change in the allowable radial distance of the 4°F isotherm. Since the third unit at Millstone is not scheduled to become operational until 1986, the final requirements for the plant have not been set.

The thermal regulations for the Millstone Nuclear Power Station have not changed appreciably in the years since the first unit became operational. Although the ambient standards for the State of Connecticut have changed, the plant operators, through extensive biological studies, have provided convincing evidence that stricter standards were not needed to protect the aquatic life in the site area. Field studies and some numerical modeling of the station's thermal plume have provided the bulk of work done in assessing the extent of thermal effluent at the site. There is, however, a striking difference between the amount of compliance verification monitoring done at the river environment discussed in Chapter III versus the short-term plume studies used to assess the compliance with ambient standards at Millstone. The approach to thermal effluent control provides the Millstone station with flexibility to operate the plant at maximum output. Although the effluent limitations are stated as maximum limits and are determined by instantaneous hourly values, they are set to include non-routine cleaning operations and emergency conditions.

Problems with natural temperature variability have occurred throughout the history of station operation, although the thermal effluent control policy for the Millstone station has been much more leniant than at Browns Ferry. Natural heating effects in Niantic Bay and Jordan Cove have always been a concern. The role that natural temperatures play in the extent of the thermal plume has also been questioned. Finally, ambient temperature used to define the standards, although not receiving much attention, was also influenced by the variability issue.

Natural temperature variation issues which must be considered in analyzing the effect of heated effluents on a coastal environment were discussed above. A predictive temperature model offers one approach in gaining a better understanding of the temperature distribution. The following sections present the application of numerical models to the prediction problem. A review of previous modeling techniques is first given as background for the modeling effort.

4.2 A Review of Temperature Modeling in Coastal Environments

Several approaches can be taken in estimating the temperature variation in a coastal environment. Field measurements offer the most direct indication of variability but measurements over large areas and long time periods are often not done due to economic constraints. The measurements also cannot provide predictive capabilities unless statistical models are used. Regression models require long periods of measurement and cannot give the detail needed for an indication of the horizontal distribution of temperatures. Therefore, deterministic models are the major approach used in temperature distribution.

The literature does not contain many examples of natural temperature predictions in near shore coastal areas. Oceanographic modeling is usually more concerned with large circulation or vertical distributions of temperature,although the evaluations of temperature fronts offer valuable insights and will be discussed in a later section on well-mixed criteria. The majority of coastal temperature investigations have been based on analyzing the far-field effects of large heated discharges from electrical generating stations. The general approach of this modeling has been to predict the excess temperature created by the heated effluent above ambient conditions. This has often been done since the bulk of the thermal control regulations has been based on the maximum temperature rise above ambient conditions. The basic characteristics of the models offer the basis for most temperature modeling efforts and are briefly reviewed since they are adapted for natural temperature modeling. Examples of modeling efforts which specifically address the background natural variability are also presented.

The natural processes affecting temperature distribution in a coastal environment are due to temperature variations, heat exchange between the water and the air, and advection by ocean currents. The ideal situation would be to model these factors in three dimensions. True three-dimensional models, however, suffer from the basic difficulties in determining parameters to adequately represent the governing mass, momentum, and heat transfer equations, as well as difficulties in specifying boundary conditions. Approximations to the true three-dimensional models usually introduce a multi-layering approach, such as developed by Leendertse et al. (1973), which uses several vertically integrated layers to represent the third dimension. Idealizations of the multi-layer model consisting of two layers, representing above and below the thermocline or the separate layers influenced by wind and tidal shears, have also been developed (Wada, 1972; and Christodoulou and Conner, 1980). The computer execution and storage requirements plus ability to adequately define boundary conditions for the two layer models often preclude their use in most applications. Therefore, two-dimensional vertically integrated models are normally used to predict the distribution of temperature in coastal areas. The assumed vertically uniform temperature distribtuion is a fair approximation for natural temperature prediction in shallow coastal areas as will be discussed in a later section.

Most temperature prediction models decouple the ocean advection mass and momentum transfer modeling from the dispersion of heat. Two-dimensional circulation models are therefore first used to predict the general water movement in a coastal area. Currently used circulation models are based on the models developed by Leendertse (1970), Abbott et al., (1973), Wang and Conner (1975), and others. Although using different computational schemes, the models generally involve similar assumptions. The Wang and Conner model, CAFE-1, was used in the water temperature modeling since it was readily available and used the finite element numerical technique, offering the advantages of variable grid size and better specification of boundaries.

Two-dimensional dispersion models developed for predicting concentrations or temperatures have usually been developed in tandem or to coincide with the circulation models discussed above. Available models in this category include Leendertse (1970), and Leimkuhler (1974).

Two models have also been developed specifically for predicting thermal plume temperatures in ocean coastal zone, Eraslan (1974) and shallow coastal seas and embayments, Palmer (1978) which do not use the excess temperature approach, modeling the actual temperature distribution. Although field data comparisons were not given for the Erasian model, Palmer provided model results of ambient temperature predictions which showed favorable comparisons with temperature monitors outside the influence of the thermal plume.

The temperature modeling discussed in later sections used the Leimkuhler model, DISPER-1, which was originally developed for modeling concentrations of pollutants based on the circulation input from the Wang and Conner model. A description of the CAFE-1 and DISPER-1 models is given in the next section.

4.3 Description of Circulation and Dispersion Models

The prediction of natural temperatures in coastal waters was approached by solving the general momentum, mass, and heat transfer equations using finite element models. Two basic models were employed which computed the water depths and circulation pattern in a tidally forced coastal area (CAFE-1), and the resultant advection and dispersion of temperatures (DISPER-1) using the depths and circulation pattern as input. Both models were previously developed using finite element numerical techniques which utilized triangular elements for the spatial discretization of a coastal body of water. The basic hydrodynamic circulation model, CAFE-1, was used in this application without extensive changes. The advection-dispersion model, DISPER-1, was adapted to solve for water temperatures using a surface heat flux source/sink based on variable meteorological input. The following briefly describes the background behind the two models and the changes that were made for the natural temperature prediction application.

The basic hydrodynamic circulation model used in the prediction of natural temperatures in a coastal area was CAFE-1, a depth-averaged two-dimensional finite element model. Full details on the mathematical derivation and testing of CAFE-1 are given in Wang (1975). This model was developed to predict the circulation patterns and surface elevation changes in coastal or "shallow water" areas where there is little variation over depth (unstratified bodies of water). More information on the applicability of the depth-averaged assumption to coastal waters is presented in Section 4.4. The CAFE-1 model has found extensive use in coastal hydrodynamic studies providing both circulation patterns as well as input for further pollutant dispersion modeling efforts. Examples of various uses of CAFE-1 can be found in Chau (1977), Pagenkopf et al. (1976), and Heureux (1980). The following provides a brief summary of the approach to solving the conservation of mass and momentum equations used by the CAFE-1 model (from Wang, 1978). The vertically integrated equations of motion for shallow water are:

$$\frac{\partial \eta}{\partial t} + \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} = q \tag{4.3-1}$$

$$\begin{aligned} \frac{\partial q_x}{\partial t} + \frac{\partial u q_x}{\partial x} + \frac{\partial u q_y}{\partial y} &= f q_y - g(h + \eta) \frac{\partial \eta}{\partial x} + \frac{\tau_x^2}{\rho} \\ &- C_f \frac{\sqrt{q_x^2 + q_y^2}\, q_z}{(h + \eta)^2} + \frac{\partial F_{xx}}{\partial x} + \frac{\partial F_{yx}}{\partial y} \end{aligned} \tag{4.3-2}$$

$$\begin{aligned} \frac{\partial q_y}{\partial t} + \frac{\partial v q_x}{\partial x} + \frac{\partial v q_y}{\partial y} &= -f q_x - g(h + \eta) \frac{\partial \eta}{\partial y} + \frac{\tau_y^2}{\rho} \\ &- C_f \frac{\sqrt{q_x^2 + q_y^2}\, q_y}{(h + \eta)^2} + \frac{\partial F_{xy}}{\partial x} + \frac{\partial F_{yy}}{\partial y} \end{aligned} \tag{4.3-3}$$

where: H = total depth = $h + \eta$

η = surface displacement

h = depth referred to datum ($z = 0$)

q_x and q_y = discharges per unit width in the x and y directions

$$q_x = \int_{-h}^{\eta} u dz = H\bar{u} \qquad q_y = \int_{-h}^{\eta} v dz = H\bar{v}$$

$\bar{u}$, $\bar{v}$ = depth averaged velocities

q = a source

$f = 2\,\Omega \sin \phi$ = Coriolis parameter

Ω = phase velocity of the earth's rotation

ϕ = latitude north in radians

τ_x^s, τ_y^s = wind shear in the x and y directions

$\tau^s = C_D \rho_{air} U_{10}^2$

C_D = wind drag coefficient

ρ_{air} = density of air

U_{10} = wind speed at 10 meters

ρ = density water

C_f = friction coefficient

$= g \frac{N^2}{h^{1/3}}$ where N is the Manning number

g = acceleration of gravity

F_{xx}, F_{yy} and F_{xy} = internal stress terms from turbulent and velocity shear. These stresses are related to the dependent flow variables using the eddy viscosity concept:

$$F_{xx} = E_{xx} \frac{\partial q_x}{\partial x}$$

$$F_{xy} = E_{xy} \left(\frac{\partial q_x}{\partial y} + \frac{\partial q_y}{\partial x}\right)$$

$$F_{yy} = E_{yy} \frac{\partial q_y}{\partial y}$$

(Although it is unknown how the eddy viscosity coefficients E_{xx}, E_{xy} and E_{yy} depend on the flow field, in many cases the internal stresses are negligible. These terms are retained to provide a way of controlling small-scale numerical noise.)

The boundary conditions used for closure of the problem included a "no slip" condition on land boundaries where the velocities were set equal to zero. This provided a realistic representation of circulation near land areas that are strongly influenced by surface heating. The ocean boundary condition is specified by measured values of tidal elevations and tidal lags.

The basic advection-dispersion model adapted for the coastal natural temperature study was DISPER-1, a depth-averaged two-dimensional finite element dispersion model. Full details on the mathematical derivation and testing of DISPER-1 are given in Leimkuhler (1974). This model was developed to describe the dispersion of an arbitrary constituent in a coastal water of variable depth and boundary geometry under transient flow conditions. It must be remembered that the model averages over depth, hence it is only applicable in cases where the constituent is well-mixed vertically. (Criteria for thermally well-mixed coastal areas are discussed in detail in Section 4.4.) DISPER-1 was designed to accept information on transient flow conditions (nodal velocities and depths) generated from the previously described CAFE-1 circulation model. Prior uses of DISPER-1 were concerned with the concentration of sediment from a proposed sediment disposal (Pearce and Christodoulou, 1975), the concentration of larval fish near a power plant (Chau, 1977), and various other applications dealing with pollutant dispersion in coastal areas (Pagenkopf et al., 1976).

Some conversion of DISPER-1 was necessary to solve for temperature rather than a concentration of pollutant. Input data, initial and boundary conditions,had to be specified as temperatures and the proper use of depth-averaged or integrated-over-depth temperatures had to be corrected throughout the model. Surface heat transfer was introduced in the model in the form of an elemental source or sink using net heat flux equations with variable input meteorology. The remainder of this section provides further details on the revised DISPER-1 model for the natural temperature study.

The general mass transfer or convective diffusion equation is the basic governing equation solved by DISPER-1 which was converted to the following form for predicting the integrated temperature over depth:

$$\frac{\partial \theta}{\partial t} + \frac{\partial u\theta}{\partial x} + \frac{\partial v\theta}{\partial y} = \frac{\partial}{\partial x} Q_x - \frac{\partial}{\partial y} Q_y + \frac{\phi_s}{\rho C_v} \qquad (4.3\text{-}4)$$

where $\theta = \int_{-h}^{N} T \, dz = \bar{T} H$ is the depth integrated temperature (°C - m)

$\bar{T}$ = the average temperature over depth (°C)

T = the local temperature (°C)

$H = \eta + h$ is the total depth, η is the z-coordinate of the free surface and h is the bottom z-coordinate (m)

$\bar{u}$ and $\bar{v}$ = depth integrated velocities (m/s)

$$u = \int_{-h}^{N} u dz \qquad v = \int_{-h}^{N} v dz$$

Q_x and Q_y are terms accounting for turbulent diffusion and effective spreading that result from deviations from the vertically averaged temperature and horizontal velocity components. These are modeled assuming a non-isotropic "Fickian diffusion" process:

$$Q_x = -E_{xx} \frac{\partial \theta}{\partial x} - E_{xy} \frac{\partial \theta}{\partial y}$$

$$Q_y = -E_{yx} \frac{\partial \theta}{\partial x} - E_{yy} \frac{\partial \theta}{\partial y}$$

E_{xx}, $E_{xy} = E_{yx}$, and E_{yy} are "dispersion" coefficients (m^2/s)

which take into account turbulent diffusion and the velocity variation over depth

$\frac{\phi_s}{\rho C_v} = \int_{-h}^{N} \frac{\phi}{\rho C_v} d_z$ = heat input per unit projected area (Joules/m^2s)

ϕ = heat flux source (Joules/m^3sec)

ρ = density of water (kg/m^3)

C_v = specific heat of water at constant volume (Joules/°C-kg)

Input for the solution of equation (4.3-4) consists of H, $\bar{u}$, and $\bar{v}$, which are provided from the CAFE-1 computation; dispersion coefficients; boundary conditions; and heat sources or sinks. A discussion of dispersion coefficients is not within the scope of this thesis although this topic will be addressed in Section 4.6 on the case study. Heat transfer across the land boundary and bottom surface is set at zero. The ocean boundary condition will also be discussed in Section 4.6.

The only heat source and sink considered in the natural temperature application is heat transfer across the ocean surface. This surface heat flux is calculated using meteorological variables, including solar and atmospheric radiation, and the value of the water temperature. The basic equation used is (from Ryan and Harleman, 1973):

$$\phi_x = \phi_r - \{4\text{x}10^{-8} (T_s + 460)^4 + f(w_2)[(e_s - e_a) + 0.255(T_s - T_a)]\} \qquad (4.3\text{-}5)$$

where ϕ_s = net surface heat flux (BTU/ft^2 - day)

ϕ_r = net solar plus atmospheric radiation flux (BTU/ft^2 - day)

T_s = water temperature (°F)

T_a = ambient air temperature (°F)

e_s = saturated vapor pressure (mm Hg) at the water temperature given by:

$$e_s = -2.4875 + 0.2907\ T_s - 0.00445\ T_x^{2} + 0.0000663\ T_s^{3}$$

e_a = vapor pressure of ambient air (mm Hg) given by:

$$e_a = (\frac{RH}{100}) \times (-2.4875 + 0.2907\ T_a - 0.00445\ T_a^{2} + 0.0000663\ T_a^{3})$$

RH = relative humidity in %

$f(w_2)$ = wind function based on a virtual temperature difference and wind speed at 2 meters, w_2 (in miles per hour), above the water surface given by either:

$$f(w_2) = 22.4\ (\Delta\theta_v)^{1/3} + 14\ w_2 \qquad (4.3\text{-}6)$$

$$f(w_2) = 17\ w_2 \qquad (4.3\text{-}7)$$

The choice of (4.3-6) or (4.3-7) depends on:

$\Delta\theta_v = T_{sv} - T_{av}$

where T_{sv} = virtual temperature of a thin vapor layer in contact with the water surface (°R)

$= (T_s = 460)/(1 - 0.378\ e_s/p)$

T_{av} = virtual air temperature (°R)

$= (T_s + 460)/(1 = 0.378\ e_a/p)$

p = ambient air pressure (mm Hg)

If $\Delta\theta_v < 0.0024\ w_2^{3}$ equation (4.3-6) is used, otherwise equation (4.3-7) is used.

Details are given in Leimkuhler (1974) on the conversion of the vertically integrated convection-diffusion equation and boundary conditions into a set of ordinary differential equations in time,more mathematically suitable for solution by the finite element method. The revised DISPER-1 model to predict natural temperatures will be referred to as DISPER-1T in the following sections to distinguish it from the original DISPER-1 model. Criteria for applying the finite element model to the prediction of natural temperatures in coastal areas are given in the following section.

4.4 Criteria to Determine Vertically Well-Mixed Coastal Areas

Modeling natural physical processes is never an exact science. It is very difficult to consider all the factors influencing natural variability. In all modeling work assumptions and approximations must be made to solve problems. This is certainly the case in modeling natural temperature variation. In Chapter III a simplified one-dimensional representation of a river environment was used to model the temperature distribution which could be solved analytically. The horizontal extent of a coastal body of water precludes the use of one-dimensional models or analytical solutions. Advances in numerical techniques and computer technology have increased the capability to do two- and three-dimensional modeling. Though the ideal is to model a process using three dimensions, constraints on computer storage and execution time leave applications of three-dimensional models to the most critical concerns. This narrows the possibilities of modeling coastal areas to two-dimensional models.

Two-dimensional modeling must consider the significance of eliminating the third dimension as well as other assumptions and approximations necessary in using numerical techniques and models in general. The major assumption in the horizontal two-dimensional models discussed in Section 4.3 is that the variables do not vary over depth. This will be true in the case of temperature distributions if the body of water is well-mixed vertically due to the turbulence caused by wind and bottom velocity shears and buoyancy effects. Criteria for estimating when the well-mixed assumption is appropriate will be considered in this section. Estimates will point out areas where the models may adequately reflect natural conditions and areas that may be borderline or poorly represented. Particular attention will focus on the ability of tidal forces to break up stratification which develops during tidal slacks.

The temperature distribution in coastal water is determined by surface and internal heat transfers. Net surface heat transfers are the sum of incident solar and atmospheric radiation which add heat to the upper layer; plus reflected solar and atmospheric radiation, long wave radiation from the water surface, evaporative heat flux, and conduction that cause cooling of the upper layer. Internal heat transfers include internal absorption of solar radiation, horizontal advection due to bulk water movement, mixing due to wind induced currents or bottom shear, convective mixing due to density differences, and molecular and turbulent diffusion whenever temperature gradients and turbulence are present.

The effects of the above heat transfers on vertical temperature distribution can be simplified by considering their effects on buoyancy and mixing. Surface heat transfers in and out of the water column and radiation absorption can be represented by their effects on the buoyancy (density difference) of the water. Surface buoyancy flux or the rate of movement of buoyancy can then be used as a measure of "heating" or "cooling" of the water. The major vertical mixing processes from internal heat transfers are due to seasonal convective mixing and the addition of turbulent energy due to wind or bottom friction velocity shears. Buoyancy flux contributes to the seasonal convective mixing during the late fall and winter "cooling season" when cooling of the surface layer of water results in the turnover of hotter, deeper water due to density differences. Therefore, the fully-mixed assumption is valid during the cooling season for coastal areas which have a significant yearly temperature variation.

The vertical temperature distribution is more complex during periods when there is a net downward buoyancy flux due to heating in the late spring, summer and early fall months. As the surface water grows warmer, a temperature gradient develops vertically causing a positive density gradient. The less dense surface layer limits the amount of vertical mixing causing the development of a thermocline or stratification. A daily cycle of daytime heating and nighttime cooling also exists causing fluctuations in the net seasonal heating. This daily cycle can significantly affect potential stratification especially when daytime heating occurs concurrently with slack tidal velocities. If stratification can exist for a long period of time, (more than a day in the case of a coastal area) the well-mixed assumption is probably not appropriate. The following discussion on establishing criteria for fully-mixed conditions will explore the heating season when the assumption is the most critical.

One method to determine if a coastal area is well-mixed is to measure the vertical temperature distribution directly by monitoring. Economic considerations often preclude the monitoring of a large number of locations in a coastal area so a simpler method of determining the "well-mixed" condition is necessary. A modeler may also be aksed to provide an estimate of the horizontal temperature distribution without use of onsite temperature data.

In a coastal body of water potentially useful criteria must determine if tidal or wind forces can cause mixing over the full depth of the water column to prevent stratification or break it up once it exists. These forces act through the formation of a velocity shear which generates turbulent mixing. Tidal forces are usually the predominant factor since the produced velocity shear is much higher. A simple comparison of velocity shear, u_*, produced by wind and tidal velocities, confirms this result. Tidal velocities produce shears from bottom friction as given in the following equation base on the quadratic drag law:

$$u_* = \sqrt{\frac{\tau_s}{\rho w}} = \text{velocity shear or friction velocity}$$

$$\tau_s = C_D \rho_w V_T^2 = \text{shear stress} \qquad (4.4\text{-}1)$$

$$u_* = \sqrt{C_D V_T^2}$$

where: C_D = friction coefficient = $\frac{f}{8} \sim 2.5 \times 10^{-3}$ (Officer, 1976)

f = friction factor

ρ_w = density of water

V_T = tidal velocity

Velocity shear due to wind can be determined from the same formulation as for bottom friction where:

$$u_* = \sqrt{\frac{\tau_o}{\rho_w}} = \text{velocity shear}$$

$$\tau_o = C_z \rho_a V_z^{\,2} = \text{shear stress from wing}$$

$$u_* = \sqrt{\frac{C_z \rho_a V_z^{\,2}}{\rho_w}} \qquad (4.4\text{-}2)$$

where: C_z = surface shear stress coefficient for wind speed at height z

ρ_a = density of air

V_z = wind speed at height z

$\rho_a/\rho_w = 1.28 \times 10^{-3}$

A large wind speed of 10 meters per sec (m/s) at a 10 meter height leads to a C_{10} of 1.6×10^{-3} from Wu's (1969) expression for ocean shear stress coefficient:

$$C_{10} = 0.5\, V_{10}^{\,1/2} \times 10^{-3} \qquad 1 < V_{10} < 15 \text{ m/s} \qquad (4.4\text{-}3)$$

This results in a velocity shear due to the 10 m/s wind of .014 m/s. The amplitude of tidal velocities, however, is commonly .5 m/s or more in coastal areas with good flushing resulting in a velocity shear of .025 m/s. Although strong winds can produce velocity shears on the same order of magnitude as the friction shear, they occur infrequently as opposed to the tidal forces which do not vary significantly from one tidal period to the next.

4.4.1 Mixing in an Unstratified Layer

Knowledge of the velocity shear can be used to determine the potential depth that can be mixed due to turbulent momentum transfer in an unstratified coastal area. The following discussion is based on the effect of wind produced velocity shear since this is the common methodology used in studying stratified layers from lake applications. However, the velocity shear due to bottom friction causes turbulence that is conceptually equivalent to the wind produced shear. Since the critical question is to determine if the entire depth is adequately mixed, the results should be adequate for estimation purposes.

The conservation of momentum equation acts as a starting point where the average water velocity, $\bar{u}$, is considered a function of the vertical coordinant, z, and the time, t:

$$\frac{\partial \bar{u}}{\partial t} = \frac{\partial}{\partial z}\left(\frac{\nu \partial \bar{u}}{\partial z} - \overline{u'w'}\right) \qquad (4.4\text{-}4)$$

where: $\frac{\partial \bar{u}}{\partial z}$ = mean viscous transport of momentum in the z direction

ν = viscosity coefficient

$\overline{u'w'}$ = turbulent transport of momentum in the z direction

u' & w' = turbulent contributions of the velocity components in the x and z directions ($u = \bar{u} + u'$, $w = \bar{w} + w'$)

Defining z equal to zero at the ocean bottom:

$$\frac{\nu \partial \bar{u}}{\partial z} - \overline{u'w'} = \frac{\tau_b}{\rho} = u_*^2 \qquad (4.4\text{-}5)$$

where: τ_b = bottom shear stress

ρ = density

u_* = shear velocity

u_*^2 can be defined in terms of the concept of eddy viscosity where u_*^2 is assumed constant and $\bar{u}(z,t) = 0$ at time $t = 0$:

$$u_*^2 = k_{zm} \frac{\partial \bar{u}}{\partial z} \tag{4.4-6}$$

where k_{zm} is an eddy viscosity coefficient. Equation (4.4-4) then becomes:

$$\frac{\partial \bar{u}}{\partial t} = \frac{\partial}{\partial z} (k_{zm} \frac{\partial u}{\partial z}) \tag{4.4-7}$$

which can be approximated by:

$$\frac{\partial \bar{u}}{\partial t} = \bar{k}_{zm} \frac{\partial^2 \bar{u}}{\partial z^2} \tag{4.4-8}$$

if $\bar{k}_{zm}$ represents a characteristic (average) value of k_{zm} over depth. This has the solution in terms of the depth of mixing, h:

$$\frac{dh^2(t)}{dt} = 2\ k_{zm}(t) \tag{4.4-9}$$

If turbulence is only due to momentum, $\bar{k}_{zm}$ can be approximated in terms of u_* and h as follows:

$$\bar{k}_{zm} \approx c_1\ u_* h \tag{4.4-10}$$

where c_1 is an empirical coefficient approximately equal to .07 (Fischer, 1973). This leads to the equation:

$$\frac{dh}{dt} = .07\ u_* \tag{4.4-11}$$

which can be used to determine the mixing depth that would result from an average velocity shear over a given time period. This can be applied to a coastal area by considering a mixing period as one half of the tidal cycle. Using the average tidal velocity, Equation (4.4-11) becomes:

$$H = .07 \frac{T_p}{2} \frac{f}{8} u_T \qquad (4.4\text{-}12)$$

where: T_p = tidal period

f = bottom friction factor

u_T = average tidal velocity over a tidal period

This provides an estimation of the maximum mixed depth since factors that can inhibit mixing are not considered. The actual mixed depth in most cases will be less than this value especially during the heating season when a heated surface layer can impede mixing.

4.4.2 Mixed Depth Based on Energy Balance

One method of including the effect of surface heating is to consider a balance of the potential energy gain from the rate of heat input with the loss of tidal energy dissipation due to velocity shear. Simpson and Hunter (1974) found that such a balance could be used to determine the transition between stratified and vertically mixed areas in shallow seas. In their theory of tidal mixing,a fraction of kinetic energy, ε, lost from tidal motion, is available to mix a constant surface heat input over the depth of the water column. Balancing the fraction of kinetic energy available for mixing with the rate of potential energy gain over a water column:

$$\varepsilon\, C_D \rho |u_T|^3 = \frac{1}{2} \frac{\alpha g h Q}{c} \qquad (4.4\text{-}13)$$

where: C_D = friction coefficient
ρ = density of water
$|u_T|$ = amplitude of the tidal velocity
α = volume coefficient of expansion
g = gravity
h = water depth
c = specific heat at constant pressure
Q = rate of heat input, surface heat flux

and rearranging terms provides:

$$\frac{hQ}{|u_T|^3} = \frac{zC_D\rho c\varepsilon}{\alpha g h} \tag{4.4-14}$$

The term $hQ/|u_T|^3$ can then be used as a guide for the transition between well-mixed and stratified water. Contours of the stratification parameter $h/|u_T|^3$ are often plotted by oceanographers as a simple method of determining the transition based on bottom profiles and available tidal stream data or tidal velocities from numerical models (Simpson and Pingree, 1977). This formulation is, however, based on constant values of the parameters involved. This can be useful in determining the effects of net seasonal heating when Q does not vary over a short period. In coastal areas with shallow depths that can be significantly influenced by the daily cycle of heat flux and tidal velocity variations, more consideration of the dynamic nature of the mixing process is necessary.

4.4.3 Effect of Dynamic Conditions on Mixed-Layer Depth

The dynamic factors affecting the fully-mixed depth in a coastal area can be estimated using the variation of buoyancy flux (representing daily heat flux) and velocity shear (dependent on tidal velocity variations). The following formulation uses the buoyancy, b, present in the mixed layer as a representation of the change in temperature in the layer:

$$b = B(T - T_o)g \qquad (4.4\text{-}15)$$

where: B = thermal expansion coefficient

T_o = reference temperature

g = gravity

The assumption that the velocity shear, u_*, resulting from bottom shear is conceptually the same as from wind action will again be used. Figure 4.4-1 provides a schematic of the mixed layer depth expressed in terms of buoyancy. The governing equation for the analysis is the conservation of buoyancy equation:

$$\frac{\partial \bar{b}}{\partial t} = \underbrace{\frac{-B_o}{h}}_{\text{surface transfer}} - \underbrace{\frac{w_e \Delta b}{h}}_{\text{bottom of mixed layer transfer}} \qquad (4.4\text{-}16)$$

where: $\frac{\partial \bar{b}}{\partial t}$ = the change in average buoyancy in the mixed layer over time

B_o = buoyancy flux including surface heat flux (a negative value of B_o denotes "heating," that is, flux into the water)

h = depth of uniformly mixed upper layer

Δb = change in buoyancy from the constant buoyancy in the uniformly mixed upper layer to the buoyancy distribution at the top of bottom layer

w_e = entrainment velocity of the lower layer fluid into the upper layer due to turbulent upper layer mixing

The entrainment velocity requires further discussion since it determines the critical parameter of interest, h, the depth of the mixed layer. This velocity is determined from the following equation (from Niiler and Kraus, 1977) which accounts for the shear velocity producing entrainment, u_*, and B_o which can act to damp out entrainment during heating periods (negative B_o) or strengthen entrainment during cooling:

$$w_e = \frac{1}{\Delta b} \left(2m \frac{u_*^3}{h} + nB_o\right) \qquad (4.4\text{-}17)$$

where: u_* = shear velocity produced by wind action

m,n = empirical dissipation parameters

At this point it must be noted that the empirical dissipation parameters differ between wind and bottom produced shears. These parameters, which represent the ability of the velocity shear to cause turbulent mixing, are the topics of much debate and it must be remembered that the following can only provide a general estimation of the effect of velocity shears.

During "cooling" periods or when u_* predominates over a negative B_o, the entrainment velocity will be greater than zero and this velocity represents the change in the depth of the mixed layer over time due to the turbulent mixing:

$$\frac{dh}{dt} = w_e = \frac{1}{\Delta b} \left(\frac{2mu_*^3}{h} + n\ B_o\right) \qquad \text{for } w_e > 0 \qquad (4.4\text{-}18)$$

An assumption is made as shown in Figure 4.4-2, where $\Delta b = b$, therefore

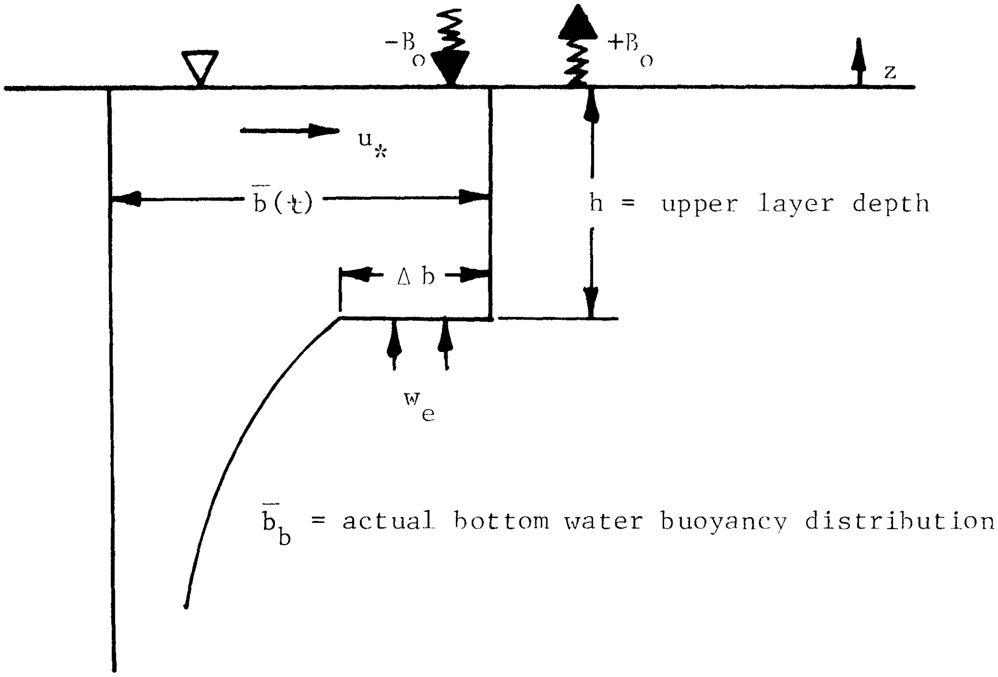


Figure 4.4-1 Schematic of Mixed-Water Depth Evaluation

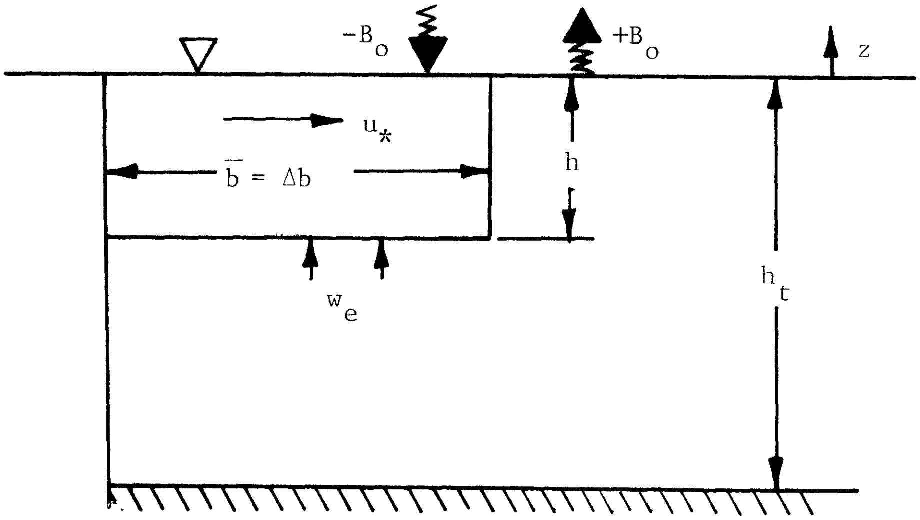


Figure 4.4-2 Approximation to Mixed-Layer Depth Evaluation

the lower layer has no buoyancy. This simplifies the solution of Equation (4.4-18) while offering a conservative result since a larger entrainment velocity (higher velocity shear or more "cooling") is needed to mix the layer to a lower depth. Equation (4.4-18) then becomes:

$$\frac{dh}{dt} = \frac{1}{b}\left(\frac{2mu_*^3}{h} + n\,B_o\right) \qquad \text{for } \frac{dh}{dt} > 0 \qquad (4.4\text{-}19)$$

If the boundary flux is negative ("heating") and sufficiently large to cancel the shear velocity term, the entrainment velocity would be negative. However, this is physically unreasonable since a non-turbulent lower layer cannot entrain the upper layer. In this situation, the entrainment velocity is zero and the depth of the upper mixed layer can be determined from equating the two terms within the brackets in equation (4.4-19):

$$h = \frac{2mu_*^3}{-nB_o} \qquad (4.4\text{-}20)$$

Equation (4.4-20) determines the minimum mixed layer depth that results during "heating" periods when velocity shear is small. Since tidal velocities during slack periods approach zero for short periods, in the absence of high wind velocities summer "heating" periods will produce a stratified layer. Once this stratification exists at a depth h, the question becomes can entrainment velocity formed from tidal forces mix the upper water to provide a fully mixed region.

Simulation studies were done solving the buoyancy conservation equation (4.4-16) and depth of the mixed layer equations (4.4-19) and (4.4-20) over a period of a few days. Sinusoidally varying B_o, buoyancy fluxes (representing the daily "heating" and "cooling" cycle) and velocity shears, u_*, (representing the influence of tidal mixing) were used as input. The objective was to determine the importance of the daily "heating" and "cooling" cycle and the diurnally produced velocity shears (simulating tidal forces) on the stratification and mixing processes.

Evaluations were done using reasonable values of B_o and u_* that would occur in a coastal region. B_o was varied to represent heat fluxes in the summer ranging from -700 Joules/m^2s ("heating") to 300 Joules/m^2s ("cooling"). Velocity shears from .0025 to .02 m/s were used representing tidal velocities from .05 to .4 m/s. Values for the dissipation parameters were set at .5 for m and .1 for n based on an average of the general ranges for these terms (Fischer et al., 1979, and Niljar and Kraus, 1977).

The effect of sinusoidally varying buoyancy fluxes was evaluated using constant shear velocities. The important case of interest is whether the daily variation in heating and cooling is strong enough to mix the upper layer below the actual depth of the area at low velocities. Figure 4.4-3 shows the progression for three velocities with buoyancy fluctuating around a "net" heating mean value of -200 Joules/m^2s. The depth at maximum heating was found to be the overriding factor in controlling the level of the mixed depth since the variation over a daily period was generally small. As the velocities increased , the daily variation became more noticeable yet the magnitude of the variation was relatively small. These variations had much more of an influence when variations in velocity shear where also included as will be seen below.

The next set of simulations accounted for a varying shear velocity,

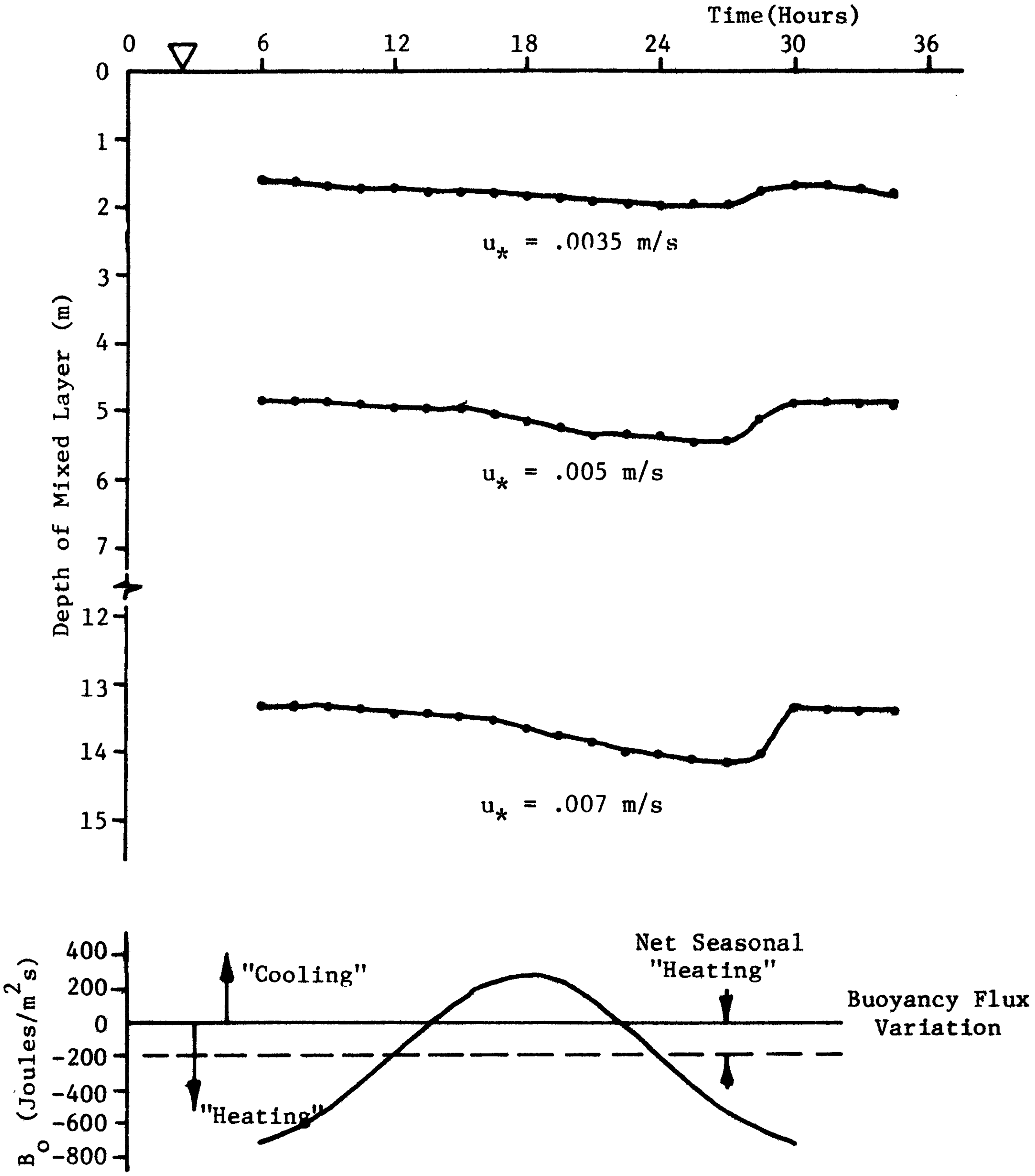


Figure 4.4-3 Mixed Layer Depth with Varying Buoyancy Flux, B_o, and Constant Velocity Shear, u_*

u_*, while the buoyancy flux, B_o, was held constant at a value representing a "net heating" of -200 Joules/m^2s. Figure 4.4-4 shows the results of varying the shear sinusoidally with four peaks in a day to represent the effects of diurnal tides. It is evident that the minimum layer depth occurs at a minimum u_*, and can be used as an indication of stratification. At low velocities with small amplitude variation, little mixing occurs as shown in Plot a. As the amplitude of the velocity variation is increased, the mixed layer increases significantly (Plots b and c). The gradual mixing is broken by the return to low velocities causing the depth to decrease to its minimum value each mixing period. The value of the buoyancy flux is important as shown in Plot c, where an added heat flux decreased the minimum mixed depth only slightly but with a much larger influence in decreasing the maximum depth. The period of velocity shear variation also must be considered. It is important to note that the mixed depth never reaches a value (essentially the stratification parameter discussed earlier) given by:

$$h = \frac{2m[u_*(\max)]^3}{-nB_o} \qquad (4.4\text{-}21)$$

since the length of mixing period is not long enough for the velocity shear to have its full effect. It takes longer for the mixed depth to increase than for the formation of the minimum stratified layer when velocities reach their minimum value. Therefore, both the amplitude and period of variation in velocity shear and the magnitude of the buoyancy flux are important in the determination of the "well-mixed" assumption.

The final set of simulations combined the effects of variations in

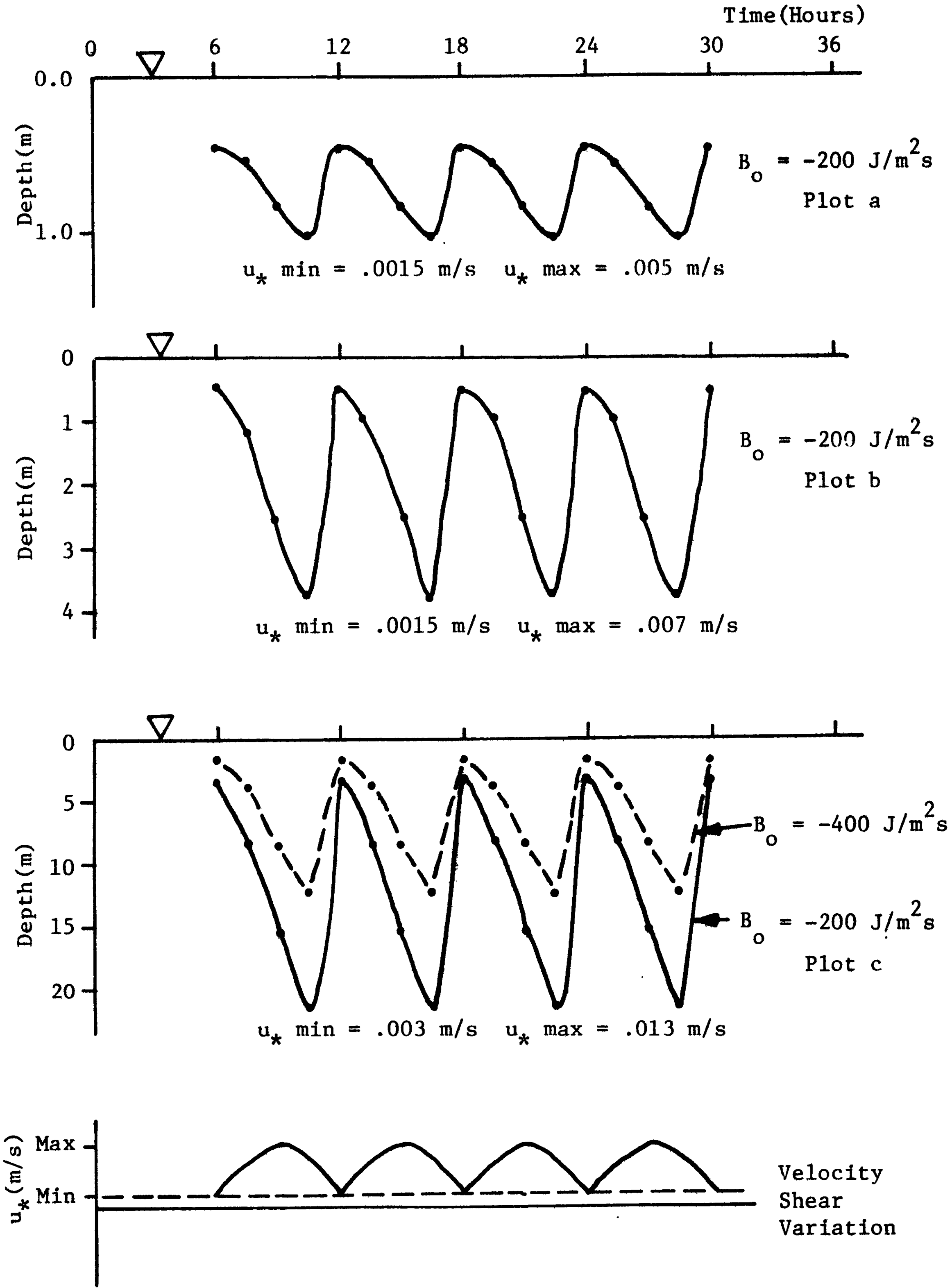


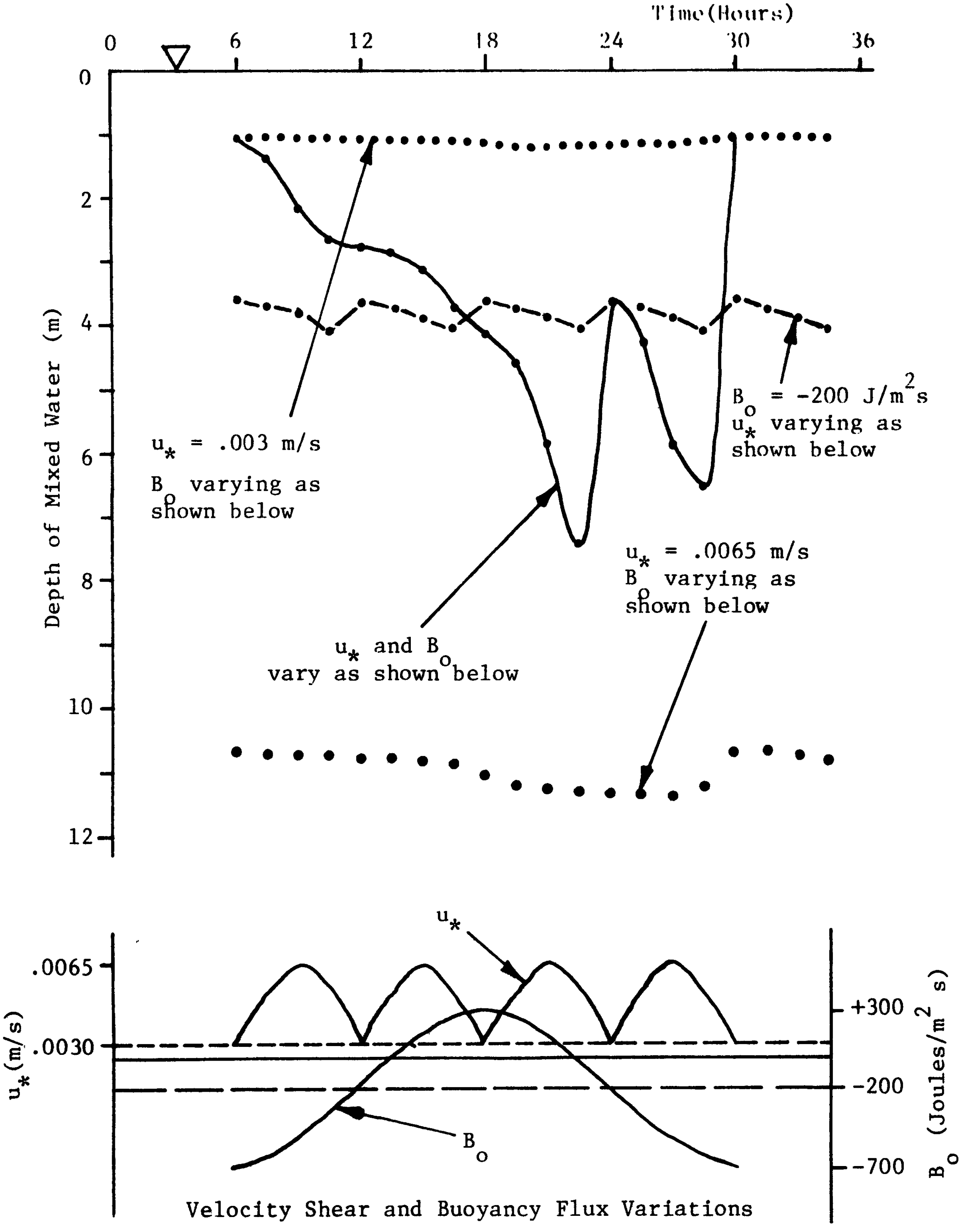
Figure 4.4-4 Mixed Layer Depth with Varying Velocity Shear, u_*, and Constant Buoyancy Flux, B_o

velocity shear and variations in buoyancy. A diurnal tide generating velocity shear was combined with a daily fluctuation of buoyancy to model actual events in a coastal area. Figure 4.4-5 shows the most conservative case where the peak "cooling" occurs at the lowest velocities.

The gradual deepening of the mixed layer due to night time cooling, as shown on the constant u_* plots, becomes a decisive factor when the variations are combined. This produced significant deepening over the plot of varying u_* with B_o constant. The occurrence of the maximum cooling coinciding with the lowest velocity does not allow the velocity shears to mix the layer to the constant maximum velocity shear and varying B_o plot. This was the same result found in the earlier varying velocity shear simulation where the period of the velocity shear was important in inhibiting the shear's full effect. Figure 4.4-6 shows the simulation where the peaks of the buoyancy flux are in phase with the velocity shears producing maximum mixed-depth conditions. The maximum shear together with maximum "cooling" cause the mixed layer depth to go below the constant maximum u_*, varying B_o plot. The second dip is not as dramatic since the lowest velocity appeared at more "heating" than in the prior simulation resulting in a depth closer to the surface. In both cases, nighttime "cooling" played an influential role in enhancing the mixing.

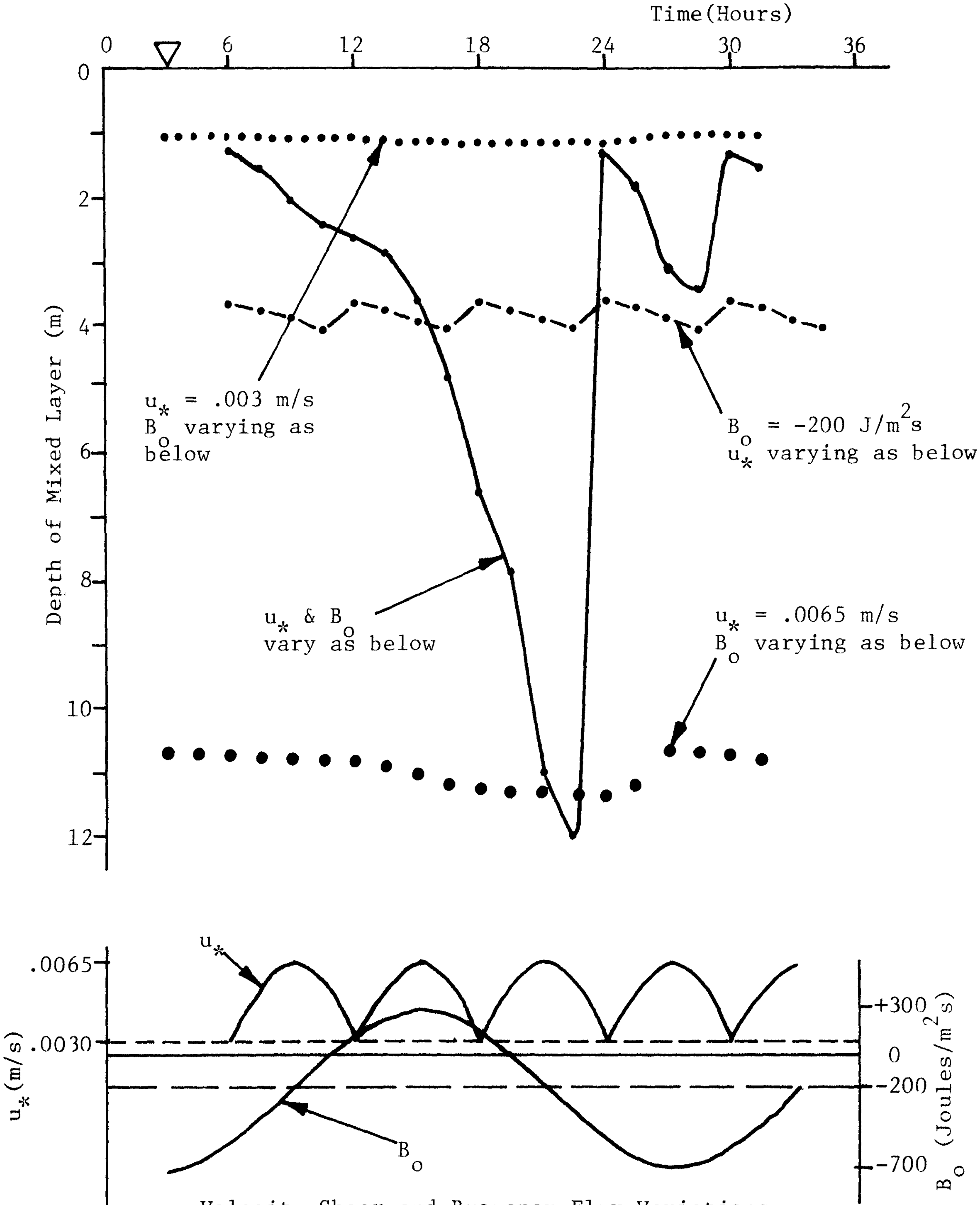
4.4.4 Conclusions on Mixed-Layer Depth

The previous analyses provided a general outline for establishing criteria for using the "well-mixed" assumption. It is worthwhile to compare the results of the analyses using constant inputs versus the later simulations that considered dynamic conditions. In the first analysis, Equation (4.4-12) presented the limit of the mixed depth since the



Velocity Shear and Buoyancy Flux Variations

Figure 4.4-5 Mixed Layer Depth with Varying Velocity Shear, u_*, and Buoyancy Flux, B_o - Most Conservative Case, Peaks out of Phase



Velocity Shear and Buoyancy Flux Variations

Figure 4.4-6 Mixed Layer Depth with Varying Velocity Shear, u_*, and Buoyancy Flux, B_o - Peaks in Phase heating factors, which were later shown to be severely inhibiting, are not included. Therefore, this does not provide a conservative value for the mixed layer depth. The stratification parameter used by oceanographers is essentially the method in determining the depth given by Equation (4.4-20) which is stated below:

$$h = \frac{2mu_*^3}{-nB_o} \qquad (4.4\text{-}20)$$

This equation also provided the minimum mixed layer depth (closest to the surface) for each of the simulation studies and showed that stratification would most likely occur during slack tidal periods (low velocities) when heating causes a shallow mixed layer to develop. The maximum u_* and B_o representing the "net" sesonal heating in this equation (as is done in oceanographic work) can provide a non-conservative estimate of the mixed layer depth in coastal waters heavily influenced by daytime maximum "heating." The variation in heating was shown to significantly inhibit the shear mixing since the mixing period was not long enough to produce the full shear's effect. Nighttime "cooling", however, in conjunction with maximum velocities produced mixing below the results of Equation 4.4-20 if the maximum B_o is used instead of the "net" heating value.

Although reasonable values for the various parameters were used, the numerical approximations and uncertainty in many of the parameters make strict quantitative estimates unfeasible. Some qualitative criteria, however, can be given based on the previous discussion serving as useful guidelines in evaluating a coastal area. Solving for the minimum depth of the mixed layer (Equation (4.4-20)) under conditions of low velocity shears, provides a simple way of determining if stratification will exist. In most coastal areas this provides an indication that minor stratification may occur during periods of slack tides. A simple estimate for measuring permanent well-mixed conditions is to use the maximum velocities in this equation to discover if minimum depth is below actual depth during maximum heating (maximum B_o):

$$h = \frac{2m[u_*(\max)]^3}{-nB_o(\max)} \qquad (4.4\text{-}21)$$

This is essentially a determination of the stratification parameter Qh^3/h mentioned above in determining shallow sea temperature fronts although the maximum B_o is used instead of the "net" seasonal value.

The above procedure, Equation (4.4-21), provides an estimate that may be slightly conservative since nighttime cooling was shown to enhance the mixing process by combining a daily period with the maximum velocity to give the maximum mixed-layer depth.

The preceding discussion offers some general insights into the difficult problem of predicting stratification in coastal areas. A study of the physics of the situation coupled with simulations using reasonable values for input parameters provided evidence that daily fluctuations in the heat flux and variations in velocities have important effects on the depth of the mixed layer. The low velocities characteristic of periods of tidal slack provide an opportunity for stratification to develop. Higher velocity amplitudes cause significant mixing which can wipe out the stratification process especially during nighttime "cooling". Some simple criteria were proposed for rough estimates of when stratification can be expected to persist for more than a day. With a general indication of when the mixed-layer models are appropriate, the discussion will now turn to the specific criteria generated for using numerical techniques.

4.5 Criteria for the Numerical Models

Both CAFE-1 and DISPER-1T employ the use of the finite element numerical technique in solving the general equations over a two-dimensional domain. This technique involves the discretization of the area of interest into a grid of triangular-shaped elements. It is a judgemental process as to what number, size, and arrangement will give an effective representation of the area. However, several criteria have been developed for the two models to aid in the choice of proper timestep and grid layout for stable numerical computations. These criteria, along with general suggestions, are presented to provide the basis for initial model application.

First, some general considerations examine the problem of executing large finite element programs on a computer. A finer grid (more nodes and elements) will produce greater accuracy in the representation of the area of interest and in the mathematic solution to the governing equations. However, higher computer execution costs and storage requirements result when using finer grids due to increased matrix size. The timestep for solving the problem is also dependent on the size of the smallest grid element; hence more timesteps are needed in smaller grid layouts for a given period of evaluation.

Outer boundary conditions must be established before the total size of the area can be set up. Land boundaries do not offer a problem if fine details are eliminated. The open ocean boundary is a more important consideration since it controls the bulk of the model results. For the tidal circulation model tidal elevations on the boundary are extremely important. The general rule is that the ocean boundary should make use of whatever data is available yet stay far enough away from specific areas of interest so that inaccuracies inherent in most data do not play an overly significant role in the results.

Once the boundaries are determined, nodes should be placed to recover details of the bottom profile. The grid must also be finer where large gradients occur, both for velocities and temperatures depending on depth variations, boundary geometry, sources and sinks. Grid dimensions should also change gradually since element shapes near equilateral yield better solutions. Several impossibilities should also be avoided as indicated by Wang (1975). At least two rows of elements should always be used in channel areas so that traverse flow can occur, and configurations near boundaries should not establish areas where an element will fill only while draining the element next to it.

The choice of timestep is critical in numerical techniques for stable solutions, i.e. resulting values that are not unreasonable. Most stability criteria for finite element methods have been empirically determined. However, the requirements may vary slightly from problem to problem. Wang (1978) presented the following stability requirements for CAFE-1 based on extensive testing:

$$\Delta t < 0.5 \rightarrow 1.5 \left(\frac{\Delta s}{\sqrt{2gh}}\right)_{\min} \qquad (4.5\text{-}1)$$

where: Δt = timestep

Δs = length of the smallest element g = acceleration of gravity

and h = depth

The coefficient 1.5 was found to produce stable results for a straight rectangular channel whereas .5 had to be used for areas with highly irregular boundaries. The timestep should also not exceed the tidal period divided by twenty.

The criteria for DISPER-1 developed by Leimkuhler et al. (1975), were found to have the most restrictions on computer work in the natural temperature application. The maximum allowable timestep for solution stability is again directly proportional to the smallest grid element. Empirical study found that both of the following criteria must be met where the coefficient 10 was not exact:

$$10\ \Delta t < \frac{\Delta s^2}{E} \quad (4.5\text{-}2) \qquad \text{and } 10\ \Delta t < \frac{\Delta s}{u} \qquad (4.5\text{-}3)$$

where: Δt and Δs as in equation (4.5-1)

u = velocity from CAFE-1 results

E = the dispersion coefficient

Leimkihler et al., also found that, given velocities and grid lengths, the range of allowable dispersion coefficients will be limited as follows where the coefficient of 2 is not exact:

$$\frac{\Delta su}{E} < 2 \qquad (4.5\text{-}4)$$

Christodoulou and Conner (1980) developed a two-layer version of DISPER-1 which included the following criteria for computational stability:

$$\Delta t < \frac{1}{1.2\,\frac{u_i}{\Delta s} + 8\,\frac{E_i}{\Delta s^2} + \frac{k}{2} + \frac{\ell}{2}} \tag{4.5-5}$$

where: u_i = velocity of layer i

E_i = dispersion coefficient of layer i

k = decay rate

ℓ = a layer transfer coefficient

Disregarding the layer notation and decay rate, the following provides a stability criteria that includes both velocity and dispersion directly:

$$\Delta t < \frac{1}{1.2\,\frac{u}{\Delta s} + \frac{8E}{\Delta s^2}} \tag{4.5-6}$$

The above criteria also provide some general guidance on the variation in grid size in any given modeling domain. The smallest grids are needed in areas of large gradients or where complex geometries must be considered. Decreasing the size of the grids will cause added computer costs due to the resultant smaller timestep required by this change. Although large grids are ideal in areas away from the above limitations on grid size, Equation (4.5-4) acts to put an upper limit on the maximum size of the grids. This result is because large velocities often occur in both the smallest grids (complex geometry) or the largest grids (offshore currents). One approach is to use smaller grids whenever high velocities are encountered to keep the value of the allowable dispersion coefficient low. Otherwise, using the common factor of the dispersion coefficient E in Equations (4.5-2) and (4.5-4) yields:

$$\Delta t < \frac{1}{5u} \frac{(\Delta s_{min})^2}{\Delta s_{max}} \qquad (4.5\text{-}7)$$

Equation (4.5-7) demonstrates that in cases where the largest velocities occur at both minimum and maximum grid sizes, the ratio of $(\Delta s_{min})^2/\Delta s_{max}$ also affects the timestep.

The general guidelines and criteria for numerical stability provide the background for the application of the finite element models found in the next section.

4.6 Verification and Application of Models

Verification of the CAFE-1 and revised DISPER-1T models consisted of both comparisons with analytical solutions, and field data from measurements near the Millstone Nuclear Power Station. Since the CAFE-1 model was basically unchanged for the natural temperature application, comparisons with analytical tests centered around assuring that the computer code worked as originally intended. Extensive comparisons of analytical solutions, and comparisons with actual velocity and tide measurements in Massachusetts Bay can be found in Wang (1975). The basic transport and dispersion properties of DISPER-1 were previously tested by Leimkuhler (1974) in the original model formulation. Some revisions were made to DISPER-1 requiring testing of the surface heat transfer coding. This new natural temperature model was compared to analytical solutions for heatup in a one-dimensional channel. Finally, the results of the two models are compared with actual velocity and temperature measurements from the Millstone site.

4.6.1 Analytical Comparisons

The major analytical comparisons focused on the changes to the DISPER-1 coding to test the inclusion of a heat flux which depended on meteorological input and water temperatures. After testing of the actual heat flux values, a one-dimensional channel grid was modeled for steady state conditions using a constant velocity. The general one-dimensional convective diffusion equation for temperature was the basis for the analytical comparison:

$$\frac{\partial T}{\partial t} + \frac{\partial uT}{\partial x} = E_L \frac{\partial^2 T}{\partial x^2} + \frac{\phi s}{c_v h} \qquad (4.6\text{-}1)$$

where: T = water temperature

ϕ_s = heat flux

ρ = density of water

c_v = specific heat of water

E_L = longitudinal dispersion coefficient

h = water depth

u = velocity

At steady state conditions the first term of Equation (4.6-1) equals zero. The dispersion term was neglected since it was kept small compared to advection. The equation was then solved by linearizing the heat flux term using a heat exchange coefficient, k:

$$\phi_s = -k(T_s - T_E) \qquad (4.6\text{-}2)$$

where: T_s = surface water temperature

T_E = equilibrium temperature necessary for $\phi_s = 0$ in Equation (4.3-5)

k = linear heat exchange coefficient

Equation (4.6-1) then takes the form:

$$\frac{\partial uT}{\partial x} = \frac{-k(T_s - T_E)}{c_v h} \qquad (4.6\text{-}3)$$

which has the following solution, given $T_s = T_o$ at $x = 0$:

$$T_s = \exp[\frac{-kx}{hu\ c_v}]\ (T_o - T_E) + T_E \qquad (4.6\text{-}4)$$

This provides the temperature, T_x, at any given distance, x, from the $x = 0$ boundary.

The model was tested for heatup of a 1 meter deep, 5 by 10 kilometer channel with the following constant velocity, meteorological input and boundary conditions:

velocity, u = .1 m/s

wind speed at 2 meters, w_2 = 3.67 m/s

relative humidity = 70%

pressure = 746 mm Hg

solar + atmospheric heat flux = 609 Joules/m^2s

air temperature = 15.5°C

T_o (at x = 0) = 15.8°C

T_e = 19.5°C from equation 4.3-5 when $\phi_s = 0$

The model produced temperatures that reached 17.8°C after steady state had been reached in approximately 40 hours. The average water temperature, $\bar{T}_s$, from the initial boundary (15°C) to the temperature at the end of the channel (17.8°C) was 16.4°C. Equation (4.3-5) was used to generate a ϕ_s

equal to 122 Joules/m^2s from T_s and the constant meteorological conditions. Equation (4.6-3) was then solved for an appropriate linear heat exchange coefficient using T_E, ϕ_s, and the average water temperature $\overline{T}_s$ resulting in a value for k of 39.4 Joules/m^2s°C. Table 4.6-1 and Figure 4.6-1 show the results of the model test compared to the analytical solution Equation (4.6-5) for T_x as a function of distance.

Table 4.6-1 Steady State Analytical Solution Test

Channel distance x (km)	Analytical Result T_s (°C)	Temperature Predicted by Model (°C)
0	15.0	15.0
1	15.41	15.38
2	15.77	15.75
3	16.11	16.07
4	16.41	16.37
5	16.69	16.65
6	16.94	16.91
7	17.17	17.15
8	17.38	17.35
9	17.57	17.56
10	17.75	17.73

The comparison shows very little deviation between the analytical solution and model results.

4.6.2 Millstone Comparisons - General Criteria

With reasonable assurance that the models worked for analytical cases, the next step was to use the circulation and advection-dispersion models for an actual natural water temperature prediction for a coastal area. The Millstone site was chosen since field measurements were available for both velocities and temperatures. The objective of the modeling effort was to reproduce both spatial and temporal variability of

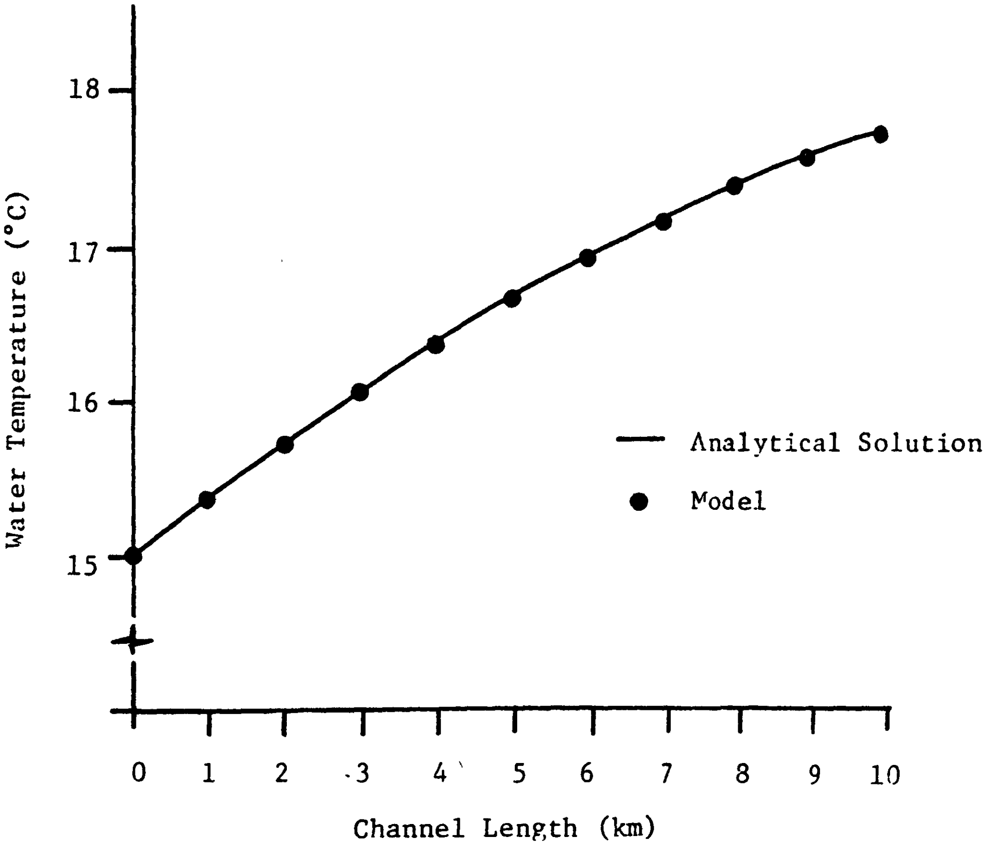


Figure 4.6-1 Steady State Analytical Solution Comparison

temperatures in the vicinity of the site. The estimates given in Section 4.4 for vertically well-mixed regions, will first be applied to determine what areas of the general coastal area can reasonably be represented by the two-dimensional temperature model. The CAFE-1 circulation results are then evaluated in terms of field measurements and other modeling efforts. Finally, the temperatures generated from the revised DISPER-1T model are compared with various sets of field measurements including infrared surveys.

The general criteria developed in Section 4.4.4 were first used to provide an estimate for fully-mixed conditions near the Millstone site. One of the approaches was to consider a plot of the stratification parameter used in oceanography work, h/u_T^3, where h is the depth and u_T is the tidal velocity. Figures 4.6-2 and 4.6-3 show plots of $\log_{10} [h/u^3_T]$ for tidal flood and slack after flood conditions. The velocities and depths used in this evaluation were from the CAFE-1 modeling results. The relative magnitudes of the values shown in the figures can be used to give an indication of those areas which may not be well represented by the vertically well-mixed assumption. The results show that areas below Millstone Point, some of Niantic Bay and the neck from the Niantic River outfall are probably well-mixed during most of the tidal period. Larger values of the parameter in Jordan Cove and the upper left side of Niantic Bay represent areas most likely stratified during some portions of the day. The variation over a tidal cycle is apparent since the slack period had much higher values of the parameter, hence more stratification. As found by other investigations (Simpson and Pingree, 1977), the contours of $\log_{10} [h/u_T^3]$ agree well with temperature isotherms, which was the case in

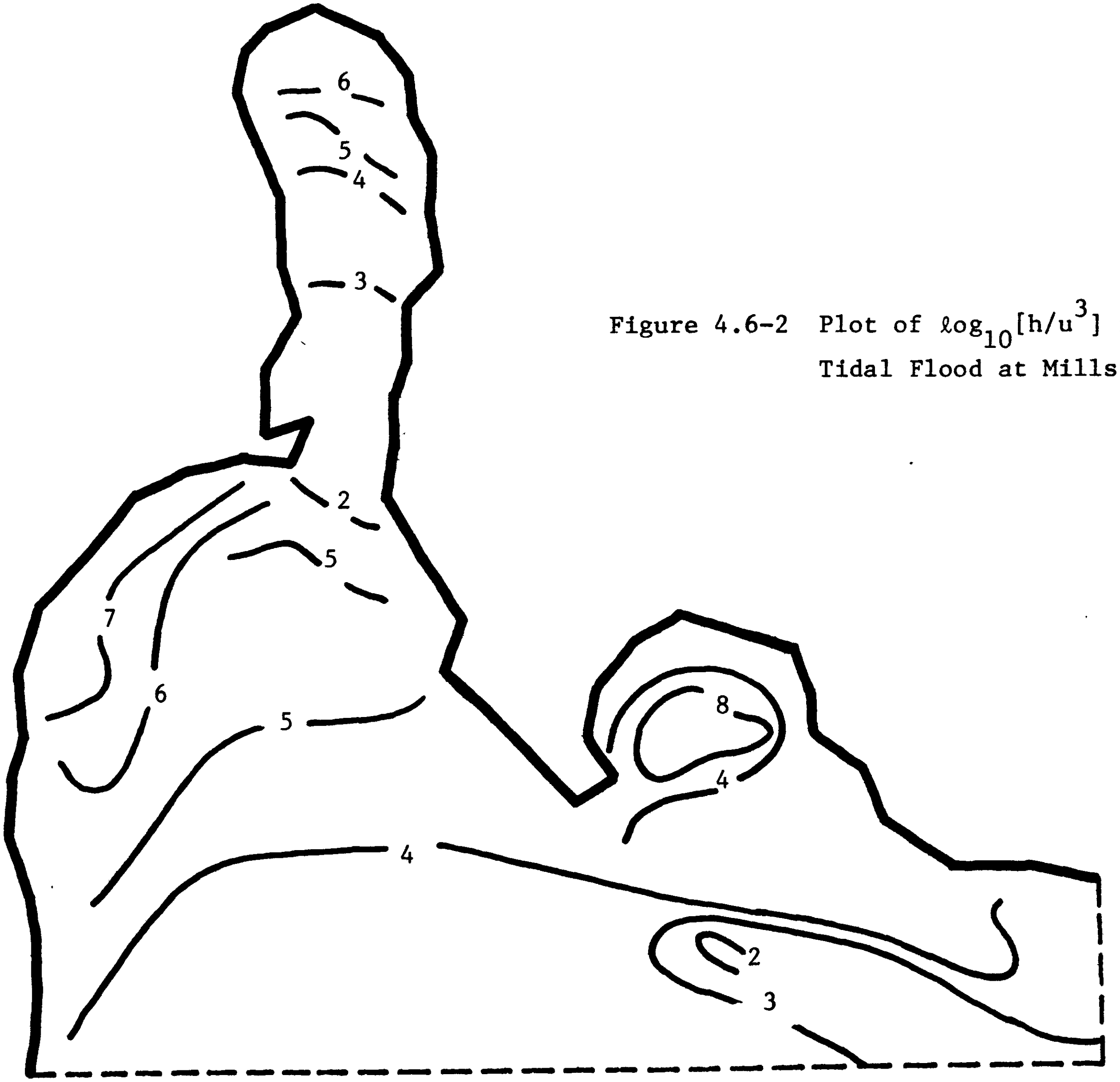


Figure 4.6-2 Plot of $\ell og_{10}[h/u^3]$ for
Tidal Flood at Millstone Site

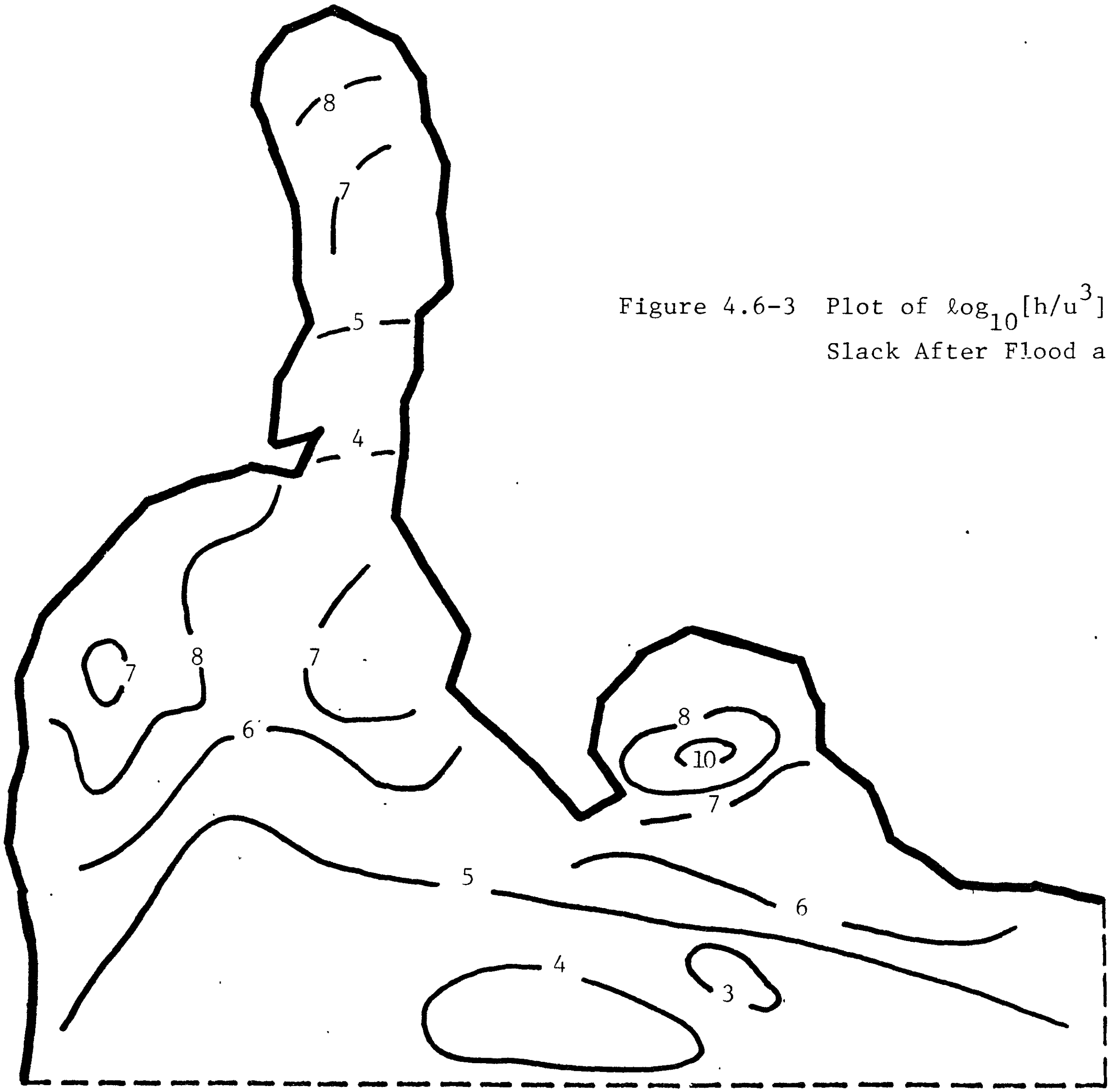


Figure 4.6-3 Plot of $\log_{10}[h/u^3]$ for Tidal Slack After Flood at Millstone Site

the temperature model results discussed later in this section.

The simple criterion developed in Section 4.4.4 Equation 4.4-21 can be used to provide a general estimate that takes into account the surface heat transfer. Using values of buoyancy flux representing $-700 \text{ Joules/m}^2\text{s}$ heat input, m equal to .5, n equal to .1, the depth of the mixed layer can be estimated as follows:

$$h = 2m \frac{[u_*(\text{max})]^3}{-nB_o(\text{max})} = \frac{(2)(.5)}{-(.1)} \frac{(.05)^3}{(-2.5\text{x}10^{-7})} u_T^{\,3} = 5.0 \text{ x } 10^3 \; u_T^{\,3}$$

where: $B_o(\text{max}) = \frac{\beta g \phi}{\rho c_v}$ (4.6-5)

β = thermal expansion coefficient

g = acceleration of gravity

ρ = density of water

c_v = specific heat of water at constant volume

ϕ = heat flux

$u_* = \frac{f}{8} u_T \approx .05 \; u_T$

u_T = amplitude of tidal velocity

At the Millstone site the amplitudes of tidal velocities ranged from .05 m/s in Jordan Cove to .6 m/s in areas below Millstone Point (Northeast Utilities Service Company, 1975). This results in estimated mixed layers of approximately .6 meters in the shallow areas in Jordan Cove and over 1000 meters in areas off Millstone Point. Depths in the vicinity of the site ranged from less than 1 meter in shallow areas to about 20 meters in the deepest areas off of White Point. Velocities of .16 m/s or more would be enough to mix to the largest depths encountered at the site. Shallower areas (such as Jordan Cove) with low velocities may not be represented as accurately since the estimated depths are near those actually found in the area.

Measurements of the vertical temperature distribution at the Millstone site were made at the locations shown in Figure 4.6-4 on a summer day. The daily progression of temperatures is shown in Figure 4.6-5 (Raytheon Company, 1968). An increase in surface temperature is noticeable over the period of a day due to daytime solar heating, especially at monitoring location C, yet the morning temperature distribution is farily uniform vertically. This agrees with the simulations done in Section 4.4.4 which found daytime "heating" caused stratification normally broken up by a combination of the maximum tidal velocities and nighttime "cooling."

4.6.3 Millstone Comparisons - Velocities

The circulation mode, CAFE-1, was used to compute a set of velocities and depths for input to the advection-dispersion model. The information used as model input is first presented followed by the results and comparisons with field measurements and other model studies.

Input for the CAFE-1 model consisted of the geometry of the region to be studied, specification of ocean boundary, wind speeds, timestep, bottom friction factors and eddy viscosity coefficients. Coastline and bottom topography near the nuclear plant site were obtained from an Environmental Sciences Services Administration (ESSA) Coast and Geodetic Survey bathymetric chart of the Niantic Bay and Jordan Cove area. Land boundary nodes were positioned to represent the major details of the

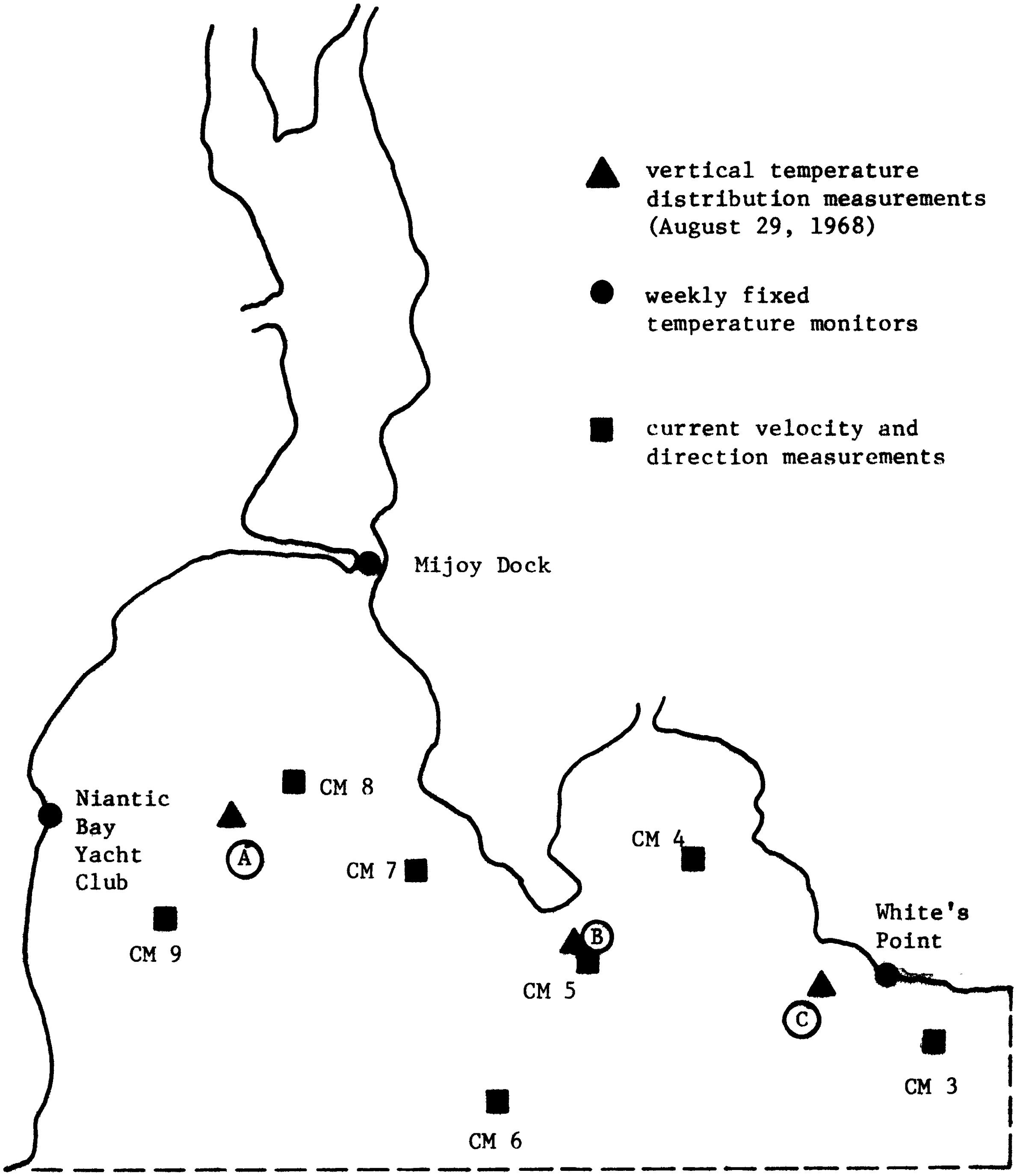


Figure 4.6-4 Location of Various Temperature and Current Measurements at the Millstone Site

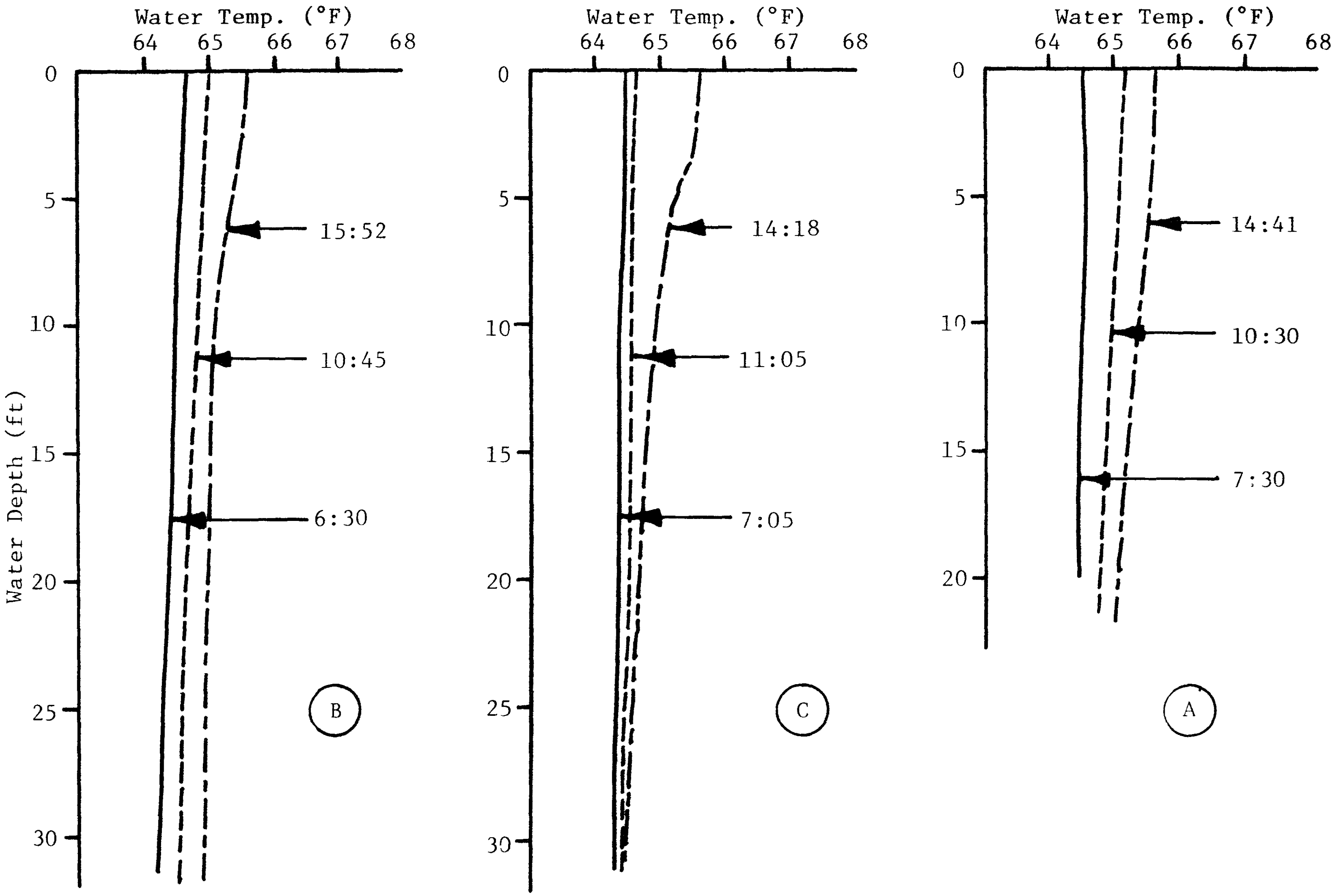


Figure 4.6-5 Natural Heating Over Daily Period Near Millstone Point

area. Interior nodes were placed at locations following the prominant bottom topography. Actual depths were used except on the land boundary where a minimum depth of 1 meter provided better numerical stability. A small island (Two Tree Island) and nearby sandbar located outside of Jordan Cove (as shown in Figure 4.1-2) were represented by minimum depths of 3 meters with depths changing gradually around the small area. Figure 4.6-6 shows the resulting finite element grid that was developed to represent the region. Larger elements were needed in the inlet to the Niantic River to provide for better numerical stability.

The ocean boundary for the tidal circulation model was specified using tidal elevations and tidal lags (shown in Figure 4.6-6) and a tidal period of 12.4 hours obtained from previous site investigations (Liang, 1980, personal communication). The tidal information was found to be in close agreement with daily tide predictions for an area near the site (U.S. Department of Commerce, 1977) for the actual period of evaluation.

The sensitivity to wind action was studied using average meteorological conditions, wind rises of speed and direction (Northeast Utilities Service Company, 1979), obtained during the period of temperature field measurements. The results showed no noticeable effect on the velocities or depths generated from the model and will not be discussed in the following evaluation.

For the grid shown in Figure 4.6-6 a timestep of 25 seconds produced a stable result. The smallest elements were approximately 200 meters with depths at 3.7 meters resulting in a coefficient for the timestep criterion from Equation 4.5-1 near 1.0. A uniform friction factor of .01 and an isotropic eddy viscosity coefficient of 100 m^2/s were used.

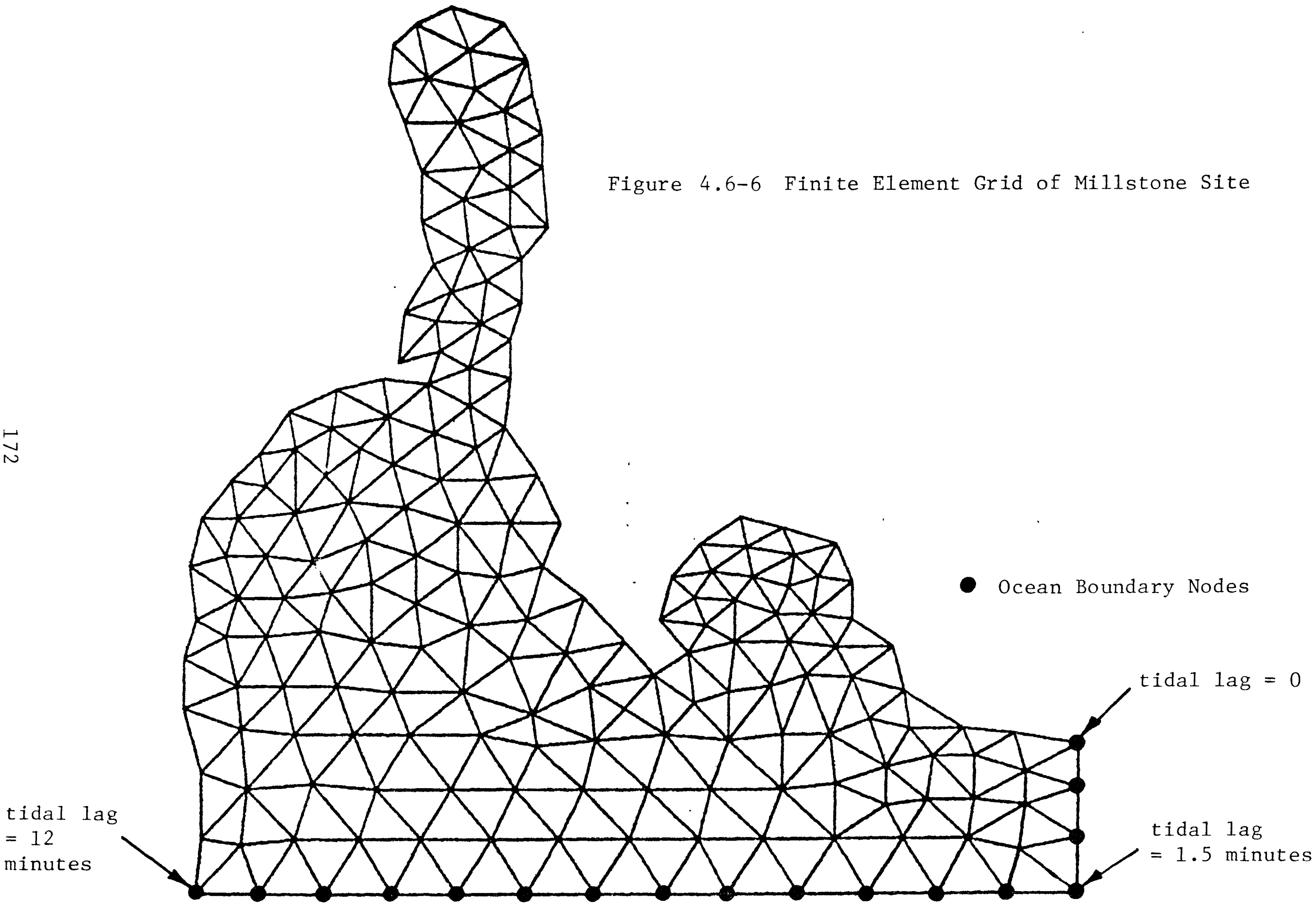


Figure 4.6-6 Finite Element Grid of Millstone Site

The results of the circulation modeling are shown in Figures 4.6-7 through 4.6-10 which display velocities at low slack, strength of flood, high slack, and strength of ebb. These figures show the major details of the circulation pattern which compared favorably with previous circulation modeling at the site (Northeast Utilities Service Company, 1975). Flow during the flood is from the east to the west with the higher velocities remaining below Millstone Point. During the ebb the situation is basically reversed. Both upper Niantic Bay and Jordan Cove have small tidal velocities throughout all the modeling period. The resulting computations were compared with velocity and direction measurements taken at locations shown in Figure 4.6-4 (Northeast Utilities Service Company, 1975). The comparisons shown in Figures 4.6-11 and 4.6-12 agree quite well for the direction of the velocities in all cases except in Jordan Cove where low velocities and lack of consideration of upper Jordan Cove area may have influenced the directions. The generated velocities were,however,smaller than the actual measurements at the site. Several factors could have caused the lower velocities predicted by the model. The boundary conditions used were obtained from a separate modeling of the circulation patterns. The tidal height variation used was sinusodial whereas other modeling used a complex variation based on detailed tide surveys. Adjustments in the lag time could also cause variations in the tidal currents. A uniform friction factor was used in the modeling effort although more variation of this term may give better results.

4.6.4 Millstone Comparisons - Velocities

The DISPER-1T model discussed in Section 4.3 was then used to

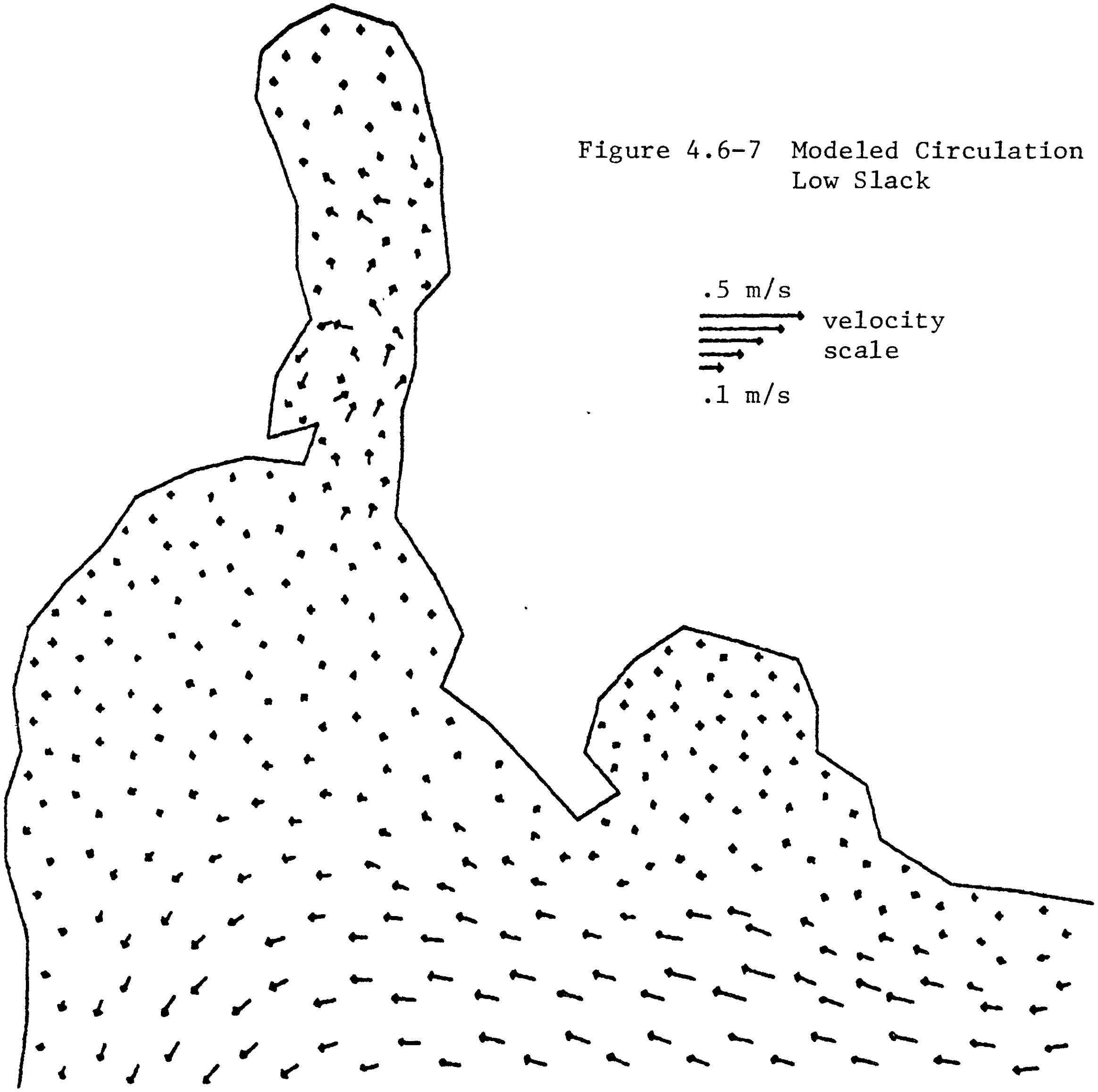
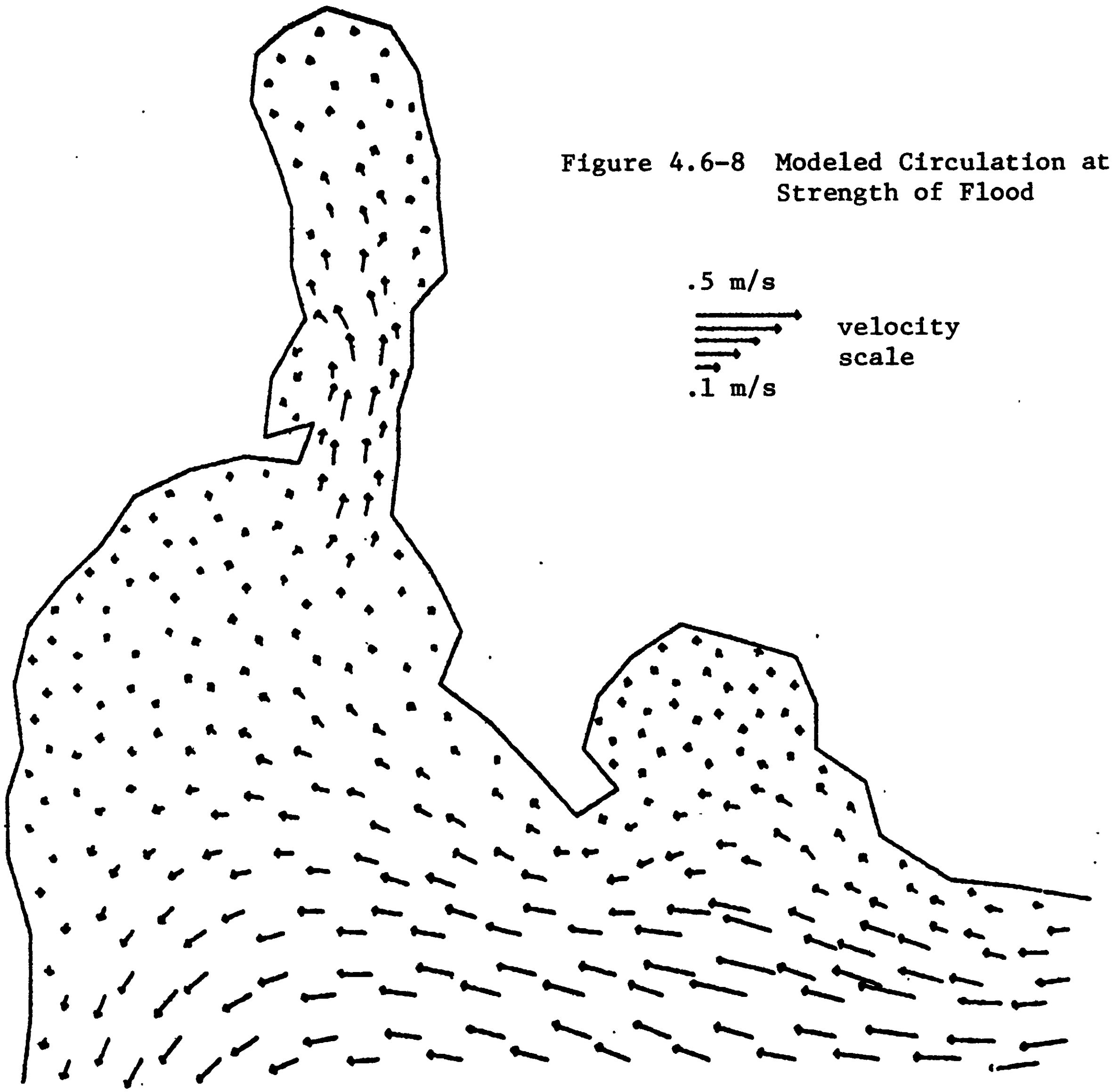


Figure 4.6-7 Modeled Circulation at Millstone Site - Low Slack

Figure 4.6-8 Modeled Circulation at Millstone Site - Strength of Flood



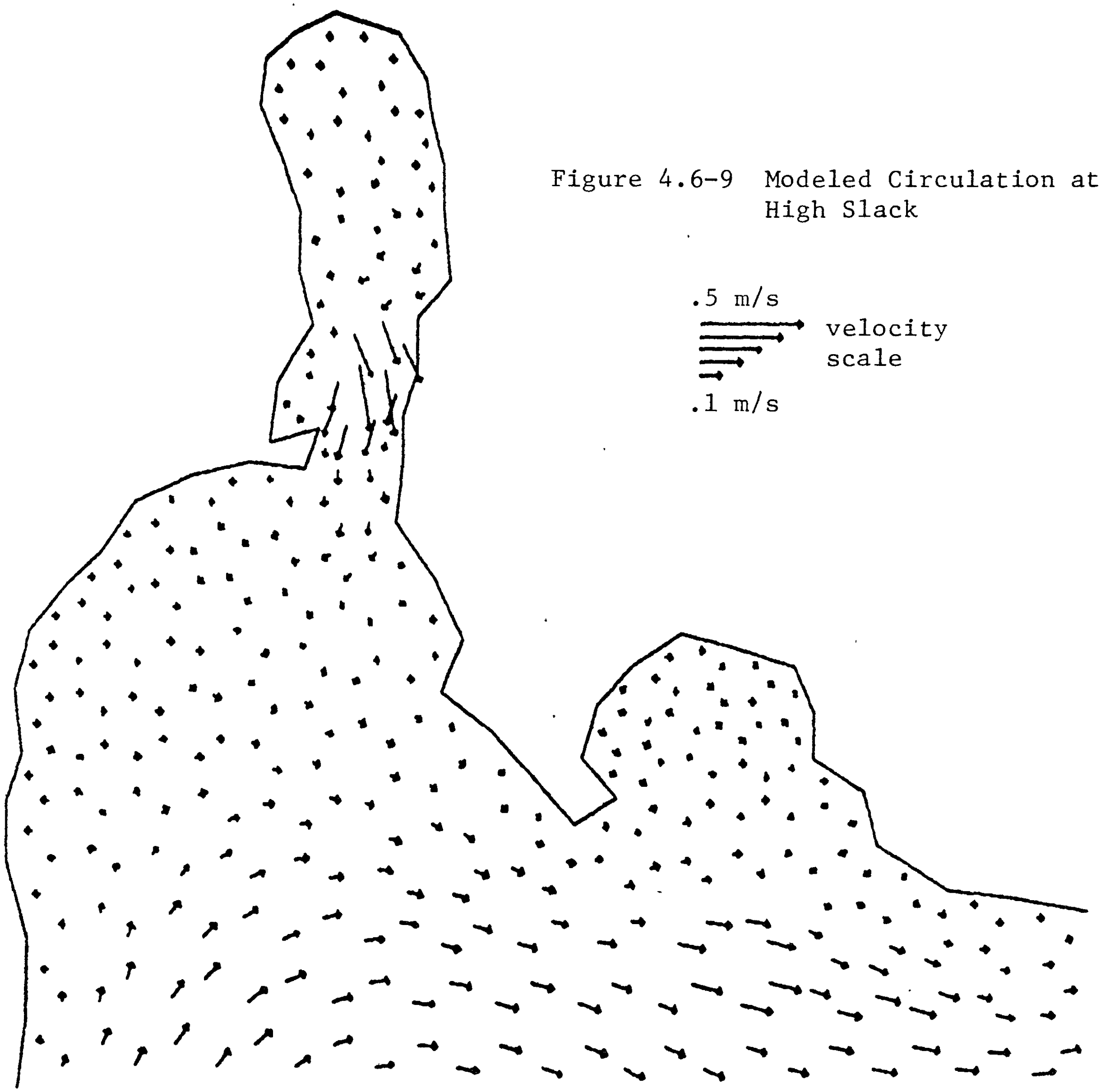
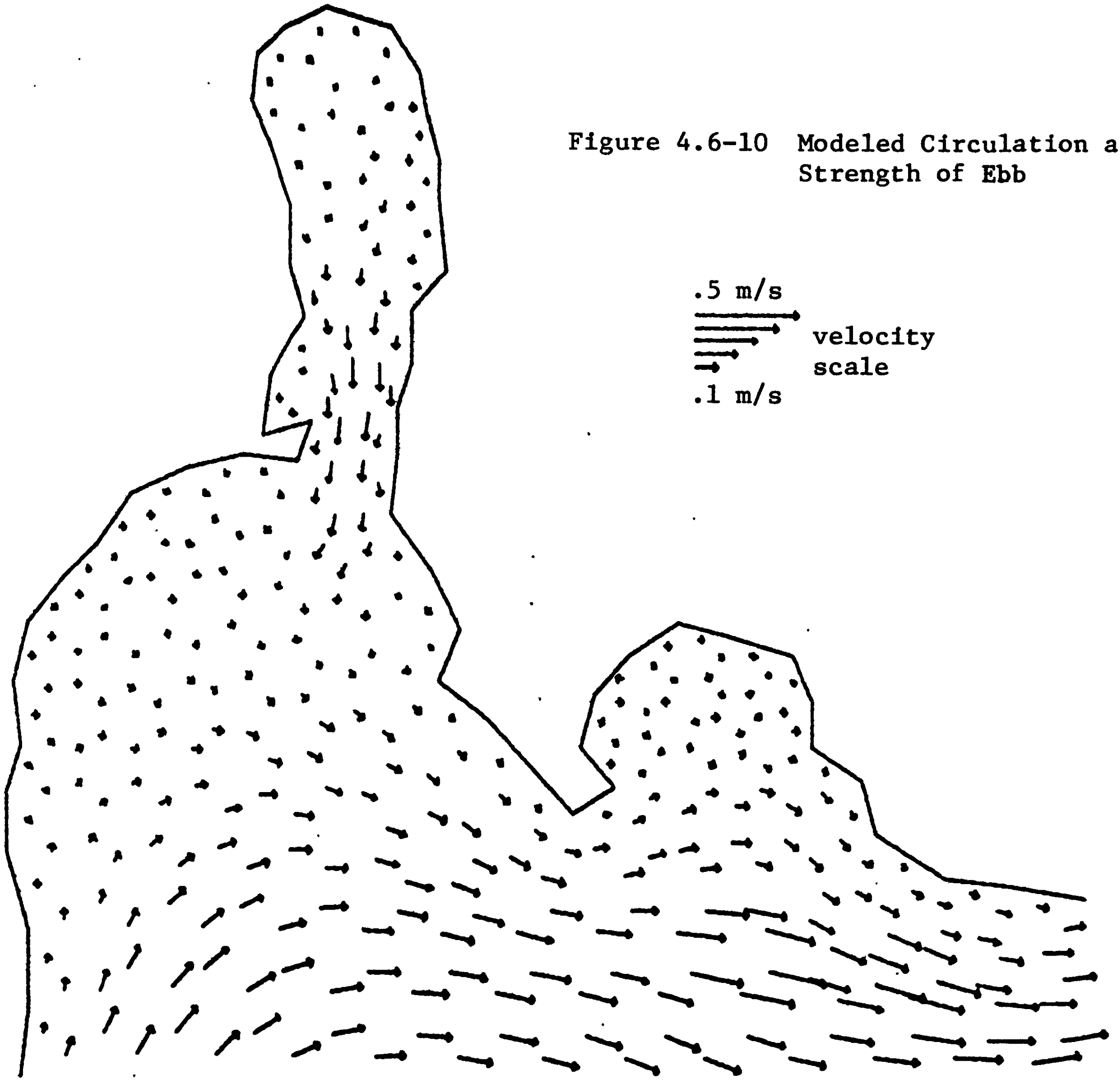


Figure 4.6-9 Modeled Circulation at Millstone Site - High Slack

Figure 4.6-10 Modeled Circulation at Millstone Site - Strength of Ebb



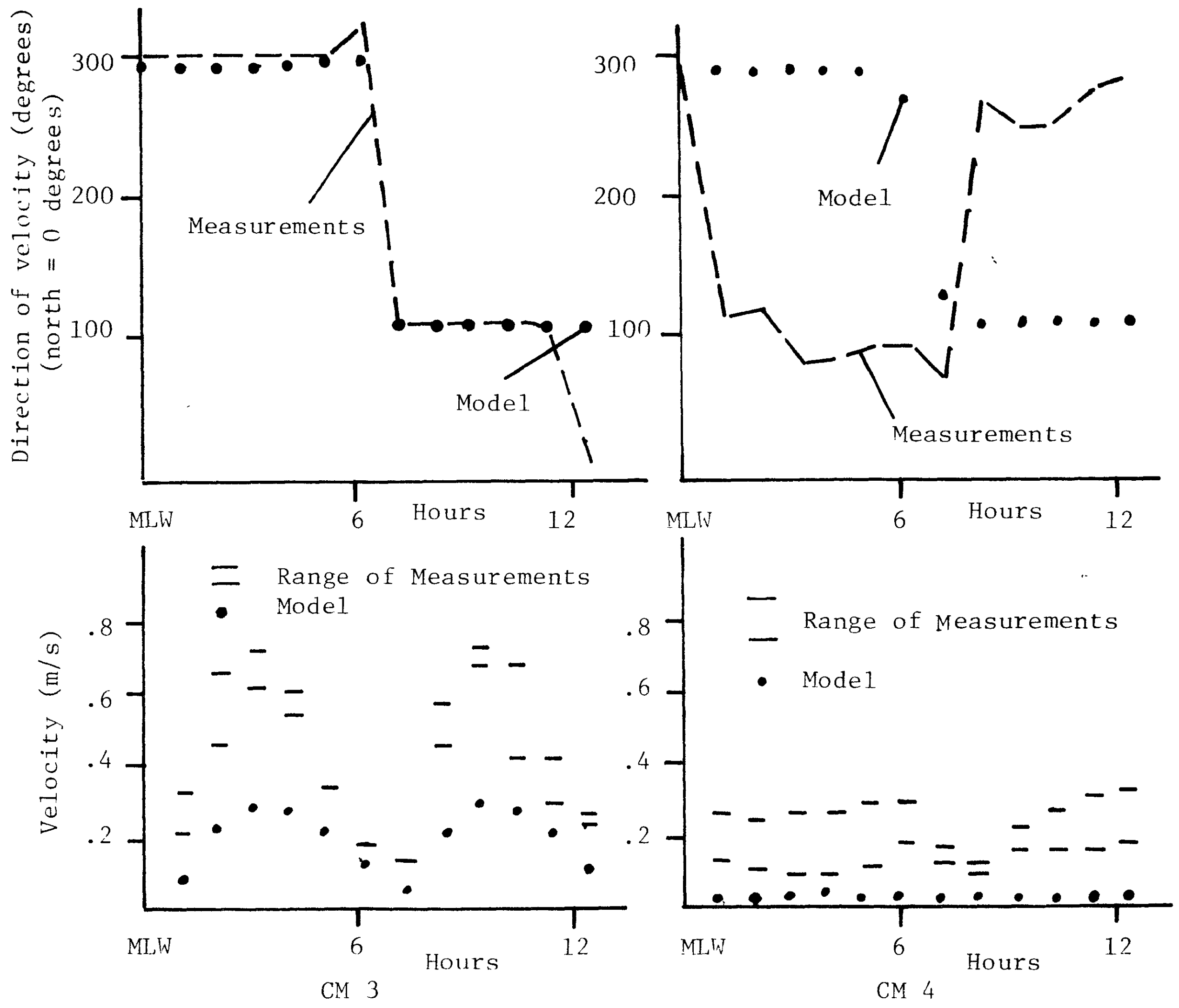


Figure 4.6-11 Comparison of Field Measurements and Circulation Model Current Data

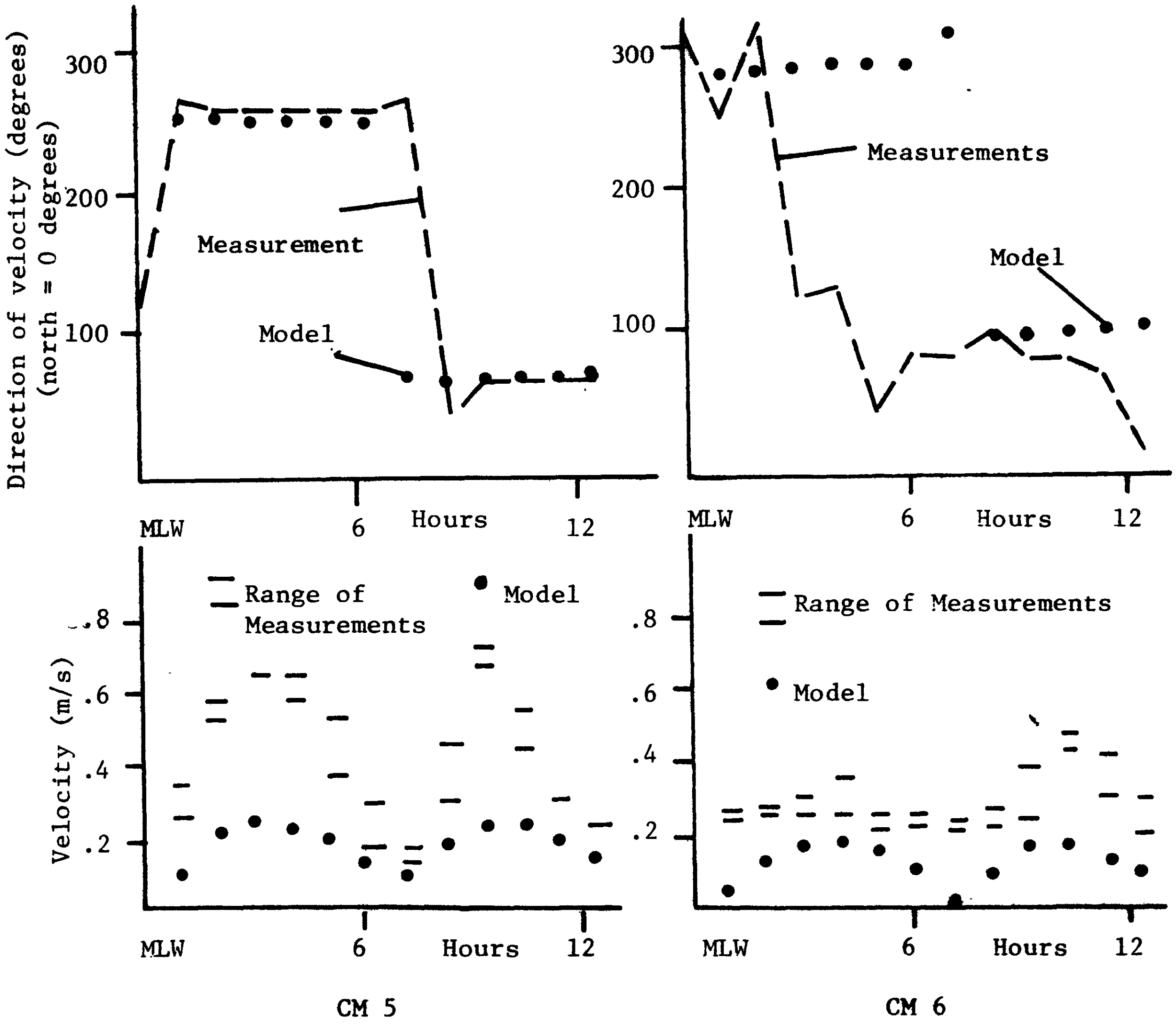


Figure 4.6-11 Comparison of Field Measurements and Circulation Model Current Data

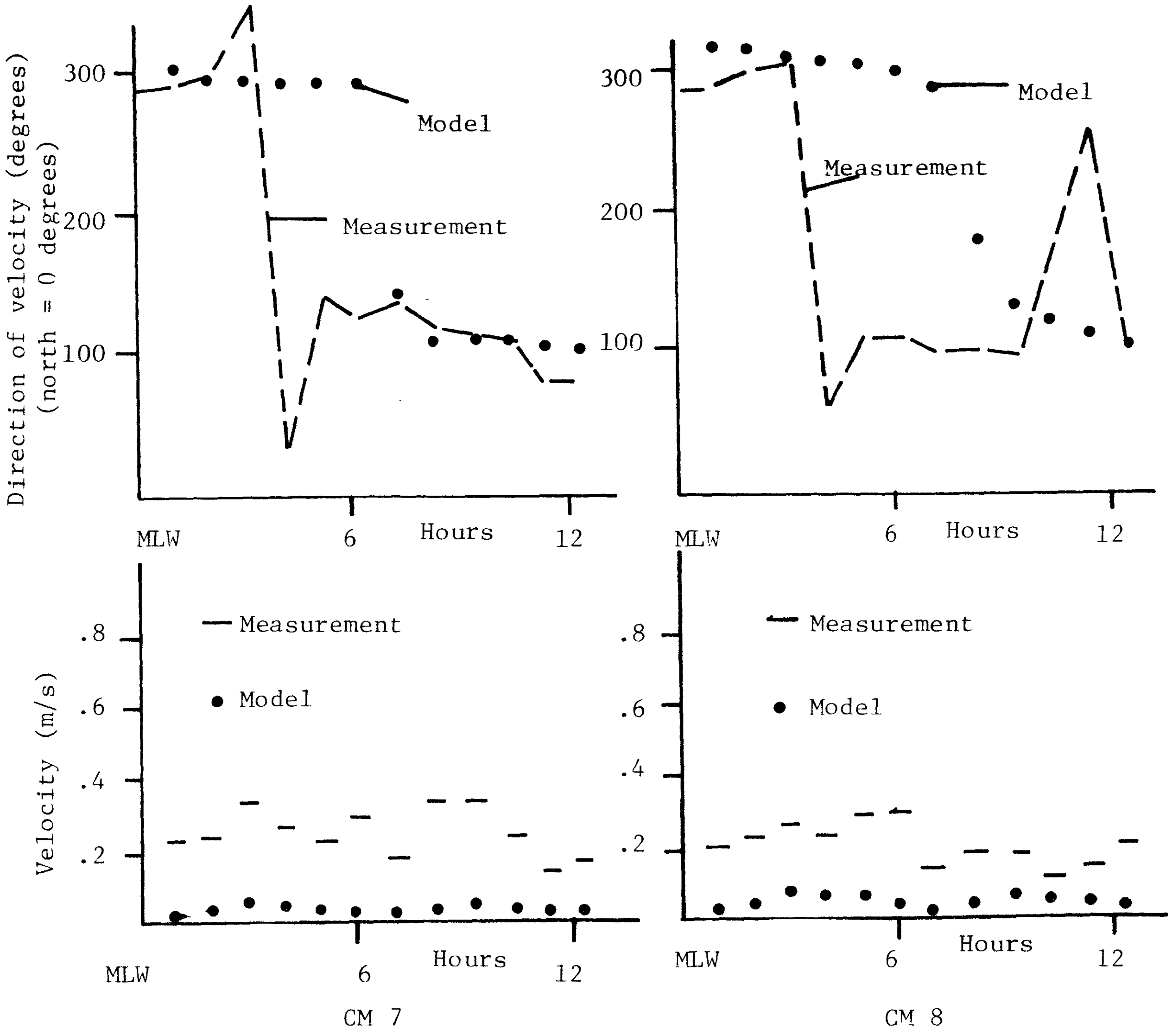


Figure 4.6-12 Comparison of Field Measurements and Circulation Model Current Data

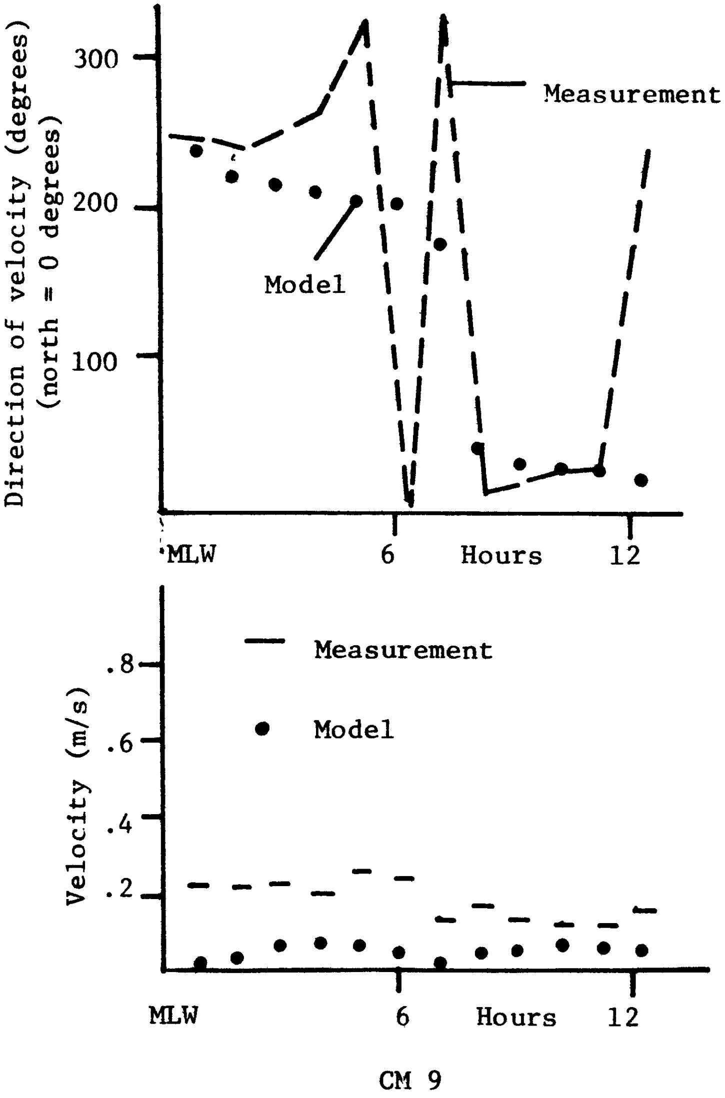


Figure 4.6-12 Comparison of Field Measurements and Circulation Model Current Data

simulate natural temperature variations to compare with field measurements taken at the Millstone site. Input conditions and the sources of data are first described followed by the modeling results. Comparisons are made with field measurements of temperatures to determine the ability of the model to predict both spatial and temporal variations of temperatures in a coastal environment.

The same finite element grid was used for the DISPER-1T computations as described for the CAFE-1 model. Velocities and depths for one tidal cycle were generated using CAFE-1. These values were input to DISPER-1T which reread the velocity and depth data for each continuing tidal cycle of temperature computations. The use of a single tidal cycle of velocity and depth inputs reduces computer costs and storage significantly since CAFE-1 is expensive to operate due to small timesteps and large amounts of data. The potential error was not considered significant since the average tidal amplitude was used. A more rigorous approach for longer modeling periods would be to generate a few tidal cycles using CAFE-1 gradually varying the tidal amplitude, and use them as input to DISPER-1T. This was the approach used by Chau (1977) to model the larval fish distribution over a larval season of 238 tidal cycles.

Numerical stability requirements for the DISPER-1T model were developed from the criteria presented in Section 4.5. The CAFE-1 results for the Millstone site showed velocities ranging to .3 m/s near elements with lengths of approximately 500 meters. This produced an allowable dispersion coefficient, E, of 75 m^2/s from Equation (4.5-4). Using this result with a minimum value of Δs of 200 m yielded a timestep of 50 seconds using Equation (4.5-2). A 50 second timestep also met Equation (4.5-3).

For the Millstone application the criteria developed by Christopoulou and Conner (1980), Equation (4.5-6), produced a timestep below 60 seconds using s = 200, u = .3 and E = 75. However, an actual run with a 50 second timestep required a dispersion coefficient of 30 to produce stable results. After experimentation it was found that a 100 second timestep for DISPER-1T with E = $10m^2/s$ provided results that contained some minor instabilities but were in favorable agreement with the shorter timestep runs. To reduce computational costs and storage requirements the 100 second timestep was finally used to give adequate results.

The ocean boundary for the natural temperature predictions was represented by a constant temperature at each of the ocean boundary nodes. The actual value used was based on average ocean temperatures for the period of interest at a distance removed from the site. Initial temperature conditions were not important since the temperature analyses were allowed to run a long period of time before the actual results were obtained. The "warm up" time was determined from a simpler evaluation of the time needed for the body of water to reach equilibrium temperature under constant meteorological conditions.

The driving force for the natural temperature model is the surface heat fluxes. These fluxes are determined from several meteorological parameters as described in Section 4.3. Onsite data, where available, including direct solar radiation measurements, are the ideal input for the computations. However, few sites have all the necessary parameters at intervals needed to model water temperature variations within a tidal period. Meteorological observations at 3 hour intervals are available for some National Weather Service (NWS) meteorological stations. Even though these stations are fairly far apart they must often be used to provide the necessary meteorological data. The Millstone analyses used observations from the NWS station at Sikorsky Memorial Airport in Bridgeport, Connecticut (U.S. Department of Commerce, 1977) shown in Figure 4.6-13. This was the closest station to the site which recorded 3 hour observations of all the needed parameters and had a similar coastal environment.

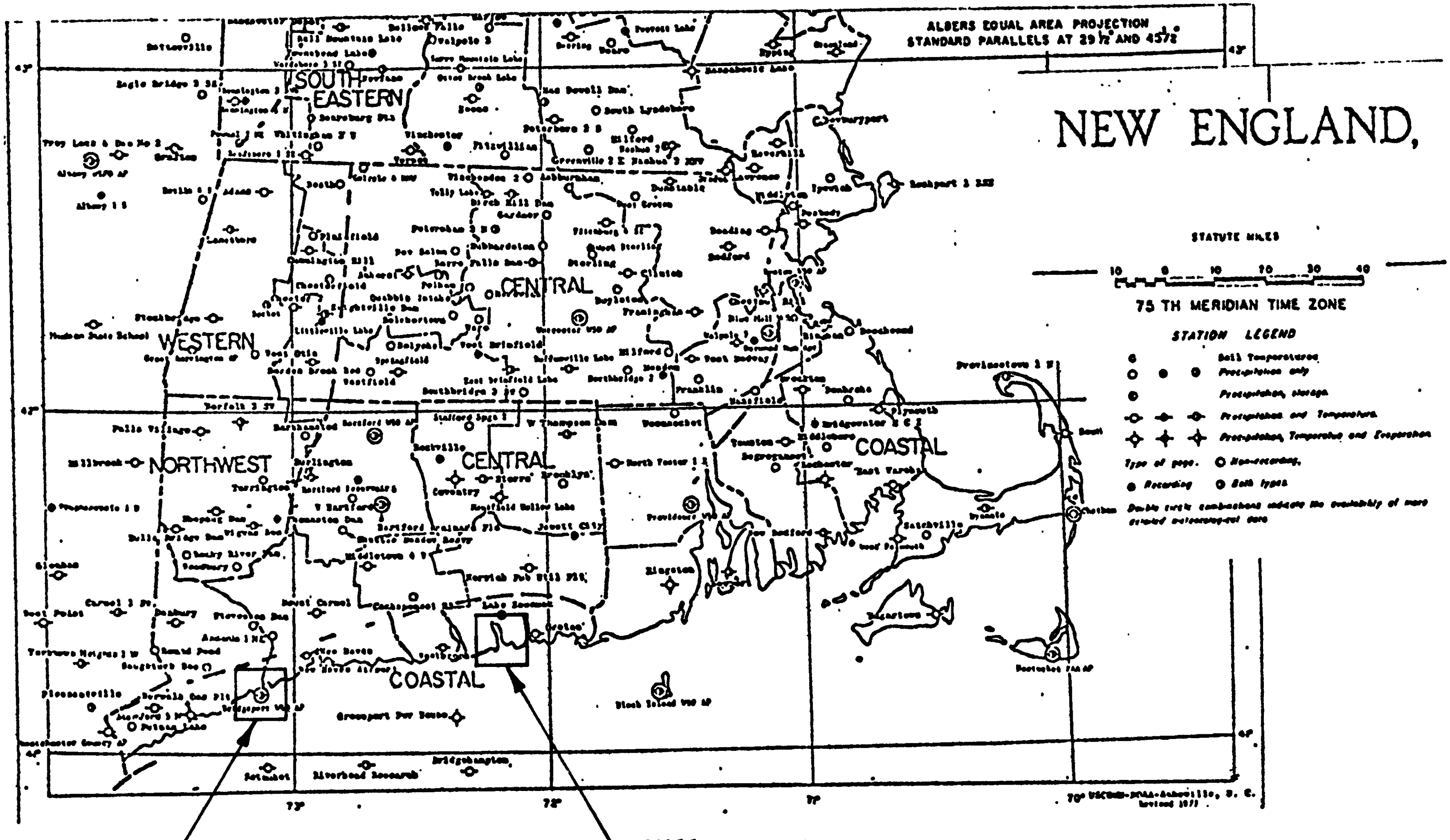
Since observations of solar and atmospheric radiation flux were not available they were computed using the approach outlined by Wunderlich (1972) which requires air temperatures and cloud cover (obtainable from NWS stations). Wind speed, from the NWS data given in knots at 25 feet (w_{25}) was converted to wind speed at 2 meters in miles per hour (w_2) using the following correction from Ryan and Harleman (1973):

$$\frac{w_2}{w_{25}} = 1.151 \times \frac{\ln(\frac{z}{z_o})}{\ln(\frac{z}{z_o})} \qquad (4.4\text{-}6)$$

where $z = 25$ feet $= 7.6$ m

$z_o = .005$ m = wind roughness height

The DISPER-1T model was used to compute temperature predictions at the Millstone site for the period July 26 through August 2, 1977. This provided results to compare with weekly average temperature data taken near the site and temperature data from an intensive survey on July 29, 1977. Although the July 29th data was taken with the plant in operation, it provides the best available information for temperatures at the site. The natural temperatures can often be differentiated from the plume to provide



meteorological observations

Millstone site

Figure 4.6-13 Meteorological Station Location Compared to Actual Modelling Site good data for comparison. Comparisons were also made with a daily temperature survey at three locations near the site conducted on August 29, 1968. Conditions were slightly different at that time but the range of values over a daily period still provides an interesting comparison.

The first comparisons of spatial and temporal temperature variations were made with infrared surveys, conducted during the July 29, 1977, field studies, to determine the spatial resolution of the predictive model (Texas Instruments Incorporated, 1978). Figures 4.6-14 through 4.6-19 show plots of the horizontal temperature distribution near the site. These figures show the general horizontal characteristics of the change in temperatures over a daily period. The morning flood tide bringing water from the cooler ocean is coupled with nighttime cooling to produce low temperatures up to Millstone Point and into the right side of Jordan Cove and Niantic Bay. Hotter temperatures still remained on the upper left side of Jordan Cove as is confirmed by the infrared photo shown in Figure 4.6-20. As daytime heating progressed, the influence of the outer boundary was less prevalent as shown in the model results, Figure 4.6-15, and infrared photo, Figure 4.6-21. The next set of figures at ebb tide show that heated temperatures crossed over to the opposite side of Jordan Cove, apparent from the 18.5°C isotherm in Figure 4.6-16 and the infrared photo Figure 4.6-22. The next set of figures continues the heating in Jordan Cove, Figure 4.6-17 and Figure 4.6-23. The last infrared photo, Figure 4.6-24, shows the interaction of the flood tide pushing back the isotherms in Jordan Cove. The photo also shows the same type of heating occurring along the west side of Niantic Bay. The model predictions

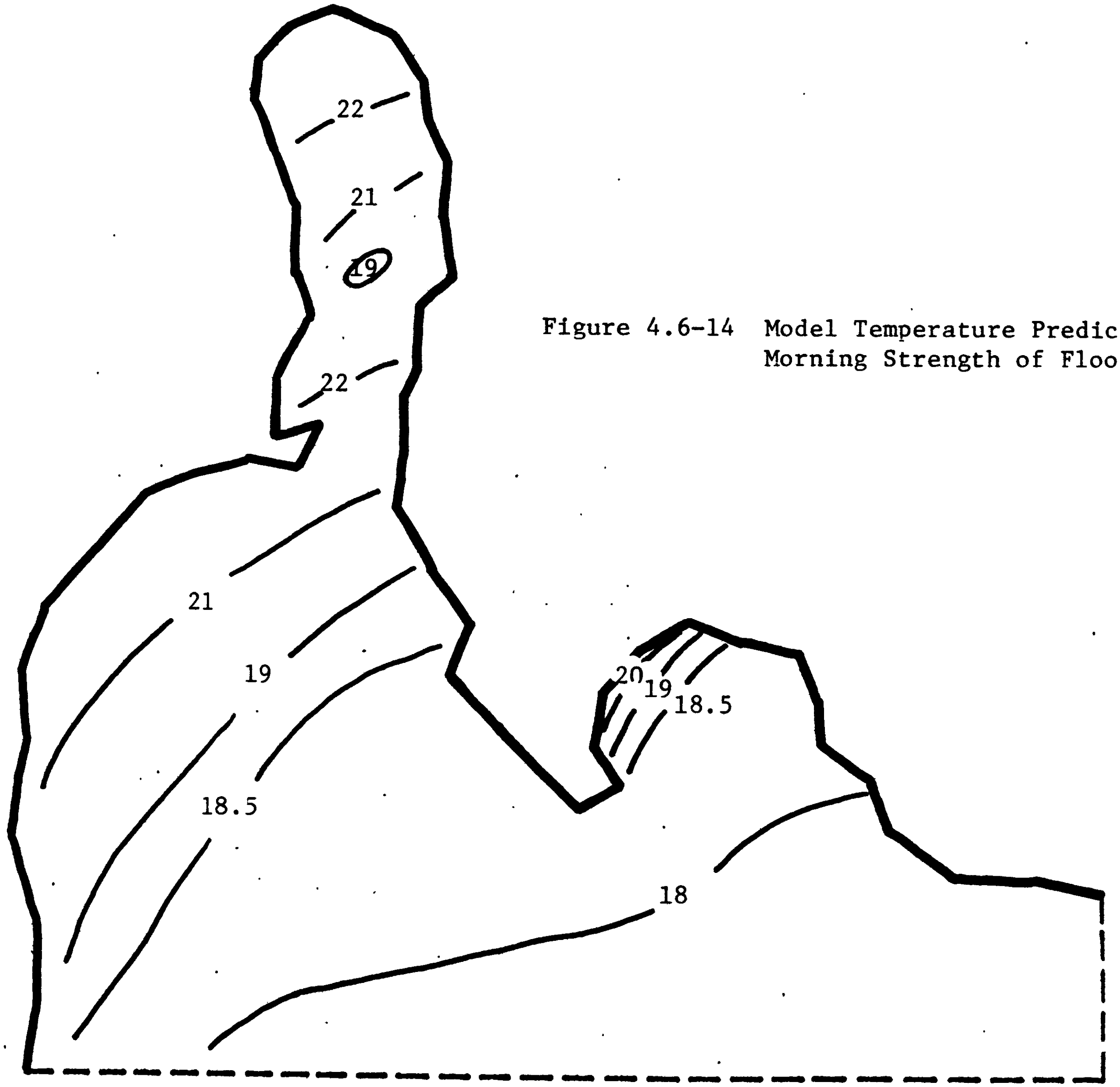


Figure 4.6-14 Model Temperature Prediction - Morning Strength of Flood

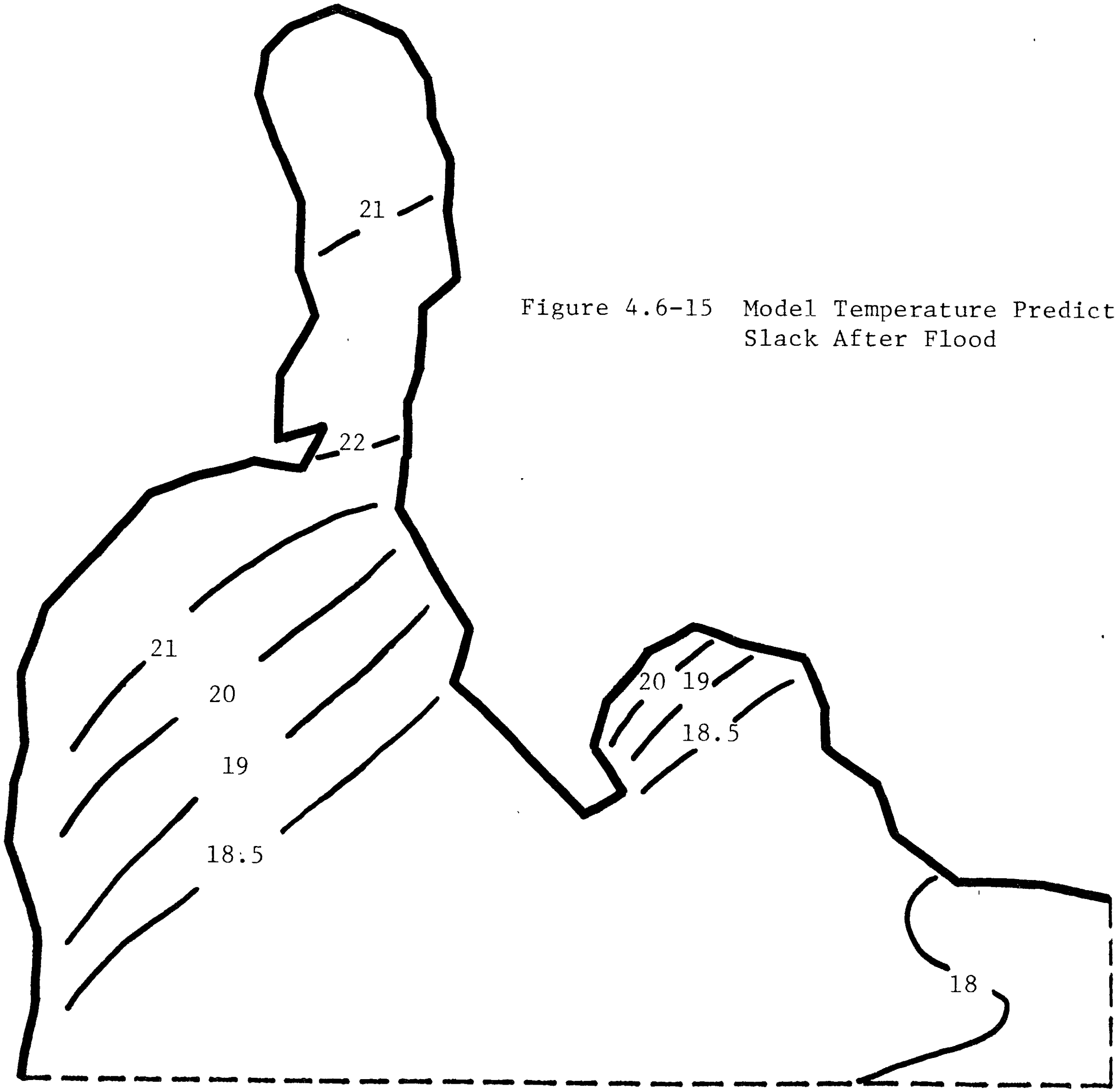


Figure 4.6-15 Model Temperature Prediction - Slack After Flood

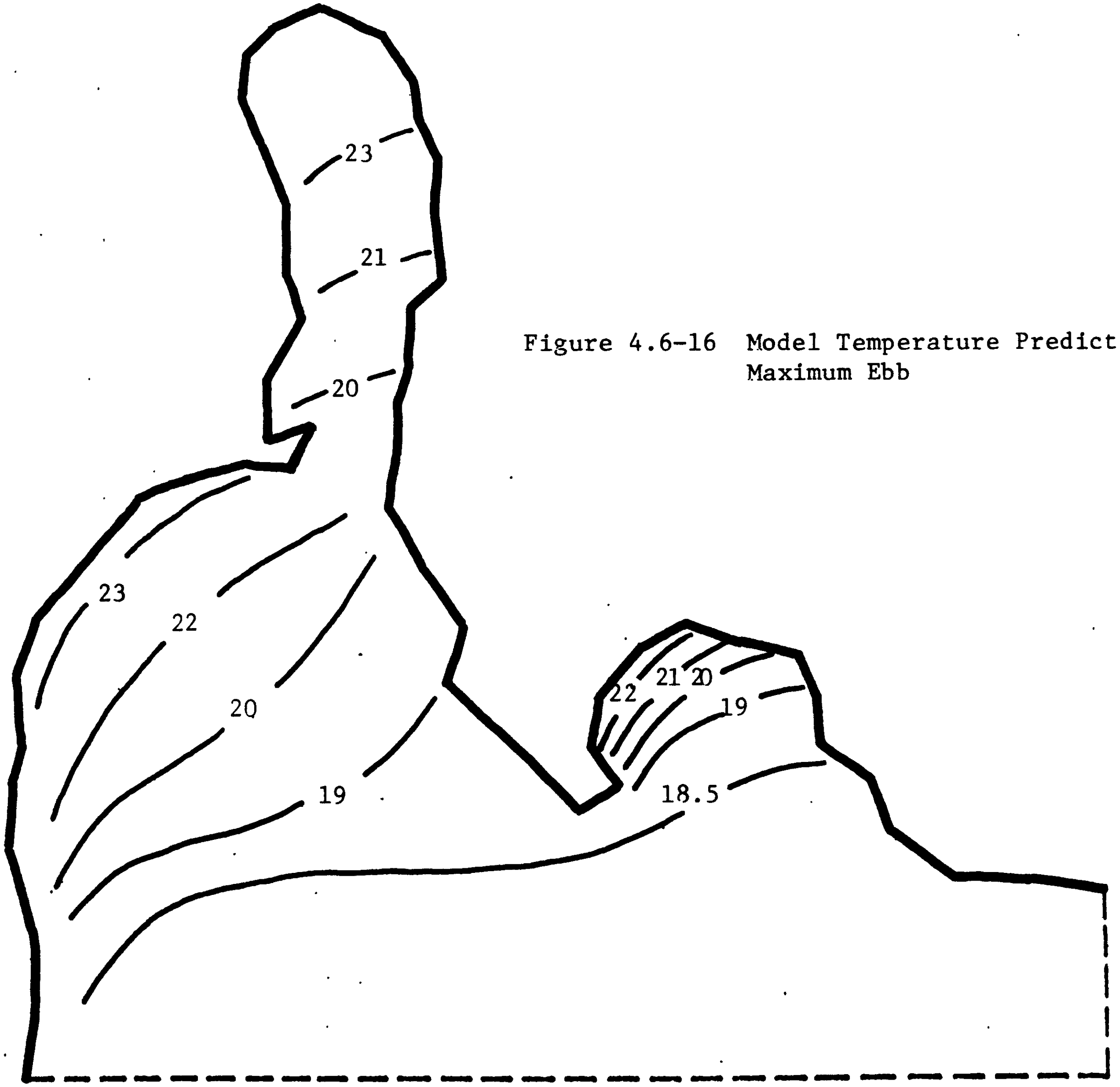


Figure 4.6-16 Model Temperature Prediction - Maximum Ebb

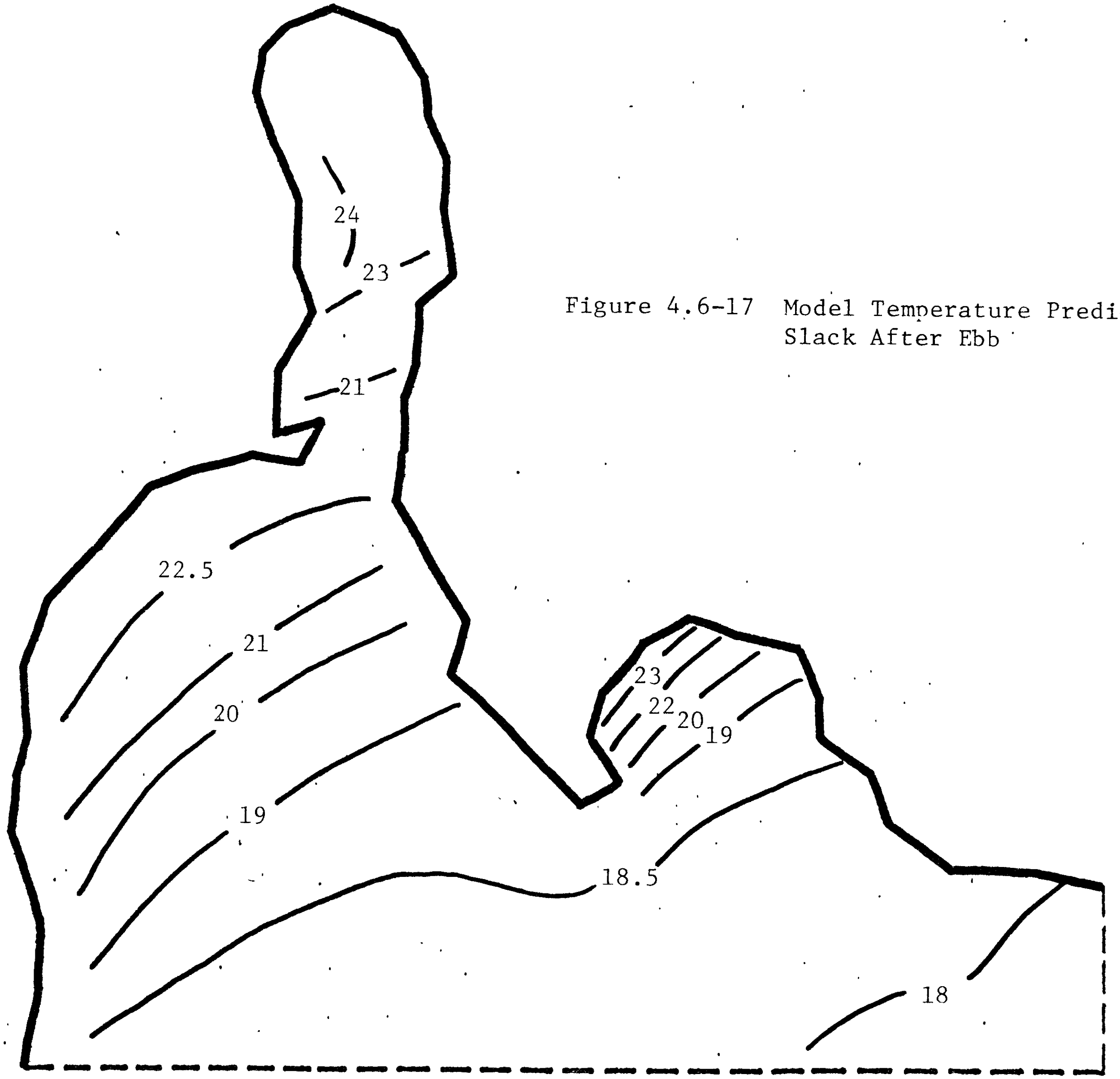


Figure 4.6-17 Model Temperature Prediction - Slack After Ebb

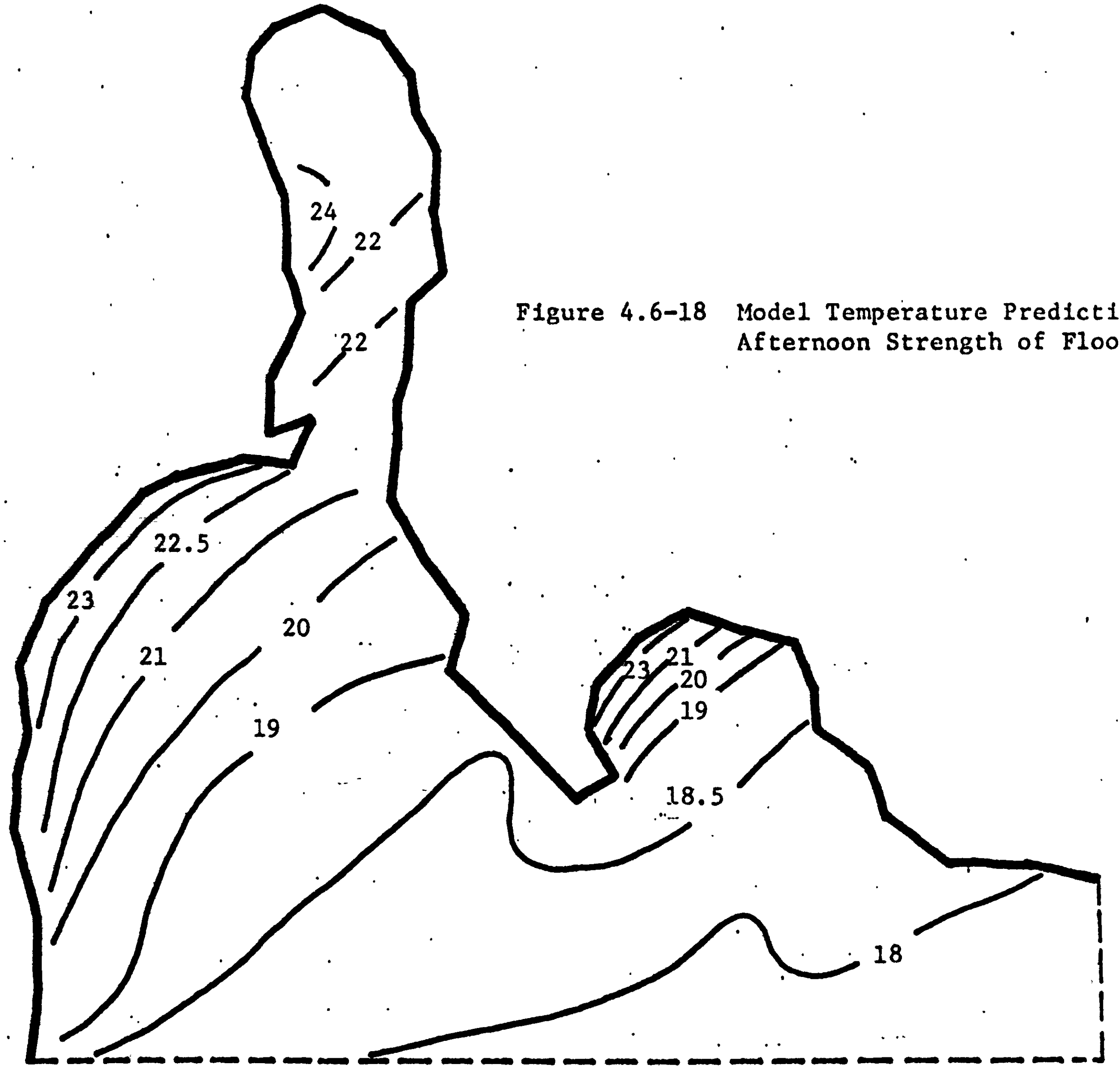


Figure 4.6-18 Model Temperature Prediction -
Afternoon Strength of Flood

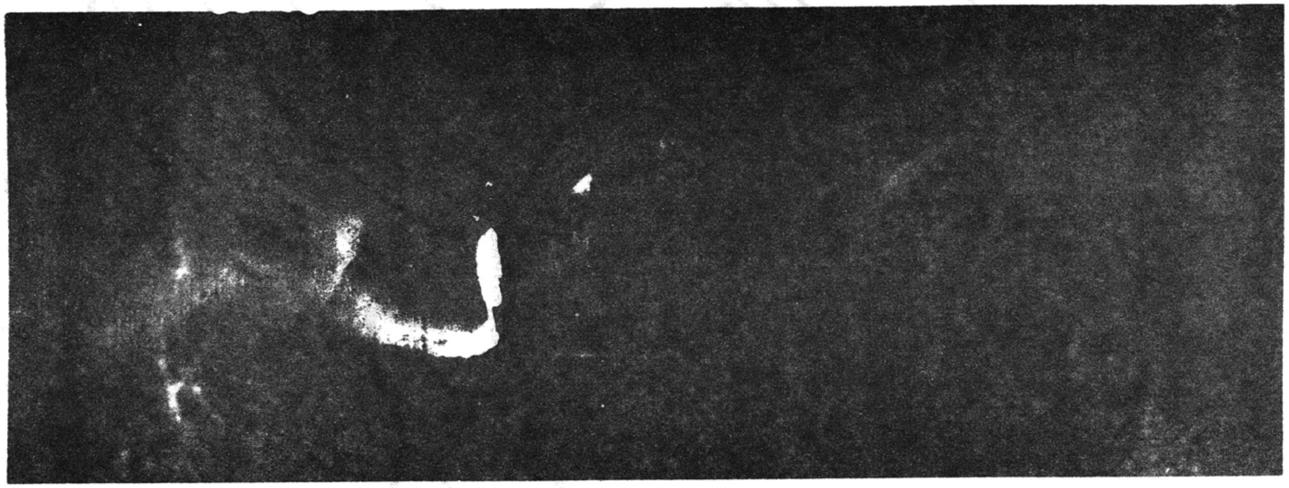


Figure 4.6-20 Thermal Infrared of Millstone Site - Strength of Flood (6:36)

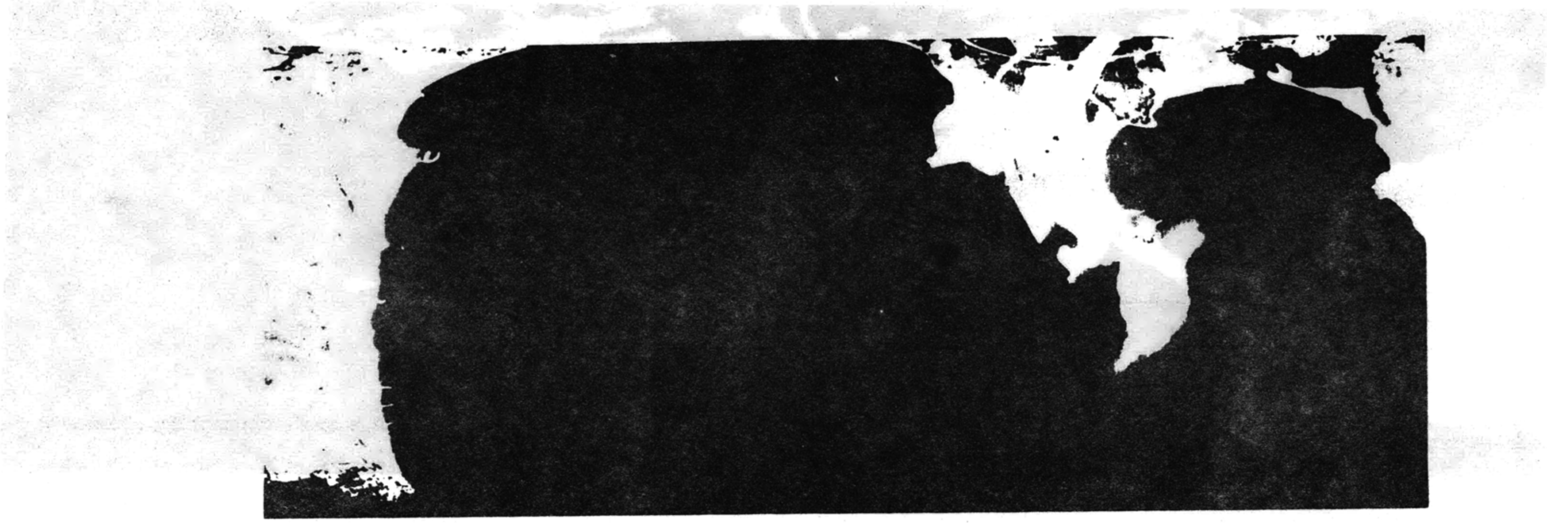


Figure 4.6-21 Thermal Infrared of Millstone Site - High Slack (10:08)

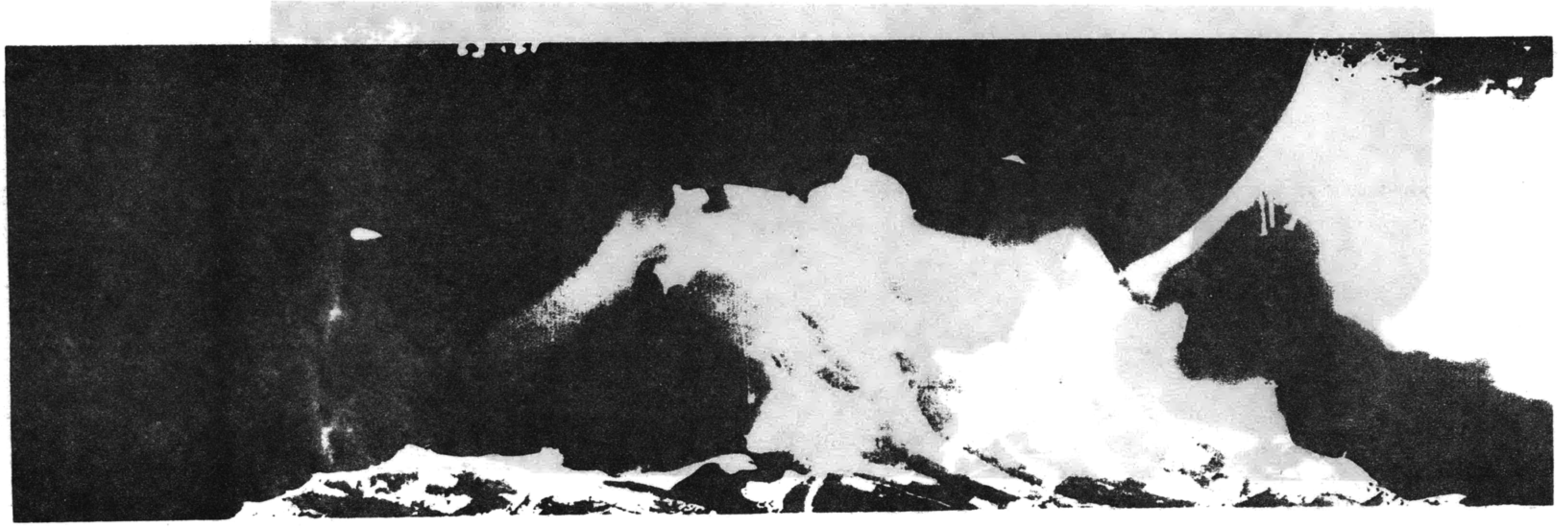


Figure 4.6-22 Thermal Infrared of Millstone Site - Strength of Ebb (12:52)

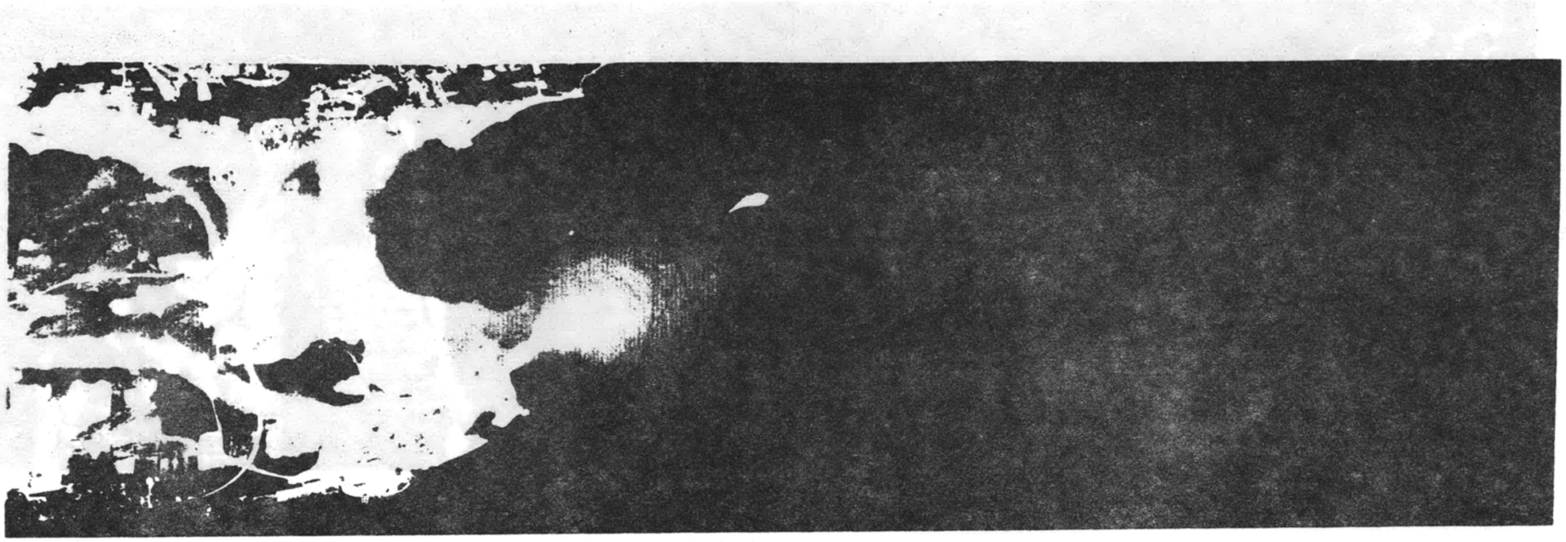


Figure 4.6-23 Thermal Infrared of Millstone Site - Low Slack (16:42)

Figure 4.6-24 Thermal Infrared of Millstone Site - Strength of Flood (18:42)

produced similar effects where the hotter isotherms were pushed back and the same pattern was found in Niantic Bay. The previous figures show very good spatial agreement between the results of the model and the infrared photos. The influence of daily heating and tidal flows on the horizontal temperature distribution were well characterized. The next comparisons will consider the model's ability to reproduce natural temperature variations over several time scales.

The second set of comparisons focused on the numerical values for temperatures quantified from the thermal infrared survey results. A typical result from the survey is shown in Figure 4.6-25. Values obtained near the west side of Jordan Cove from such figures were compared with the numerical values at nodes from the temperature prediction model. The resulting comparison is shown in Figure 4.6-26. Equilibrium temperatures are shown on the plot, calculated from Equation (4.3-5), to provide an indication of the meteorological conditions. The equilibrium temperature is the water temperature necessary to make surface heat flux equal to zero. Therefore, heat flux into the water (solar radiation) is translated to higher water temperatures. The figure shows the range of the infrared values on the west side of the cove and the range and average of the model results in this same area. The model results are on the low end of the infrared data, but show the variation over the period of study fairly well. The biggest discrepancy was at the hottest temperature. There are several reasons for this. The ability of the infrared survey to capture only the surface radiation means that the infrared results may be higher on the average than temperatures at a mean depth. The fact that the model predicts a mean temperature over the water column may cause such a

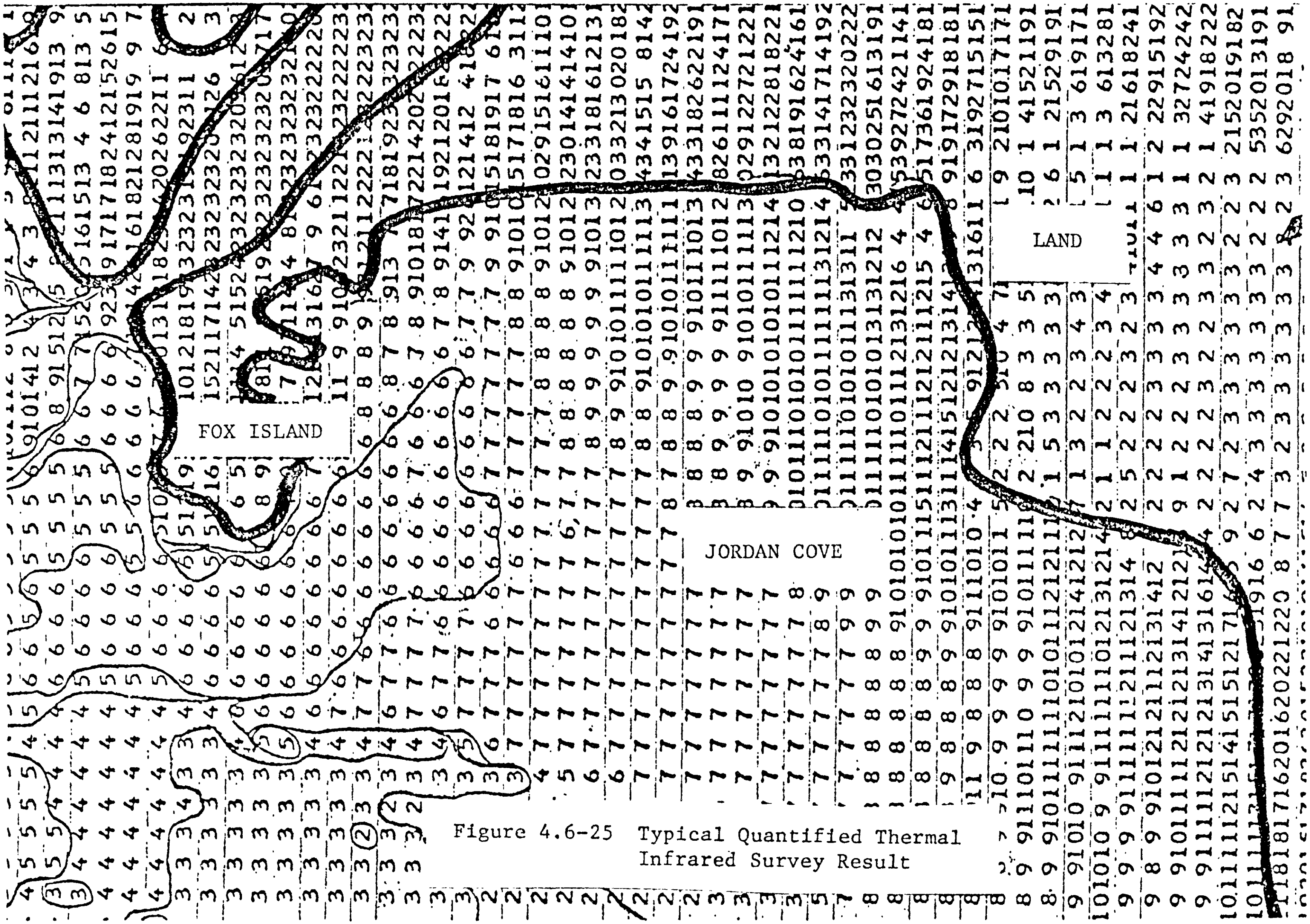


Figure 4.6-25 Typical Quantified Thermal Infrared Survey Result

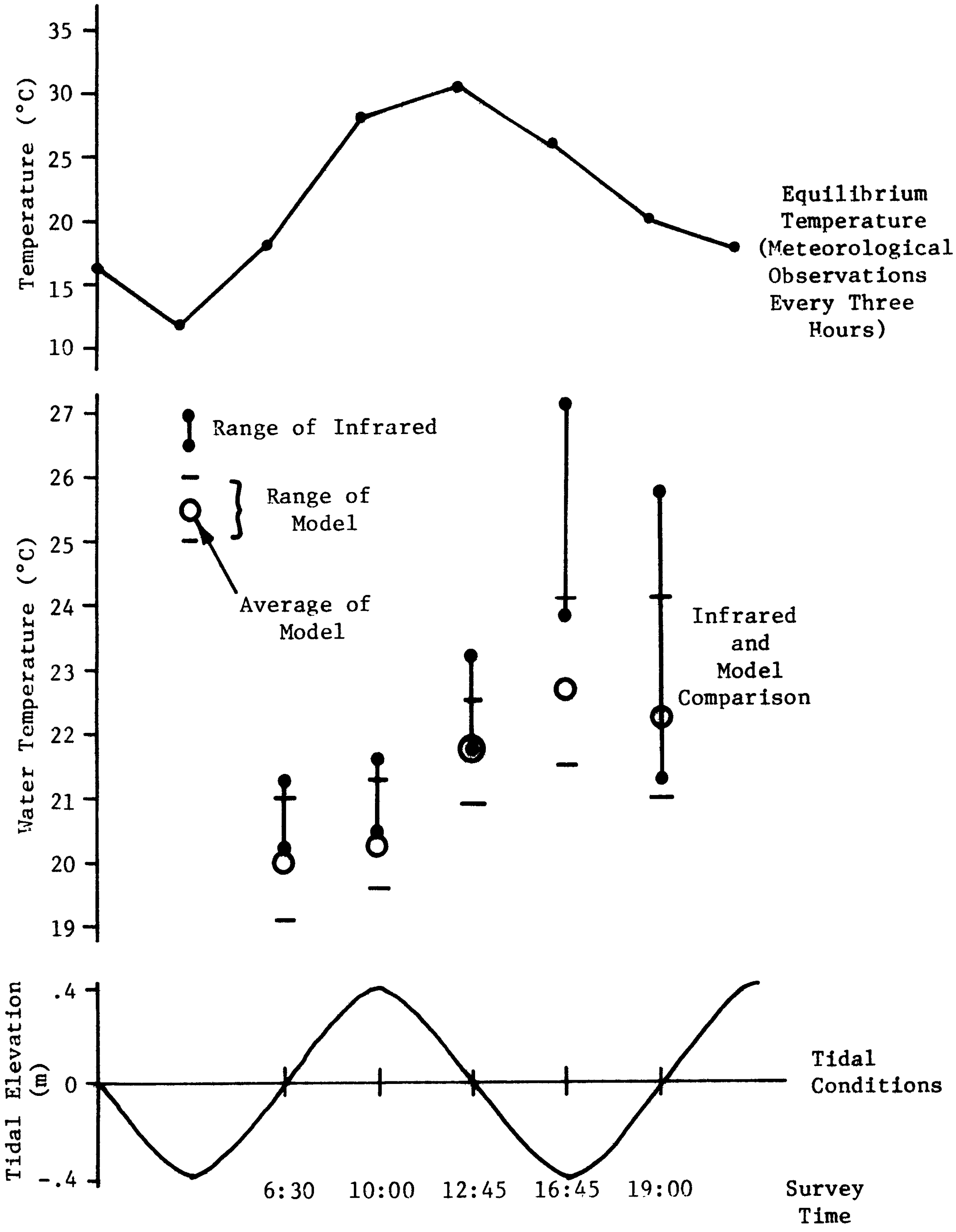


Figure 4.6-26 Comparison of Natural Temperature Prediction Model with Quantified Infrared Survey

difference. Section 4.4 also showed that during maximum heating the body of water can become stratified for a short period until maximum tidal velocities can break up this development. This is probably the major cause in the large difference in temperatures at the hottest point (survey time 16:45). The effect of the thermal plume may also have been a factor since this is the time when the plume was closest to this area. This will be discussed in more detail in Section 4.7.

Several sensitivity analyses were done varying the input meteorological conditions. Figure 4.6-27 shows the results of decreased sky cover during the previous infrared survey period. Sky cover used in the original model prediction (ranging from 30% to 100%) was decreased by half for the sensitivity analyses. This produced variations in water temperatures up to one degree Celsius showing the sensitivity of meteorological input. The decreased sky cover was also more compatible with general observations from the field survey which described weather conditions as "...clear and sunny with calm seas on July 29, 1977..." (Northeast Utilities Service Company, 1979). Therefore, onsite meteorological observations can make a significant difference in the natural temperature predictions.

Figure 4.6-27 also shows the effect of averaging the meteorological input over a two day period. The original model results demonstrated the ability of the natural temperature prediction model to respond to the changes in meteorological information. The trend of the model results followed the equilibrium temperatures fairly well and showed the ability of the model to reproduce daily temperature variations. When the input meteorological conditions were averaged over a two day period, only the general warming trend was shown. The daily fluctuations in water

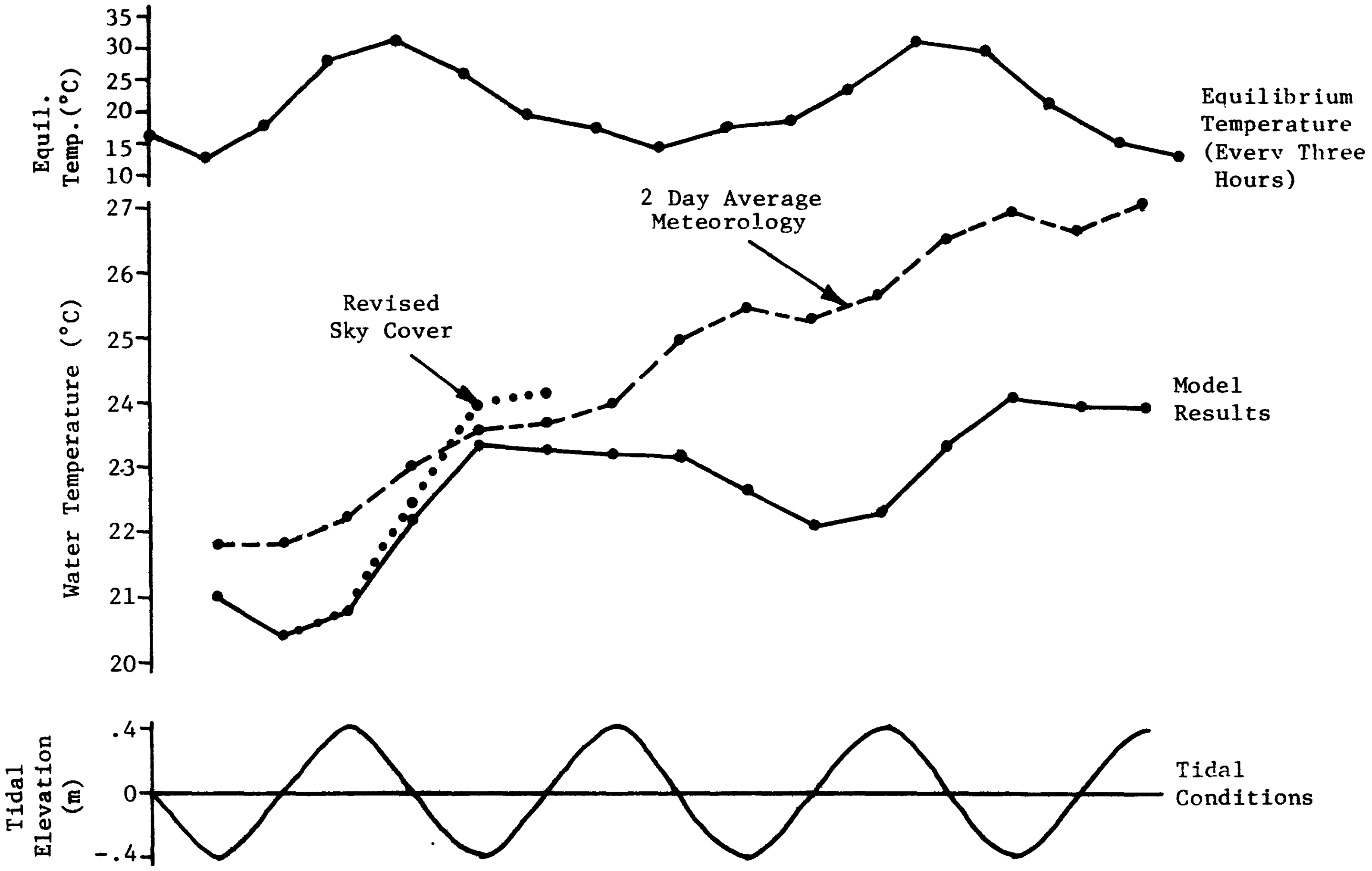


Figure 4.6-27 Sensitivity of Natural Temperature Prediction Model to Sky Cover and Meteorological Averaging

temperature were not apparent.

A comparison was made with a longer set of temperature data near the plant site. The best data available were weekly average temperatures at three locations; White's Point, Niantic Bay Yacht Club (NBYC), and Mijoy Dock, shown in Figure 4.6-4. The maximum, minimum, mean, and range for both the field data and model predictions are shown in Table 4.6-1 for the period July 26, 1971 through August 2, 1977.

Table 4.6-1 Weekly Average Comparisons

	Maximum		Minimum		Mean		Range	
	observed	model	observed	model	observed	model	observed	model
Mijoy Dock	23.2	27.37	18.3	21.34	20.0	23.84	3.9	6.03
NBYC	23.3	24.19	18.9	21.55	20.0	22.83	4.4	2.64
White's Point	21.7	18.89	18.6	17.97	19.4	18.31	3.1	1.1

The best model predictions were found at the NBYC location. The generally higher temperatures may have been influenced by the lower velocities used in the modeling effort. This would cause less flushing of the Niantic Bay area and a larger buildup of heat. The Mijoy Dock was not modeled very well. The larger grid sizes needed to produce numerical stability in this region probably led to this discrepancy. The infrared photos, Figures 4.6-22 and 4.6-23,show that the White Point observations may have been influenced by the nuclear plant's thermal plume. White Point is also near the ocean boundary used in the modeling analysis and was probably the largest factor in the lower temperatures experienced. The comparisons of temperatures over a longer period were greatly influenced by the lack of extensive data. The three locations used were also near the land boundary which is a difficult area to model due to the approximations used (i.e. no slip velocity condition and minimum depth of 1.0 m).

The last set of comparisons used the vertical temperature surveys at three locations (shown in Figure 4.6-4) which were discussed earlier in the context of the well-mixed assumption. Although conditions were slightly different, the range of the data gives a general indication of the predictive capacity of the model. This data is useful since it was taken when the plant was not in operation. Table 4.6-2 shows the maximum, minimum, and range of the data for the comparison between observations on August 29, 1968, and the model results from July 29, 1977. Meteorological conditions were very similar between the two days with air temperature ranges of 13.9°C - 21.7°C in 1968 and 16.7°C - 22.2°C in 1977. Wind speeds averaged 3.9 m/s in 1968 and 4.4 m/s in 1977. The largest difference was due to the tidal conditions which had tidal elevations out of phase (i.e. high slack occurred in 1968 at the time of low slack in 1977).

Table 4.6-2 Comparison of 1968 Temperature Survey and 1977 Modeling Results

	Maximum(°C)		Minimum(°C)		Range(°C)	
	observed	model	observed	model	observed	model
Point A	18.6	18.7	18.1	18.2	.5	.5
Point B	18.2	18.6	17.9	18.2	.3	.4
Point C	18.5	17.9	18.4	18.0	.6	.4

The results show agreement for monitors farther away from land boundaries than the previous comparisons.

The overall results of the Millstone application demonstrated that the natural temperature model could reasonably predict both the spatial (horizontal) and temporal variation of natural temperature. Good results were obtained for spatial resolution as the influences of daily heating and tidal flushing were well characterized. Comparisons over various modeling periods were hampered by the lack of detailed data. Results showed, however, that the model could reproduce most of the fluctuations in natural temperatures over a daily period. The problem at maximum heating was mainly due to the model's inability to consider stratification occurring over short periods of time. Comparisons of the model over longer periods did not match the observed temperatures very well due to the location of the field measurements and the assumptions on land boundaries.

Although the model did reasonably well in reproducing the natural temperature variations at the site, the analyses pointed out several problem areas that must be addressed. The lower velocities predicted by the CAFE-1 model may have had an influence on the temperature variations, especially in Niantic Bay. For longer periods of modeling, variations in the tidal amplitude and the ocean temperature must be considered for proper ocean boundary specification. Meteorological conditions, influencing the solar and atmospheric radiation reaching the water surface, were shown to significantly affect the predicted temperatures. Therefore, onsite data and solar radiation measurements (if possible) could be used to give more accurate results. Instabilities occurred during the model predictions in Niantic Estuary. Smaller grid sizes could be used to alleviate some of this problem.

4.7 Inclusion of Natural Temperature Model

Natural temperature variations in the coastal area around the

Millstone Nuclear Power Station have raised several issues in the history of thermal effluent control at the site. Section 4.1 discussed the natural heating in Niantic Bay and Jordan Cove; the effect on the extent of the plume; and finally the ambient temperature used to define verification of the thermal standards. Section 4.6 demonstrated that a natural temperature prediction model could be used to generate reasonable predictions of the horizontal temperature distribution in a coastal environment. The following section discusses how the natural temperature prediction model presented in the previous sections can be factored into modeling, monitoring, and regulating approaches that take natural temperature variability into account.

Initial studies at the Millstone site raised concern about the natural heating occurring in Niantic Bay and Jordan Cove. Several monitoring techniques have been used to address this issue. Continuous land-based temperature recorders have been located at several points along the shore (shown in Figure 4.7-1) at locations potentially affected by the thermal plume. Dye studies of the mixing characteristics of the near shore area were also used to estimate the effects of unit 1 and unit 2 operation. Problems can be associated with both monitoring techniques used to detect changes in natural heating. The continuous monitors have limitations since they monitor only selective points and not a large area. The monitors in Figure 4.7-1 were placed at locations which showed a high potential for plume effects but were farther from the northwest areas of Niantic Bay and Jordan Cove which showed maximum heating effects in the natural temperature modeling studies in Section 4.6. Dye studies have

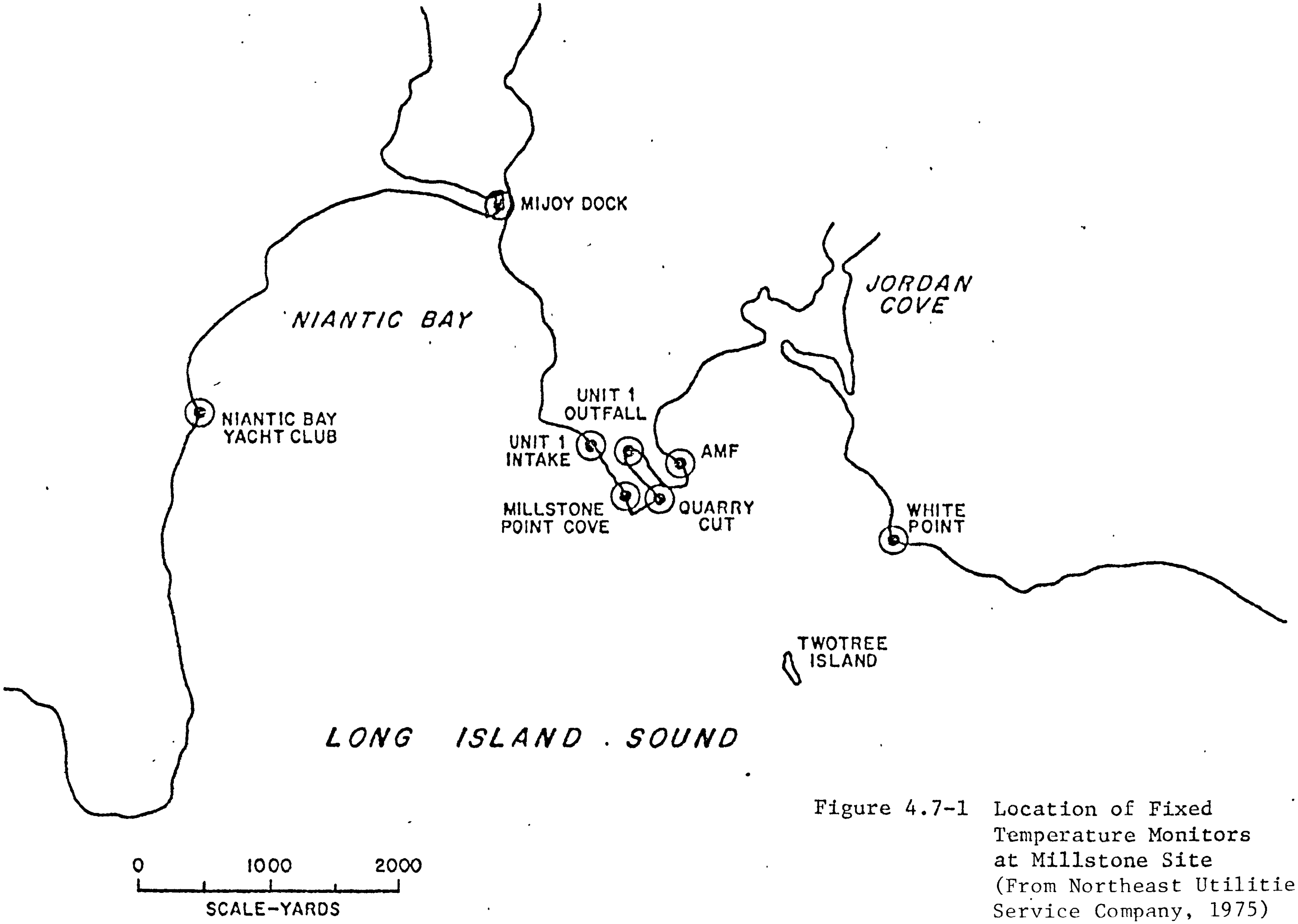


Figure 4.7-1 Location of Fixed Temperature Monitors at Millstone Site (From Northeast Utilities Service Company, 1975)

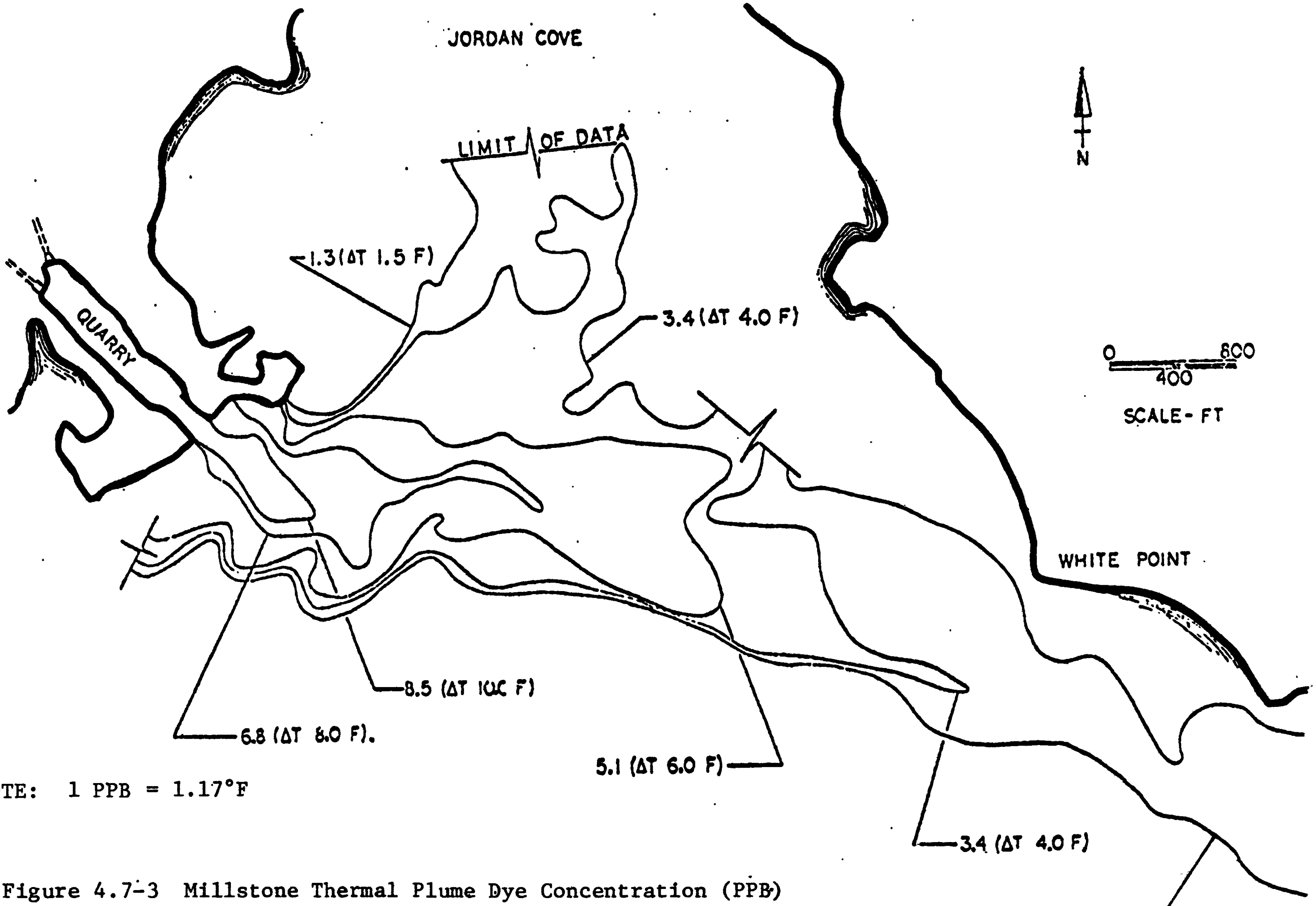
inherent difficulties in simulating the natural characteristics of a heated effluent which are affected by density differences (stratification) and surface heat loss. Lack of consideration of stratification may underestimate the effect of a heated plume, however the lack of surface loss (often the overriding factor) overestimates it. Dyes also are not useful for longer periods of study due to the effects of residual dye buildup.

A generalized modeling simulation of natural temperatures carried out early in the site investigations could provide an understanding of the natural heating effects in a coastal area to overcome some of the problems discussed above. Natural temperature modeling can consider larger horizontal temperature distributions and identify areas of potential concern or good locations for continuous monitors. Worst case conditions can also be evaluated using historical values of meteorological and hydrodynamic data. A design period could then be simulated accounting for both worst case and average conditions. The modeling results might also be compared with biological studies to determine biologically sensitive areas already receiving high natural temperatures or very little temperature variations. (The biological significance is discussed below regarding the form of thermal standards.) Modeling the natural heating can also be used instead of relying on dye studies to characterize the station's effect on the thermal plume versus natural heating conditions. By providing modeled background temperatures during a thermal field study, the extent of the thermal plume can be identified. This can be used to supplement thermal infrared studies which cannot monitor below the upper surface layer. This may become a more important consideration at

Millstone when the third unit becomes operational (approximately 80% more waste heat) since two unit operation thermal infrared studies showed the plume extending far out into Jordan Cove.

Natural heating has also affected the extent of the thermal plume as was found in the first studies of unit 1 operation. Later plume studies used simultaneous dye studies to separate natural heating. The dye studies are often conservative in overestimating the actual size of thermal plume, since they do not include surface heat transfer (cooling). The results of the thermal plume study for units 1 and 2 operation found this to be the general case as shown in Figures 4.7-2 and 4.7-3 (Northeast Utilities Service Co., 1979). Caution must be exercised, however, since the two unit operation showed significant plume extent into Jordan Cove which has high natural temperatures due to solar heating. With three units in operation, the plume may be significantly influenced by the natural heating occurring in the cove. To better identify the plume, the natural temperature model would actually be used as a far-field model to link the more distant effects of the plume with natural conditions. The variations in plume size governed by changes in natural hydrographic parameters in both average and worst case conditions could then be evaluated.

The limiting standard in most cases at the Millstone site is the maximum allowable rise in temperature standard of 4°F. The ambient temperature, used as the base value, is determined at the plant intake on the west side of Millstone Point. The maximum recirculation of heat into the intake was estimated to be approximately 12% of the 3 unit operation heat rejection rate. This corresponds to about a 3°F temperature rise at the intake for a relatively short period (less than an hour)



NOTE: 1 PPB = 1.17°F

Figure 4.7-3 Millstone Thermal Plume Dye Concentration (PPB) at 1.5 Foot Depth - Strength of Ebb (From Northeast Utilities Service Company, 1979)

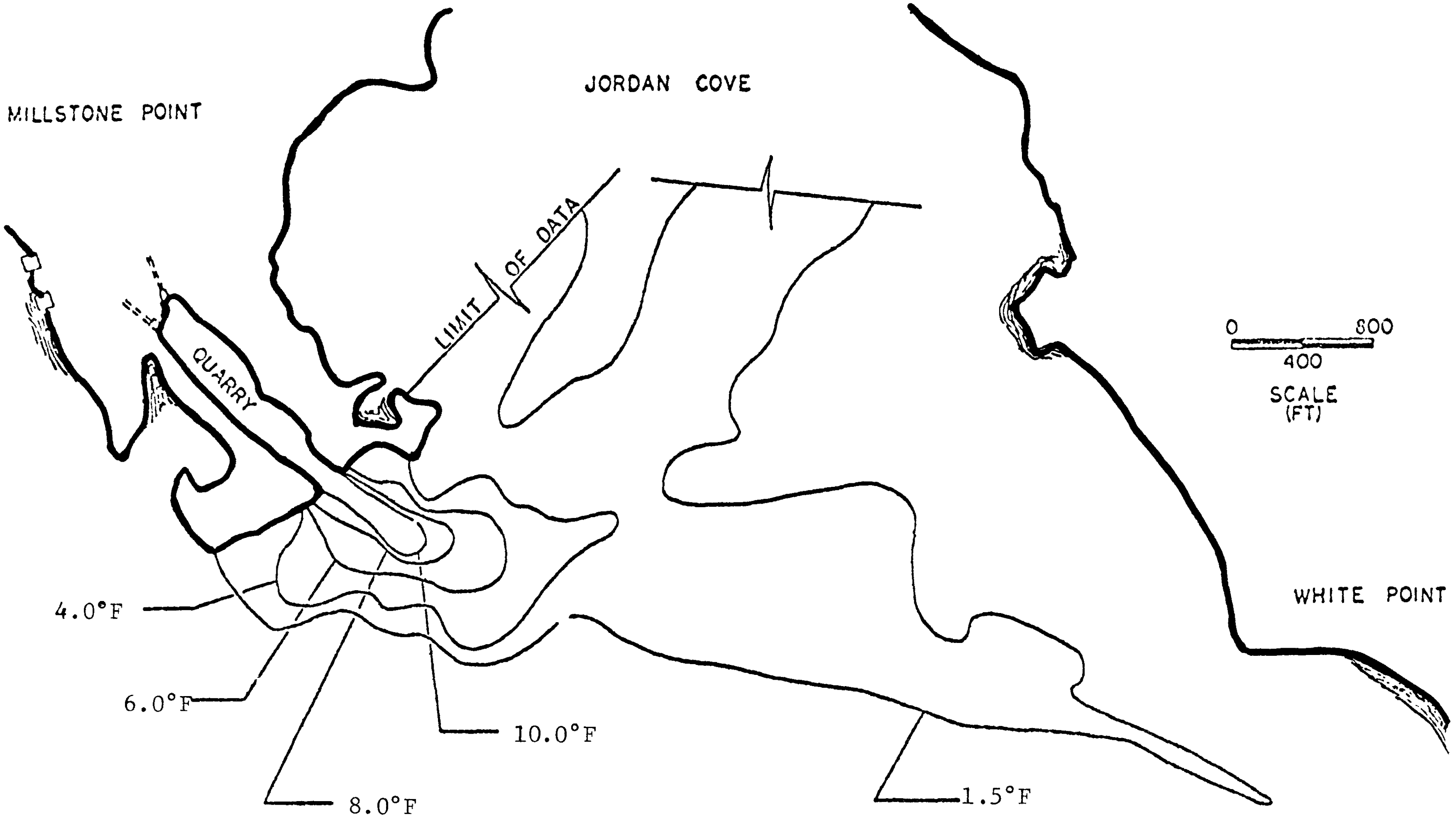


Figure 4.7-2 Millstone Thermal Plume Temperature Rise above Intake Temperature of 68°F at 1.5 Foot Depth-Strength of Ebb (From Northeast Utilities Service Company, 1979)

during flood tide. During ebb tide the recirculation was estimated to be 2% corresponding to an increase of .4°C at the intake (Northeast Utilities Service Co., 1975). Generally, recirculation probably causes less than 1°F change in the ambient temperature which is within the range of variations in the ambient temperatures found at the site. However, during the flood tide the effect of the thermal discharge on the definition of ambient temperature is significant. One approach to providing a better definition of the standard is to use the natural temperature variation model to determine a location away from the site that would better represent the ambient conditions. Another approach that could be used in surveys to verify compliance is to run the model for a period concurrent with field plume surveys to define the ambient conditions.

The form of the thermal standards also influences the application of natural temperature modeling. At Millstone the radial distance of the 4°F maximum rise in temperature isotherm is the critical standard. Temperatures near the site never reach the 83°F maximum temperature limit to present a problem. Although the State of Connecticut's ambient thermal standards contain a requirement for a 1.5°F isotherm during the summer months, this has not been used as a standard at Millstone. A change to a 1.5°F isotherm standard would make the natural variability problems discussed earlier very crucial. The effect of recirculation on the ambient temperatures would be equal to the standard in some cases. The measured 1.5°F isotherm during the two unit operation thermal plume study extended far into Jordan Cove and would become hard to distinguish from natural conditions. The marine temperature part of the 1976

Quality Criteria for Water (US EPA, 1976) includes a maximum acceptable increase in the weekly average temperature due to artificial sources as 1.8°F (1°C) during all seasons of the year. Adoption of this criteria as a standard at Millstone would have nearly all the effects of the 1.5°F standard, although a weekly average temperature is specified. The use of a weekly average temperature may take into account much of the variability in the thermal plume found at the site. The 1976 criteria also suggest summer thermal maxima. However, the south shore of Long Island is the farthest point north that is specifically addressed. Upper limits for the Millstone area would have to be established on a site-specific basis. The criteria also state the following:

> 2. daily temperature cycles characteristic of the water body segment should not be altered in either amplitude or frequency (US EPA, 1976)

Adoption of this provision would almost certainly entail more field monitoring in areas away from the shore. The natural temperature model can also give an indication of daily temperature cycles over a large horizontal area. These suggested federal criteria may never be considered at Millstone due to the large amount of biological data present at the site which demonstrates minor effects from the thermal discharge.

As mentioned in Section 4.2, the excess temperature approach has been used to model thermal plumes in coastal areas. In summary, the important benefits of using the general temperature prediction models to first model ambient temperatures are considered. First of all, a natural temperature prediction model provides a good assessment tool in understanding the basic thermal characteristics of any site. The model can identify good locations for continuous monitors or areas of potential concern for biological studies. It can also identify the amplitude and frequency of daily temperature cycles which are of biological importance. Modeling of extreme meteorological and hydrographical conditions also provide estimations of maximum temperatures normally expected in a region.

Natural temperature modeling can also begin the work necessary for later thermal plume modeling. Considering the natural temperatures initially can adapt the model to site-specific characteristics. A comparison with ambient temperature measurements supplies a good intermediate stage verification for later thermal plume prediction. The model also indicates locations away from the site used to define the ambient temperature for compliance with thermal standards.

Combining the thermal plume model with the natural temperature model results in predictions to be compared with actual thermal plume measurements. Therefore, dye studies need not be used to separate natural heating effects on the extent of the plume. Natural heating in shallow areas can also be easily separated from the effects of the thermal plume by subtracting the results of earlier natural temperature model computations.

4.8 Conclusions

A breakdown of the major aspects of thermal effluent control of the Millstone Nuclear Power Station follows. Station operation has not been significantly affected by the applicable thermal standards although natural variability issues have appeared throughout the site's history.

Thermal standards

Thermal standards at the site contained both a maximum allowable temperature of 83°F and a maximum allowable rise in temperature of 4°F at locations out of the specified mixing zone. The standards have never critically affected plant operation since the size of the mixing zone (radial extent of 4000 feet from the discharge) was established to allow full open-cycle operation. Although the State of Connecticut has changed its ambient standards, the critical summer maximum rise in temperature of 1.5°F has never applied to the Millstone site. Biological information has continually shown that the thermal discharge caused minor effects, therefore the stricter standard was not used.

Facility siting, design and operation

The coastal location of the Millstone station provided an area for good distribution of waste heat without significant biological effects. The tidal action, although variable within a tidal cycle, supplied good mixing that was fairly constant from day to day. Natural temperature variations at the site both spatially and over a period of a day, however, approached the maximum rise in temperature standard of 4.0°F. This issue would be critical if the standards were changed to 1.5°F or 1.8°F.

The natural temperatures at the site have never reached the maximum temperature standard so this limit has not been a factor at the site. Several natural variability issues have appeared such as the natural heating in Jordan Cove and Niantic Bay and the effect of natural heating on the extent of the thermal plume. These issues could become more critical during three unit operation due to a sizable increase in the thermal effluent.

Open-cycle cooling with a surface discharge has been the only heat dissipation system used at the Millstone site since surrounding coastal water provided adequate mixing of the thermal plume. The thermal standards for operation were based on the predicted extent of the thermal plume and therefore were not critical control issues.

Compliance with thermal standards

The compliance monitoring at the site has been heavily weighted toward biological monitoring of the effects of the thermal plume. Thermal plume mapping has only been done for short periods to verify the thermal plume modeling predictions. The mapping occurred twice during one unit operation and once during two unit operation. The plume mapping was used to verify compliance with the ambient standards for the site. Although the monitoring results never showed the 4°F isotherm extending farther than the specified 4000-foot limit, the plume with only two units in operation came close to the limit for three unit operation.

All of the temperature modeling at the site has been to determine the induced temperature caused from the thermal plume. Previous estimates of the plume did not consider natural variability, although it is not clear that this was the major problem in the latest comparison with actual plume measurements.

Modeling variability

A natural temperature prediction model for the Millstone site provided reasonable predictions of the horizontal temperature distribution in the coastal environment. Comparison with infrared and field temperature measurements demonstrated that relative changes over the tidal cycle could be represented. The model, however, did not do as well at predicting temperatures at exact locations due in part to limitations in the available data used for comparisons. The natural temperature model can provide an assessment tool (if properly combined with baseline temperature monitoring) to increase understanding of the basic thermal characteristics of a site. It also has potential uses in verification of compliance with thermal standards by combining with thermal plume monitoring and modeling efforts.

The previous breakdown appears in the same format as used for the Browns Ferry case study so that a comparison can be made in the next chapter. This chapter will specifically address the best approaches to the natural variability consideration in thermal control policies based on the case study results of the river and coastal environments.

V The Role of Natural Temperature Variations in Thermal Effluent Control Policies

This thesis has been concerned with the impact of natural variability on the regulation of environmental impacts. Two case studies of large thermal effluents indicated the effect of natural variability on facility design and operation under existing control policies. The following chapter draws together the results of the two case studies and background material on general pollution control into a discussion of approaches concerning the effect of natural variability in thermal effluent control policies. Several major issues are identified as important. Ambient standards provide a good method for the control of pollutants having large natural sources which are adequately dissipated by the environment. (This is especially true for thermal discharges where the heat can dissipate without long-term buildup.) The site, design, and operation of a facility are significantly affected by natural variability in environmental conditions and by the standards used to control discharges. Verifying compliance with the applicable thermal standards is affected by the statement of the standard, the natural environmental conditions, and the operation of the facility. Modeling natural variability is useful in compliance efforts and in understanding basic site characteristics. The chapter ends with recommendations for incorporating natural variation into actual pollution control policies and for further work in this area.

5.1 Environmental Regulations

The review of general pollution control practices in Chapter I focused on the use of ambient and effluent standards as the mainstays of pollution control policies in the U.S. Ambient standards were popular in the past and were set to protect the environment and human health from adverse impacts while still taking advantage of the assimilative capacity of the environment. In recent years there has been a greater emphasis on the use of strict effluent controls stated in terms of allowable discharge levels at the source. Two major reasons for this trend follow. First, the long-term effects of low levels of pollutant concentrations on the environment are often hard to determine. Second, variability of both natural and induced phenomena make it difficult to demonstrate compliance with ambient standards. For example, the biological effects studies at the Browns Ferry Nuclear Plant were unable to spot significant impacts on fish populations, although there was some concern over increased algal populations and possible eutrophication. Extensive biological monitoring efforts were unable to resolve whether or not these effects were caused by the thermal discharge. The plant also had difficulties in demonstrating compliance since the real-time monitoring system continually showed violations of the standard which were not caused by plant operation. The trend toward easily monitored technology-based effluent standards has gained popularity in providing a conservative basis for environmental protection resulting in less use of the potential assimilative capacity of the environment.

Ambient standards, however, remain a viable regulatory approach for those effluents with costly treatment, particularly where large natural variability indicates that the environment has a significant capacity to assimilate additional inputs. Although particular cases exist where a body of water cannot handle increases in temperatures, there are also numerous examples of open-cycle electric power plants that have caused minor ecological damage (Utility Water Act Group, 1978). The Federal Water Pollution Control Act Amendments of 1972 recognized this issue and provided an exemption to stringent thermal limitations if adequate biological information showed the maintenance of a well-balanced indigenous aquatic community. This exemption was also due to the significant construction and operational costs as well as decreased plant efficiencies resulting from closed-cycle cooling. This thesis has assumed that a plant can be designed to use open-cycle cooling in areas with good mixing without causing significant biological harm. The two cases studied generally supported this assumption and demonstrated that ambient standards were a viable approach in considering varying site characteristics and varying conditions at a single site. Ambient standards, rather than a no discharge rule, allowed both facilities to make the most of the assimilative capacity of the receiving water without significant environmental impacts. In the study of the Browns Ferry Nuclear Plant, ambient standards gave the plant operational flexibility to adapt to wide variation in mixing conditions. The use of a single effluent standard, based on a worst case ambient condition, could not consider the large variability in natural conditions and would severely restrict plant output. At the Millstone site, a highly unrestrictive standard recognized the excellent assimilative capacity of the coastal area.

A major problem with ambient standards has been the variability in induced and natural concentrations even though these variations were part of the justification for initially using ambient standards. Most air quality ambient standards have addressed this problem by using long averaging times to smooth over the high infrequently occurring pollutant levels. Both short-term and long-term standards are used to account for all potential acute effects. Many water quality standards, however, completely fail to address the variability issue. The thermal standards for the two case studies did not consider the variability problem since both sets of standards were assumed to represent maximum levels never to be exceeded.

As will be discussed in the following sections, this deficiency in the regulatory approach to thermal standards has had an impact on the location, design, and operation of facilities and on efforts to show compliance with the regulations.

5.2 Facility Siting, Design, and Operation

Two case studies provided an understanding of actual thermal effluent control problems. The studies are characteristic of many thermal discharge sites since they included evaluations of a river environment (which showed a large variation in natural conditions affecting the dispersal of heat), and a coastal environment (which had a fairly constant dispersal over long periods). The results of these studies showed that the natural characteristics of the site and applicable thermal standards can significantly affect the design and operation of electricity generating facilities. It was also found that a facility could be designed to meet changing natural conditions without resorting to operation based on meeting the worst case condition at all times.

The availability of water and the biological significance of an area are crucial determinants of the ability to site large electricity generating stations. In the past, most stations have been located on large bodies of water utilizing open-cycle cooling. The case studies showed, however, that there was a considerable difference in the ability of large bodies of water to dissipate waste heat sources due to the variable nature of mixing conditions.

The study of the Browns Ferry Nuclear Plant showed that the variable nature of river flows significantly affected operation and design of the heat dissipation system. The original design of the plant utilized diffusers to provide rapid mixing of the heated discharge to keep the mixing zone small, and considered adverse heat dissipation conditions by regulating river flow (through dam operation) or plant output.

The adoption of new thermal standards was critical to the design and operation since an extensive new heat dissipation system was necessary. Problems arose because the new ambient standards were very close to the natural conditions at the site. The 86°F maximum temperature standard was exceeded on several occasions without discharges of waste heat. Natural variations in temperatures were also on the same order as the maximum rise in temperature standard of 5°F. Cooling towers were added to the Browns Ferry plant and the system was designed to use open-cycle cooling, supplemental cooling, or fully closed-cycle cooling depending on changing natural conditions. The ability to change cooling modes gave the facility considerable savings in capacity, and was found to have only 10% of the power loss due to fully closed-mode operations.

The Millstone Nuclear Power Station was located in a coastal environment where mixing conditions, although variable within a tidal period, were fairly constant from one period to the next. Mixing during strength of flood and strength of ebb tidal conditions were large enough to adequately dissipate the thermal discharge. Water temperatures at the Millstone site never reached the ambient maximum temperature standard of 83°F. The 4°F maximum temperature rise standard was the most limiting factor. The openness of the site and good mixing conditions allowed heat dissipation without effects on sensitive biological areas. Therefore a mixing zone was set (the limit of the 4°F isotherm) a long distance from the discharge,allowing open-cycle operation at all times.

In summary, site characteristics are the initial important factors in the design and operation of thermal discharges. Open water for mixing at a coastal site can provide ample area for heat dissipation without biological effects; therefore ambient standards may not be critical issues. The thermal standards were the more decisive factors in design and operation where mixing conditions were more variable and natural variability was close to the specified standards. Mixed-mode cooling systems were found to offer flexible plant operation making the best use of the assimilative capacity of the receiving water without violating the thermal standards.

5.3 Verification of Compliance with Standards

Pollution control policies must provide a means of verifying pollution control standards before and after facility operation. The two case studies showed dramatically different approaches to verifying compliance with the thermal standards. Emphasis on the thermal standards, plant design and operation, site variability, and natural temperature variations all proved important in the compliance efforts.

The characteristics of the two site locations played the largest role in determining the amount of preoperational study of the thermal discharge. Because Millstone Nuclear Power Station was located on a coastal site, short-term studies which characterized the tidal movement and flushing at the site, provided coverage of the major factors affecting the dispersal of the plume. The Browns Ferry Nuclear Plant, on the other hand, was sited on a river reservoir environment with more variable conditions which necessitated more preoperational studies.

The ambient standards played a significant role at Browns Ferry since the plant was to be run near the thermal limits. Therefore, the operation of the facility had to be studied closely to determine potential variations of the standards during a variety of changing natural conditions. Extensive use of preoperational temperature monitoring and both physical and analytical models were used to predict the effects of plant operation. Although the general form of the standards was the same for both plants, there was far less emphasis on the standards at Millstone. The number of preoperational field measurements and physical model studies were relatively small. Significantly, at neither Millstone nor Browns Ferry were natural temperature variations recognized as important in the preoperational studies.

Once the two facilities became operational, the difference in sites and emphasis on standards again led to differences in the approaches used to verify compliance with the standards. Since Browns Ferry was run near the thermal limits under varying conditions, it was necessary to provide continuing verification of compliance. The owners first decided to accomplish this by using real-time monitoring. The basic difference in the operational monitoring at Millstone was the number of measurements necessary to characterize the variability at the site. Since mixing conditions were not much different from day to day and the Millstone station was not under pressure to adjust facility operation, only short-term field measurements were carried out. Measurements characterizing the extent of the plume during one tidal cycle were essentially done to confirm previous estimates of plume extent. The latest set of plume measurements during two unit operation showed results within the standards set for three unit operation. However, the extent of the plume was farther than expected which led to more modeling studies.

Natural temperature variations caused significant effects on compliance monitoring at the Browns Ferry site since the standards' limits were close to natural variability. Various spatial and temporal variations caused problems in the real-time measurements. The biggest problem was the maximum rise in temperature standard which entailed a separation of plant effects from natural conditions. It was difficult to define a representative ambient standard to provide a basis for the measurement. Therefore, using real-time monitoring to separate plant-induced effects from natural conditions could not provide a realistic approach to show compliance with the maximum rise temperature standard.

The effects of natural temperature variations at the coastal site caused concern over solar heating in shallow areas, potential influences on the size of the thermal plume, and the definition of the ambient temperature for maximum rise standard. Short-term tracer-dye studies and thermal infrared surveys were used to address these concerns. The measurements indicated possible interaction of the thermal plume with natural heating in the shallow Jordan Cove area.

At Browns Ferry, a variety of strategies for handling natural variability were investigated using simulation techniques. Changes in the statement of the standards were found to have the greatest effect. Monitoring strategies including temporal and spatial averaging were only partially effective because of persistant large scale trends in variability. As will be discussed in the next section, attempts to model the natural variability were successful except for the shortest variability scales for which adequate physically-based models were not feasible.

In summary, the extent of verification of compliance with thermal standards is dependent on characterizing the variability of conditions found at a site. Where variations are minimal, as in coastal sites, short-term studies covering the existing variation are sufficient. At site locations with greater variability, studies must be done at frequencies characterizing the changing conditions. One of the most interesting aspects of the compliance problem related to natural variability is the trend towards the translation of ambient standards into effluent restrictions. At both sites studied, the difficulty of dealing with natural variability through the use of more extensive monitoring or modeling of natural temperatures led to strategies which modeled plant effects as a means of differentiating plant from natural effects. Model results were used to estimate the extent of the plume and to translate operation to an effluent standard for compliance purposes. An effluent standard at the Millstone site included the largest expected thermal output because model studies had shown that the plant's largest projected output would not cause significant biological damage. At Browns Ferry the measurement of the ambient maximum rise temperature was replaced by modeling plant effects to convert compliance to a flexible effluent standard based on natural conditions. Since most regulatory agencies require some form of continuous verification of compliance, the use of such quasi-effluent standards satisfies the regulators and provides the plant operators with an easy method of monitoring.

5.4 Modeling of Natural Temperatures

Natural temperature models are a possible approach to separating the effects of a thermal discharge from natural conditions. The case studies of thermal effluents indicated that such models can be useful in verifying compliance with thermal regulations as well as gaining a better understanding of the site environment.

A one-dimensional model of natural temperatures at Browns Ferry was evaluated as a possible approach for separating natural temperatures from plant effects. The model provided a fair comparison with 49-hour averages of the actual conditions but did not provide adequate resolution of the natural conditions needed for compliance with standards requiring measurements on the order of hours.

The two-dimensional model applied to the Millstone site showed reasonably good resolution of natural conditions and could reproduce most of the temporal variation within a tidal cycle. The coastal natural temperature model could not be directly tested in a compliance situation since adequate data was not available. The model did show promise in solving many of the questions of natural heating in shallow areas, natural heating effects on the extent of the thermal plume, and the determination of an ambient temperature.

Both modeling efforts met difficulties in predicting short-term effects which changed the natural temperatures. Many of the problems were due to the fact that three-dimensional models could not be used. The one-dimensional model was restricted since it could not include lateral effects caused by topographic changes and density effects due to stratification. The two-dimensional model, although providing better prediction of the horizontal temperature distribution, also met difficulties due to stratification during periods of intense solar radiation. Both models suffered from the approximations used to predict the velocity field of the body of water which had a significant influence on the temperatures. Empirical methods for estimating the heat transfer for a natural water surface were used. Site-specific data was not available on the order of timescales which affect the heat transfer. Therefore, small-scale changes due to winds and cloud cover could not be adequately predicted.

It is disturbing to note that the trend in compliance activities has been to rely even more heavily on the continued use of models that predict only induced temperatures from plant effects thus leading away from programs that could be used to gain a better understanding of the site environment. Modeling of natural temperatures and the associated data collection provides a means to continue the advancement of methods to better characterize the environment around the thermal discharge. This evolution of basic understanding and development of predictive techniques is necessary to complement biological investigations concerned with increasingly complex environmental impact phenomena.

5.5 Recommendations

Specific recommendations follow for incorporating the results of the study of natural variation into actual thermal effluent control policies:

- Ambient standards should continue to be used as a method of adapting thermal discharges to the assimilative capacity of large bodies of water where water availability and biological considerations do not pose significant problems.
- To the greatest extent possible, ambient standards should reflect the natural variability at facility sites.
- Mixed-mode cooling systems should be considered in the design of heat dissipation systems to provide flexibility in facility operation at sites with significant changing mixing conditions.
- Real-time ambient monitoring of compliance with maximum rise temperature standards should not be used in areas of high natural variability. In such cases, effluent monitoring based on predicted plant effects should be used to determine continuous verification since it provides the easiest approach from regulating agencies' and facility operators' view points. Effluent standards, however, should be flexibly based on changing natural conditions, thus providing a control policy making use of the natural assimilative capacity of the environment.
- Natural temperature models offer one form of separating plant effects from natural occurring temperatures. The state of the art does not allow the use of these models for compliance verification when highly varying conditions are present due to many natural factors. However, natural temperature models should be used to provide a means of gaining

better insight into the factors affecting an aquatic environment used for dissipating thermal discharge. Such information is valuable in addressing possible interaction of natural conditions with the thermal plume, and determining natural temperature variations in sensitive biological areas. More extensive monitoring of baseline conditions is required to compliment modeling efforts. This policy forces emphasis on discovering both the physical and biological characteristics of site environments before changing them.

All of these recommendations may be implemented within the existing framework of thermal effluent control policies. The 316(a) demonstration provisions allow for changes in thermal standards based on evidence that the aquatic community will not be significantly impacted. Use of ambient standards, and mixed-mode cooling also fall into this category. The various recommendations on compliance must be agreed upon by appropriate pollution control authorities, in most cases the states, through negotiations in the National Pollution Discharge Elimination System permitting process. Flexible effluent standards based on modeling of ambient impacts and the exact amount of compliance verification must be components of these agreements. In general thermal assessment, the use of natural temperature models should be stated as a requirement in regulatory guidelines for preoperational power plant assessments.

5.6 Future Work

Several opportunities for further research were identified throughout the coastal modeling work. One possibility currently under investigation links the natural temperature model with a near field thermal plume model.

Such a combination would increase the predictive capability in areas where man-made thermal plumes interact with highly variable natural conditions.

A problem that was identified in the coastal study was the lack of baseline natural temperature data for model comparison. A detailed ambient temperature survey over an extended period would be helpful in fine tuning natural temperature modeling efforts.

When numerical models are used to simulate complex geographic areas, small grid sizes and small timesteps are normally needed to solve numerical instability problems. Advanced numerical models are needed to solve the governing equations over long periods without excessive use of computer time. Better methods of handling boundary conditions in numerical models should also be evaluated to provide more realistic predictive capability.

Since the bulk of present thermal effluent control relies heavily on biological data, more interaction with biologists should be encouraged to clarify the needs for physical models. This includes a determination of time scales and ranges of results that would be helpful in predicting the biological impacts of thermal discharges.

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