The Role & Contributions of Hydraulic Testing Labs: Part III, After World War II

Hydraulic testing laboratories have played key roles in advancing the science, practice and teaching of fluid mechanics. One on-going laboratory has made far-reaching contributions in the field.

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In the years following World War II, the United States underwent a fundamental change. The G.I. Bill expanded educational opportunities and low-cost loans were available for homes, farms and businesses. Housing stock was upgraded, and homes became larger. There also was a baby boom that necessitated the construction of more schools, hospitals and other facilities — all using electricity. Families were moving to the suburbs. In 1956, under President Eisenhower, federal funding began for the interstate highway system. Pent-up power demand from the late 1930s was unleashed along with an array of new consumer goods using power. Major items that increased power demand included televisions, electric dryers and, particularly, air conditioning, which produced a higher load in the summer when previously excess capacity had been available. Peak load still occurred in the winter, but the difference between summer and winter consumption diminished. In rapid fashion, offices, hotels and stores became air-conditioned. At the time, it was felt that power usage in the United States would double every ten to twelve years.

During the war, per capita demand peaked in 1943 (see Figure 1) after a low point in the worst early years of the depression. From 1935 to 1947, power usage about doubled in New England, with an even greater increase nation-

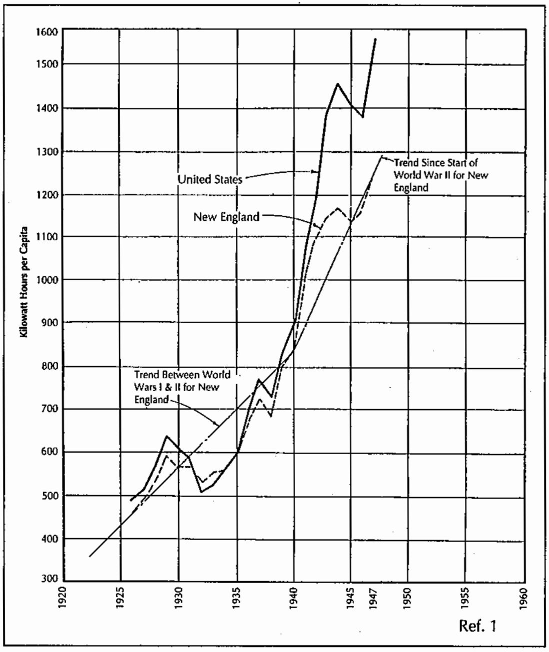

FIGURE 1. Energy consumption per capita (utility generated).

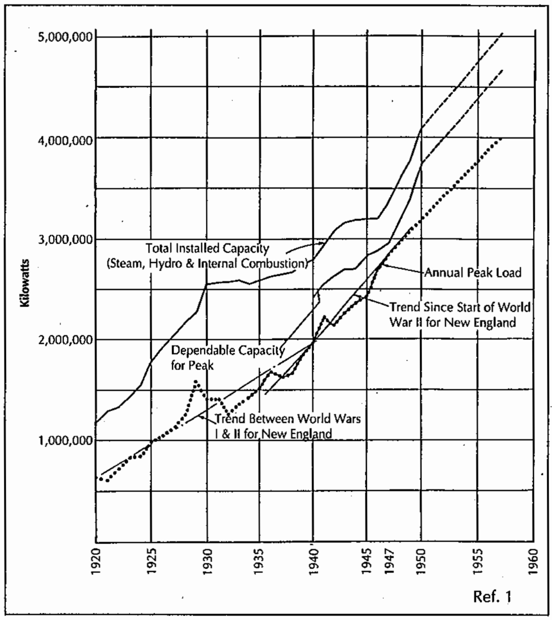

FIGURE 2. Load forecast for New England.

ally. Peak load in New England doubled from 1935 to 1950 (see Figure 2). Nationally, the very large growth and average annual use per capita (residential service) is shown in Table 1. The decreasing cost per 500 kilowatt hour is shown (not adjusted for inflation) along with the large change in the Consumer Price Index. From 1945 to 1970, national generating capacity increased by a factor of seven.

Changes After the War

Hydraulic engineering also underwent major changes in the 1950s as the field became more specialized and applied research multiplied. The study of submerged jet dilution by Albertson and others gave rise to a whole new area of study.[3] Diffusers were being used to distribute treated sewage five to seven miles offshore in California. (Diffuser fluid mechanics would have a major impact on the electric power industry in the 1960s and later as environmental laws changed with regard to thermal discharge to lakes and rivers.)

In 1945, Charles Metcalf Allen retired from teaching as Professor-Emeritus but remained as Director of the Alden Hydraulic Laboratory (Alden) until his death on August 15, 1950. His retirement had been postponed three years beyond the 70-year age limit due to the laboratory's wartime need for his services. After Allen's death in 1950, Professor Leslie J. Hooper was named Director of Alden. Having worked with Allen for 23 years, Hooper was familiar with all aspects of lab work, including the design, construction and testing of all types of models. In addition, he performed consulting and field testing, including salt velocity testing. Although Allen had invented the salt velocity method of flow measurement, it was Hooper who had refined the technique by meticulously looking at all aspects of the method. To him, each test brought a new challenge and with the challenge came ingenious ways to increase the accuracy of the method.

Hooper took up where Allen had left off before the war. The modeling of spillways, prevalent in the late 1930s, comprised a significant portion of the laboratory's work until 1960. Nineteen different spillway models were built and tested during that time period. All these studies were performed for flood control purposes.

An interesting study was conducted for a power company in 1949. Besides doing a spillway evaluation of the Holyoke Dam and its powerhouse intake on the Connecticut River, this model included the study of a fish elevator

TABLE 1.
Usage & Cost of Residential Power

Year	Annual Use per Residential Customer (kilowatt hour)	Generating Capacity (1,000 megawatts)	Average Residential Price per Customer (cents/kilowatt hour)	Consumer Price Index (1967 = 100)
1912	264	5.2	9.10	
1920	339	12.7	7.45	60.0
1925	396	21.5	7.30	52.5
1930	547	32.4	6.03	50.0
1935	677	34.4	5.01	41.1
1940	952	40	3.84	42.0
1945	1,229	50	3.41	53.9
1950	1,845	69	2.88	72.1
1955	2,773	114	2.65	80.2
1960	3,854	168	2.50	88.7
1965	4,933	236	2.25	94.5
1970	7,066	341	2.10	116.3

Ref. 2

(see Figure 3 on page 8). The Holyoke Dam is the first significant dam migrating fish encounter as they swim up the Connecticut. The fish, mostly shad with some Atlantic salmon, were blocked off from their ancestral spawning grounds by dams constructed in the 1700s and afterward. Since the upstream run of these fish is normally short (usually only during the month of May) and occurred at a time when the maintenance personnel of the company were not busy, the company decided in 1955 to build a fish elevator that would be manned by maintenance staff. The elevator resembled a large freight elevator with the floor replaced by a tank that was painted orange so the fish could be seen by the operating personnel from above. Water to attract the fish flowed through the back screen of the elevator out through the open front. When enough fish had congregated in the elevator, the front gate was dropped and the fish were elevated and deposited in the upstream pool. The model study involved researching the flow and quantity of water through the elevator.

Extension of Wartime Navy Testing

After the war, the U.S. Navy continued its open contract with Alden. Post-war studies had indicated that proper modeling of the cavity formed at water entry of ballistic devices necessitated modeling the atmospheric air pressure as well as air density. Up to this time, the atmospheric conditions were not modeled. For example, if the model scale was 1:10, the pressure above the water in the testing tank had to be one-tenth of the atmospheric pressure and the air density in the tank had to be normal atmospheric density. To achieve this condition, the pressure in the tank was reduced by use of a vacuum pump and freon gas was introduced. The projectile guns used in this tank were modified slightly for sealing purposes but, otherwise, the same equipment used in other tanks at Alden was utilized.

Torpedoes and various other similar devices were again tested for various Navy agencies. One of the more interesting programs was for a submarine missile. The missile emerged from the water, hunted an enemy submarine and reentered the water to attack. The water exit and the water entry were both studied. Water exit was studied photographically with various sized waves made by a hand-activated wavemaker. Because of the drag reduction required for the water trajectory after launch and for the air study, the missile had a streamline

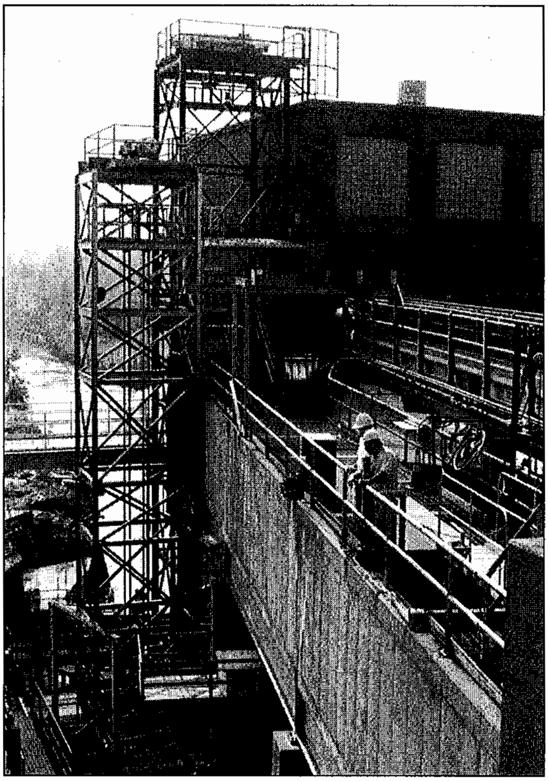

FIGURE 3. The fish elevator at the Holyoke Dam.

shape. However, the streamline shape caused unstable trajectory at water entry. The problem was solved by using a frangible nose section that truncated a small section of the nose at entry, leaving sharp corners where flow would separate, providing stable trajectories during the entry stage but not significantly increasing the drag of the missile.

A study was made for the Canadian Navy that neatly demonstrated one use of models for a signaling device used in war games. It consisted of a number of hollowed explosive cylinders held together by a spring and fitted inside a canister. The outside shell of the canister was fabricated in three parts, each part hinged to the tail, and the front parts held by a spring-loaded plate. When the device hit the water, the plate on the front would be compressed and release the three parts of the shell like the petals of a flower. At this point the explosives would be deployed in a straight vertical line. At the desired depth, a hydrostatic device would arm the charge. At the firing depth, another hydrostatic device fired the line charge. For both arming and firing, the explosive cylinders had to be in a vertical line. A test firing of 20 prototype devices by the Canadian Navy produced 19 failures. Inspection of the failed devices showed that the firing mechanism had not been armed. After one shot of the full-scale device in the Alden tank, the problem was obvious. The plate on the front did not fall off, thus preventing the explosive device from deploying until well after the arming depth. The problem was solved by attaching a strong thin wire from the plate to one portion of the canister shell. Thus, when the canister shell started to open, the plate was pulled away with the shell, and the explosives immediately began to deploy.

Steam Electric Plant Growth & Pump Intake Modeling

Also during the 1950s steam power plants were rapidly expanding in size. Table 2 shows the growth in steam electric turbine size. Higher temperatures and pressures produced greater fuel economy, and as the plants became larger, so did the condensers and circulating water flows. Greater flows required much larger pumps. Vertical mixed flow pumps 6 feet in diameter with 900-horsepower motors and discharging 100,000 gallons per minute became available. It was about the mid-1950s that interest first started in modeling pump intakes as a result of using large pumps and flows. By 1963, 200,000-gallon-per-minute pumps would be used, which in 1966, because of rough operation, were part of one of the early pump intakes modeled at Alden.

As far as can be determined, the first pump intake model at Alden was conducted in a 3-foot flume in 1957 for 50,000-gallon-per-minute circulating water pumps. The 1:6.75 scale Froude model included one pump and the concerns were vortexing and the distribution of chlorine. Test results indicated the percent of time that vortexing occurred with various designs. No vortices were observed when the pump bell was against the back wall.

A 1958 paper by Dornaus discusses an elegant pump intake model and then-accepted Froude similitude criteria.[4] The issue of the equal velocity rule (same pump bellmouth entrance velocity in model as in the prototype) was raised, discussed and commented on by D.F. Denny.[5] The equal velocity rule would be discussed and evaluated for 30 years or more. It is now generally accepted practice that Froude similitude and scaled velocity are theoretically correct when the model flow is sufficiently turbulent. It is prudent to increase the velocity by up to 50 percent to see if there is any substantial change in vorticity at the higher flow, but equal velocity is not appropriate.

Dornaus[4] also made reference to the Hydraulic Institute Standards of the time. The Hydraulic Institute (Hydraulic Society) was originally formed in 1917 when 16 industrial pump manufacturers met to solve a number of engineering problems brought about by the production needs of World War I. Standards of the pump industry were first published in 1921 in a 19-page pamphlet[6] and have been upgraded numerous times. The latest edition became available in 1998 and indicates the benefits of scale-model testing, especially for larger capacity pumps. Alden staff played a major role in formulating that section of these standards.

Recirculation of Cooling Water

With the increase in power station size also came the problem of heat disposal from the condenser to the surrounding environment. In most cases, heat was transferred to a lake or river. Later, cooling towers and ponds would be required for some plants, and costs would increase. In the 1950s, the main problem that arose from a thermal discharge was recirculating warm water back to the intake that brought cooling water to the station condenser. If the intake water were warmed due to recirculation, the efficiency of the condensers and power plant would decrease.

Since there was little relevant technical information in the literature, and analytical modeling of thermal discharges was still ten years away, hydraulic modeling was the way to address recirculation issues. "Selective withdrawal" became the newest catchphrase and a topic of research. The effect of buoyancy on flow patterns and mixing is indicated by the densimetric Froude number (the ratio of inertial to buoyancy forces).

TABLE 2.
Growth in Steam Turbines

Year	Max. Unit Size (megawatts)*
1904	5
1913	15
1916	35
1935	165
1949	180
1951	220
1955	325
1965	650
1970	850
1975	1,000

*These values compiled from various sources & are approximate. Ref. 2

The first such thermal model study in the United States was conducted in 1952 at Alden. The model for the Cromby Station Power Plant in Pennsylvania was built outdoors on a concrete slab located below the equalizing pond (see Figure 4). The area had previously been a swamp and was filled prior to building the model. To generate the heated water, a 100-horsepower boiler was reworked to prevent pressurization and, thereby, acted simply as a heater.

The data acquisition system for the model was rather simple and crude by today's standards. It consisted of acquiring temperature measurements by hand-held mercury thermometers and a few thermocouples. The density differences of the plant discharge compared to the river were reproduced, and attempts were made to evaluate heat transfer coefficients using an insulated shallow pan with a heater and mixing device.

As far as it is known, this test was the first attempt to evaluate surrounding atmospheric conditions and their effects on modeling heat losses to the environment. However, test conditions were difficult to control since the test required a long period (two to three hours) for consistent thermal patterns to develop. Wind and sun forced the testing to be done after dark. Wet and dry bulb temperature, wind and radiation data were recorded. The resulting infor-

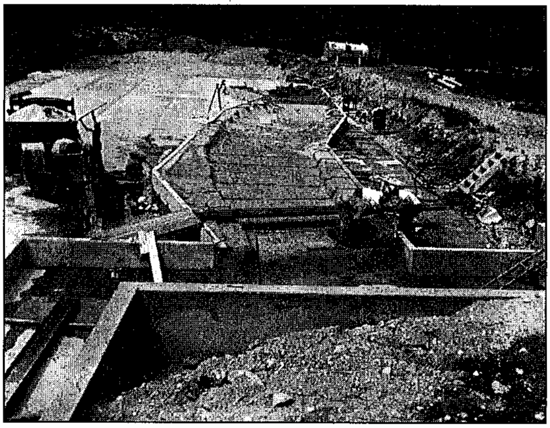

FIGURE 4. Model of the Cromby Station thermal discharge and recirculation (1952).

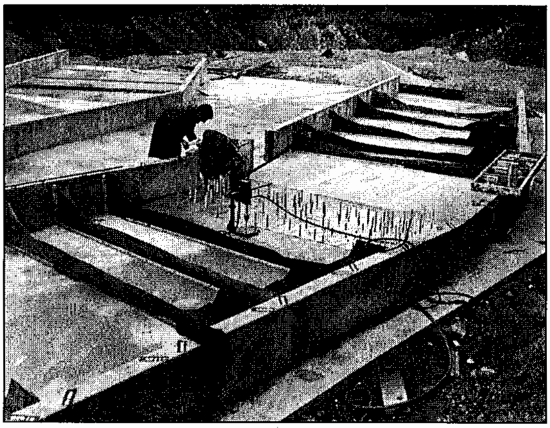

FIGURE 5. Model construction using templates and pegs.

mation was hand plotted to produce a surface temperature contour map (isotherms) in the area of the plant intake. The model was also used with fine coal to investigate siltation.

The boiler used in the Cromby Station study was later used on a number of other thermal discharge/recirculation projects. In the case of one power plant recirculation study, a siltation problem was encountered at the site. The coal-fired plant had its coal carried to the site by barges, and these barges were tied up in front of the plant. Without the barges, there were no problems with silting in the intake. However, due to the large silt load in the river, whenever the barges tied up in front of the intake, the area under the barges became restricted and the velocities increased, carrying silt into the cooling water system. The problem was solved by redesigning the intake and the area around the intake so that the silt was diverted downstream.

Model Construction Techniques

Model construction techniques were also changing. Up to this time, topography was reproduced using wood templates backfilled with sand and topped with concrete screeded to the finish elevation (see Figure 5). Another method used for decades had pegs set at the proper elevation. A topographic map was projected at the model scale onto brown paper. The paper was glued to the model cement slab, and holes were drilled into the slab at a number of locations on each contour. Pegs of the right elevation were then inserted into the holes and the model filled. In this case, the concrete was finished by hand using the peg elevations as guides.

In the case of some thermal models, the templates were made of 2×6s or 2×8s and a thin piece of plywood was nailed to the templates. The surface was then coated with fiberglass by either spraying or rolling the fiberglass on the plywood. For all models, the building technique applied was based on the topography and the purpose of the study.

Other Studies During the 1950s

During the late 1950s a railroad company and a chemicals manufacturer both contracted the laboratory to do studies on the Delaware River at the same time. The railroad had pier facilities that experienced continuous silting, whereas the chemical company had seepage of a heavy chemical into the river from a holding facility. The two sites were exactly across the river from each other. Hooper tried to convince the two companies to build one model for both studies. He was not convincing enough, however, and two models were constructed below the equalizing pond at Alden across the road from each other. Since laboratory staff was limited, personnel would work on one side of the road one day, then on the other side the following day. Many visits were also made by the clients to make sure that their model was not falling behind that of the other client.

These models were the first tidal models at Alden. The models had gates at both ends and were equipped with electric hoists to operate the gates. In addition, electric-motor-operated valves were installed in the flow meter-equipped pipelines at both ends of the models. Sensing systems (consisting of toilet floats) were mounted on arms moved by mechanical cams that simulated the tidal flows and elevations. The whole system fed into a series of relays that operated either the hoists or the valves. Unfortunately, there was no time delay incorporated into the system to account for the time the water took to enter the sensing tanks containing the floats. On the first attempt to operate the model, waves flowed back and forth from one end of the model to the other as the valves cycled continuously from closed to wide open. Needless to say, this problem was immediately corrected, and the studies recommenced.

One of several studies conducted for another power company involved the Fox Point Hurricane Barrier located at the Narragansett Station in Providence, Rhode Island. The barrier consisted of sheet piling driven into the riverbed, and gravity-operated gates were located in the barrier. The barrier's purpose was to separate the salt water from the fresh river water and to prevent salt water from entering the plant intake during flow reversal encountered usually during a hurricane or extreme high ocean water conditions. The model gates were studied relative to the flow patterns, the weight of the gate and the gate angle.

During the late 1950s and the early 1960s, a number of models were built for projects in foreign countries. Spillway studies were performed for projects at the Keban and Gokcekaye dam sites in Turkey, at Piexoto in Brazil, and at Kastracki in Greece. An intake study was performed to determine vortex formation at the Guadeloupe site in Columbia, South America. At this point in time only visual descriptions of the vortex phenomena were obtained. A glory hole intake and complicated penstock leading from the intake were modeled in clear plastic to study air entrainment and its effect on the flow of the Calima Project in Columbia.

Another study involved the rehabilitation of the Chong Pyong Dam and Powerhouse in South Korea and the rating of its spillway. Built by the Japanese during their occupation of Korea, this dam was in disrepair, with the concrete spalling off the spillway in such a way that the leakage under the 24 spillway gates far exceeded the maximum flow through the powerhouse. The work on the site was going to be performed over a period of years using local labor hauling baskets of materials along with minimal equipment salvaged from the Korean War. Depending on which part of the dam was being rehabilitated, cofferdams were built upstream and downstream to prevent water from flooding the work site. Flow conditions past the cofferdams and erosion around the dams were studied.

Little hydrological information was known about the area, and prediction of the flood flows was sketchy at best. In one case, the model had indicated that the tailwater would just reach the top of the designed cofferdam. As a safety measure, the laboratory recommended that the cofferdam be raised one foot. The following spring, with the cofferdam in place, the site experienced its worst recorded flood and the water reached the top of the dam but did not overflow. Erosion tests were simulated by running the model over extended hours until all erosion had ceased.

Built in the late 1950s, a model of the Niagara intake conduit was probably the longest hydraulic model ever constructed at the laboratory. This 600-foot-long model simulated two 5-mile-long horseshoe-shaped tunnels (see Figure 6) that carried water from the Niagara River under the city of Niagara Falls to a surge canal. A pumped-storage plant, called Tuscarora, was located at one end of the canal and a generating plant, called Lewiston, returned the water to the Niagara River at the other end. The model also contained a section of the Niagara River upstream of Niagara Falls. The model tunnels were built of steel and specially coated on the inside with a smooth ceramic coating. However, the coating was not smooth enough, model-wise, so modifications to the tunnel lengths were made to duplicate tunnel pressure losses.

The $100,000 model investigated the results of sudden closures and startups of the two plants at each end of the canal. Slower startups and closures were also investigated. Capacitor-type elevation gauges were used to measure

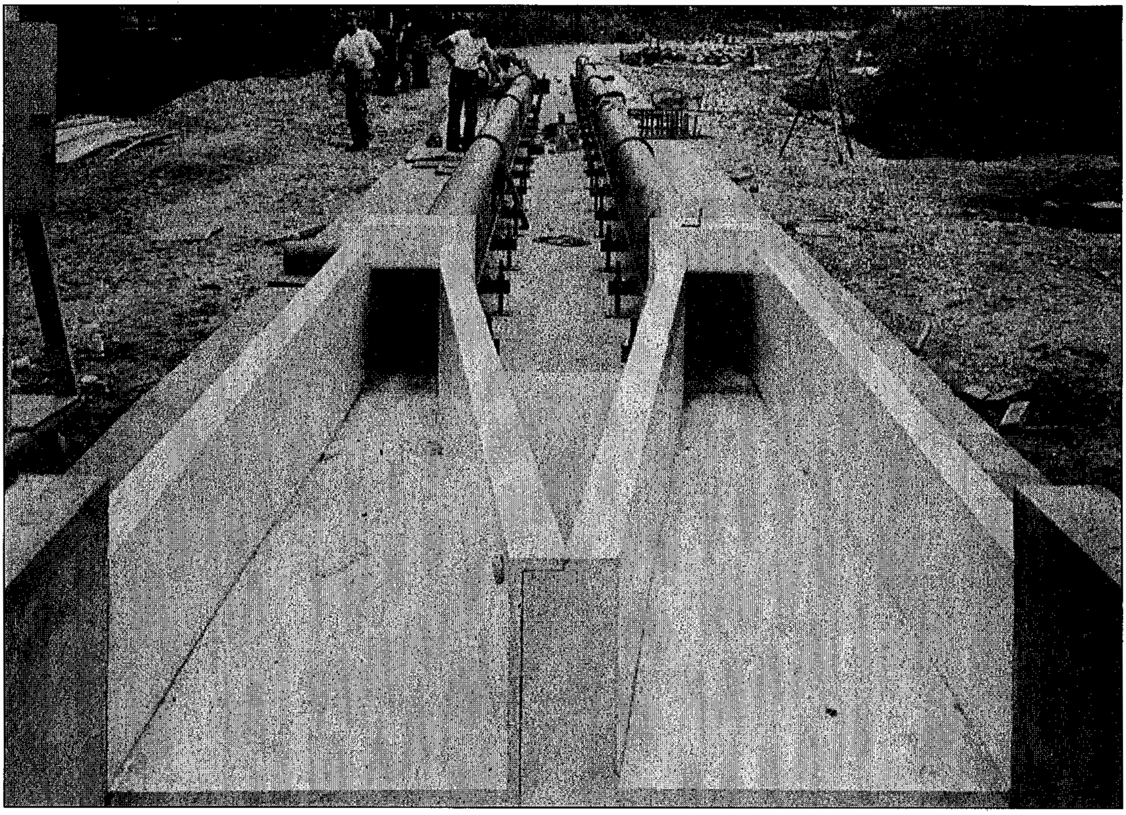

FIGURE 6. Model of the supply tunnels for the Niagara Project.

water surface elevations in the tunnels and at various locations in the canal.

Some models accidentally indicate solutions to problems not anticipated by the designers. The Niagara model unveiled such a potential problem. A visit to view the model operation was planned by Robert Moses, chairman of the New York State Power Authority. When everyone in Moses's entourage was in place, Hooper gave the signal for two graduate students to open the tunnel gates. The gates were opened as quickly as possible, and the water surged into the tunnels. When the water reached the surge canal, it hit the far wall and splashed up in the air directly in front of the visitors in a stunning display. Discussion soon ensued as to the possibility of this happening in the prototype. After the consultants returned to their office, they checked on the gate-opening controls and found that they were set to open too quickly, and re-adjusted them to open more slowly to prevent any splashing (overtopping) in the prototype.

Laboratory Operation

During his early years as director, Leslie J. Hooper appointed Lawrence C. Neale as his assistant. Neale ran the day-to-day operations of the facility and assisted Hooper in the budgeting aspects of the laboratory. Together, they advocated the use of graduate students to help in the model studies. At first, electrical engineering students were hired since the laboratory had no full-time help. Essentially, Professor Hobart Newell, in the Electrical Engineering Department at Worcester Polytechnic Institute, did any designing of instruments, with students doing the construction and testing. As the work in the modeling area increased, more graduate students were hired. A maximum of fourteen graduate students worked at one time at the laboratory in the early 1970s. At that time, the need for quick responses to clients' needs dictated that full-time technicians be hired.

Hooper also set up an advisory committee to keep him abreast of future activities in the areas of importance to the laboratory research. Laboratory expansions in the 1950s were limited to a metal Quonset hut donated by a power company to house its projects. Three years in a row — 1953, 1954 and 1955 — contained significant natural occurrences at the laboratory. In 1953, a large tornado struck a section of Holden near the laboratory, destroying many homes and lives. Immediately after laboratory personnel learned of the incident, they all left the facility with materials and equipment to help locate and extricate people in the area. A flood in 1954 and Hurricane Diane in 1955 filled all the laboratory ponds to overflowing. The laboratory staff opened all the pipes passing through the facility and opened all the gates at the ponds to pass as much of the flood flows as possible. In both years the water rose to the top of the brook passing the laboratory, but through the efforts of the staff no damage occurred to laboratory property.

During his years as Director, Hooper continued Allen's impromptu after work chit-chats in the office discussing some aspects of the laboratory work, technical presentations at some meetings, work being done in other laboratories or the state of the art in some instrumentation that might interest the staff. Since money was short, the staff could not travel to technical meetings, and these chit-chats brought them up to date on developments in the hydraulic area.

During the late 1950s and early 1960s, the laboratory's reputation continued to increase under Hooper's direction. Allen had cultivated interest in the laboratory by many utilities. Hooper continued this trend by visiting utilities and talking to their chief engineers about problems where the laboratory could be of help.

While the laboratory was experiencing its greatest growth, President Harry Storke of Worcester Polytechnic Institute (WPI, the college that founded the laboratory, and with which the laboratory had its teaching affiliation) changed the name of the laboratory from Alden Hydraulic Laboratory to Alden Research Laboratories in 1965. At the time, a new hydraulic laboratory building was being planned, and it was anticipated that all of the WPI laboratories doing consulting type work could be moved to Holden and operate as one facility. (In spite of what appeared a logical approach for the college, it never came to be and only the fluid mechanic aspect of WPI's research remained in Holden. It took twelve years to realize that no one else from the WPI community would move to Holden. In 1977, the laboratory name was slightly changed to Alden Research Laboratory.)

Continued Power Demand Growth

During the 1950s, the electric utilities reevaluated their power needs. The building of new plants during the war years had been on an emergency as-needed basis. Utilities began planning for the 1970s, 1980s and 1990s based on predicted population increases and on power growth having averaged about 7 percent a year during the previous 30 years. At a 7 percent compounded growth rate, generation capacity doubled about every ten years. In the early 1960s, there was concern that there would be possible power shortages in the late 1960s and the 1970s. In hindsight, Table 3 shows that what appeared in the 1950s as an exponential population increase towards the end of the century never materialized. Families actually got smaller, with birth control and other economic/lifestyle adjustments occurring. But the demand for electric power would accelerate over 20 years before slowing. In fact, as the table shows, the 30-year period starting in 1950 saw unprecedented power demand growth with installed capacity increasing by a factor of about 8.

Coal- and oil-fired plants were contemplated in the 1950s. The prices of coal and oil were rising rapidly, and there was concern about the future of the non-renewable fossil fuels. Furthermore, there was a fear of fuel dependency on foreign nations and concern about the pollution of the atmosphere caused by burning these fossil fuels. Considering these arguments and the expected need of large quantities of electric power, the time was ripe to consider electricity produced by nuclear energy. Most of the large hydro sites in the country had been developed, and solar technology was not developed sufficiently to produce the required energy. Therefore, nuclear energy emerged as the most likely source capable of producing the required energy in the future

TABLE 3.
U.S. Population & Power Plant Capacity

Census Year	Population (millions)	Population Increase (% during past decade)	Generation Capacity (megawatts)	Generation Increase (% during past decade)
1940	132.1	7	40,000	
1950	151.3	14	69,000	72
1960	179.3	18	168,000	142
1970	203.3	13	341,000	103
1980	226.5	11	579,000	72
1990	248.7	10	690,000	19
2000			784,000*	13
2010			830,000*	6

*Based on 1.8% annual electricity growth in net summer capacity. Ref. 2.

years and it was viewed as capable of meeting the requirements of being non-polluting and completely controlled by this country.

Nuclear power stations have similarities to coal- and oil-fired steam stations (see Figure 7). These similarities include a turbine-generator that is turned by pressurized steam, a steam condenser, a large circulating/condenser cooling water system and thermal discharge. Major differences include stack releases that continuously occur with the burning of fossil fuels, and the source of energy — the fuel. A nuclear plant requires a nuclear reactor that uses uranium for energy and this reactor is located within the containment building.

The first nuclear power plant in the United States went into service on July 17, 1955. The modicum of power was supplied to the community of Arco, Idaho. The Shippingport Atomic Power Station, set up as an experimental station, generated 60 megawatts. The first atomic energy reactor to produce power for distribution was the $57 million plant in Rowe, Massachusetts, that went on line in November 1960, producing 135 megawatts of power. The 210-megawatt Dresden Nuclear Power Station in Morris, Illinois, came on line at about the same time. Engineering, construction and startup trials were accomplished in about four years. With the successful operation of these small plants, the apparent financial benefits of nuclear power, fuel independence and its perceived environmental benefits (less air pollution), large electricity-producing nuclear plants loomed in the near future. Bigger stations came on line rapidly.

Nuclear Power Growth & Environmental Concerns

During this time, the U.S. Congress was trying to promote peaceful use of nuclear power. Under the Atomic Energy Act of 1946, the Atomic Energy Commission (AEC) was established, placing complete control for further development of nuclear technology under civilian (AEC) rather than military control.[7] Eight years later, President Eisenhower was instrumental in getting the Atomic Energy Act of 1954 passed, which allowed the AEC to license private companies to use nuclear materials and to build and operate nuclear power plants.[8] Although ownership of the fuel was retained by the government, this act, in effect, permitted the establishment of the nuclear power industry in the United States. Private ownership of fuel was given to the reactor owners later with the passages of other laws in 1969, 1971 and 1973. The Federal Energy Reorganization Act of 1974 created the Nuclear Regulatory Commission (NRC) by separating the promotional and regulatory functions of the AEC.

Coupled with the rise of nuclear power production were the environmental concerns that emerged during this period. The Federal Water

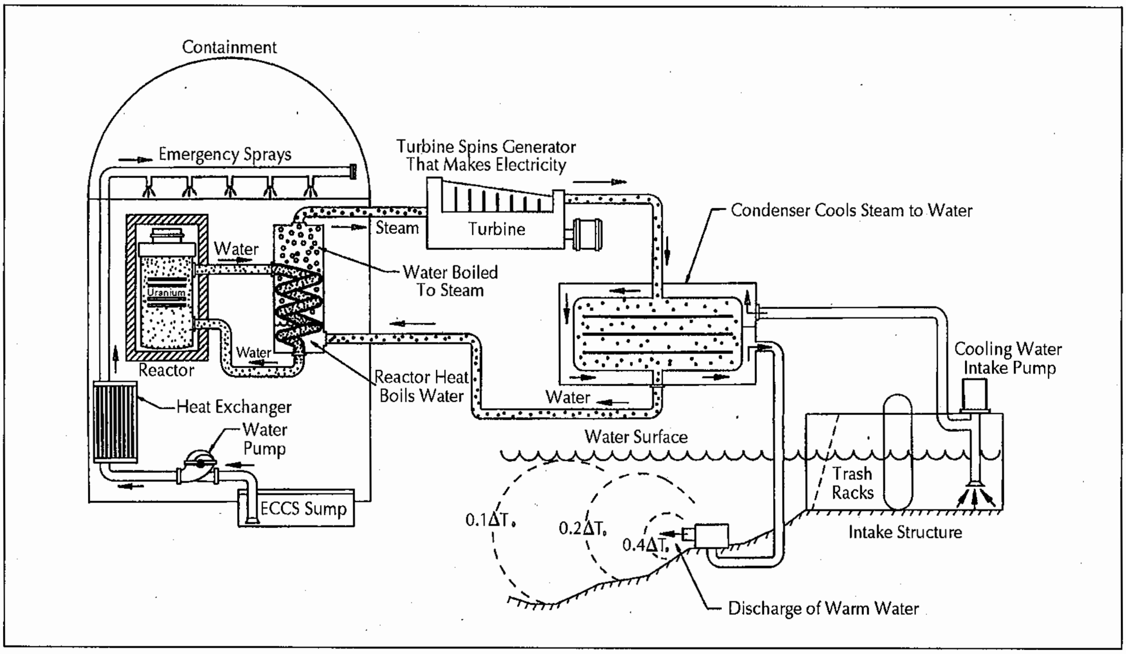

FIGURE 7. Schematic of a pressurized water nuclear power plant.

Pollution Control Act of 1948 and the Clean Air Act of 1955 put the utility industry on notice that power plants could not operate as they had in the past. People and organizations in the United States were demanding action. The environmental group called the Sierra Club blocked the building of the Echo Park Dam in 1956. Rachel Carson's much-read book *Silent Spring* raised environmental concerns that caught the public's attention in 1962.[9] The Vietnam War, from 1961 to 1973, raised much discontent in the late 1960s. An environmental rally in 1970, called Earth Day, received an influx of anti-establishment protesters whose actions later contributed to causing delays and cost escalations in the building of nuclear power plants.

For the electric power industry, two significant changes in the regulatory environment occurred with the Water Quality Act of 1965 and the Clean Air Act of 1967. These acts were implemented just as power plant design and construction were leaping ahead. The National Environmental Policy Act of 1969 required complete hydrologic, biologic and aquatic studies for all proposed projects needing federal licenses.

In 1972, the U.S. Congress enacted amendments to the Federal Water Pollution Control Act that required the use of the best available technology to dissipate the heat produced in power generation. Initially, zero discharge was considered by some to be the national goal, possibly intended to mean evaporative cooling towers having their own drift and fog problems. Entrainment and mortality of organisms and fish in circulating water systems became a concern that affected designs, spurring the investigation of behavioral barriers. (Basically, behavioral devices such as sound and lights are used to direct fish away from the area of concern without physical barriers.)

Waste heat management became a buzzword. Numerous conferences were organized and papers on all aspects of waste heat management were presented due to the enormous amount of on-going construction. In 1977, 350 thousand megawatts of steam-generating capacity were in the design or construction phase, amounting to about 80 percent of the national capacity at that time. Some people were talking about energy "parks" having 5,000 megawatts (4 or 5 large stations) of generating capacity. Field measurements to verify surface temperature predictions also became a substantial activity (see Figure 8). Aerial surveys using infrared technology to measure water

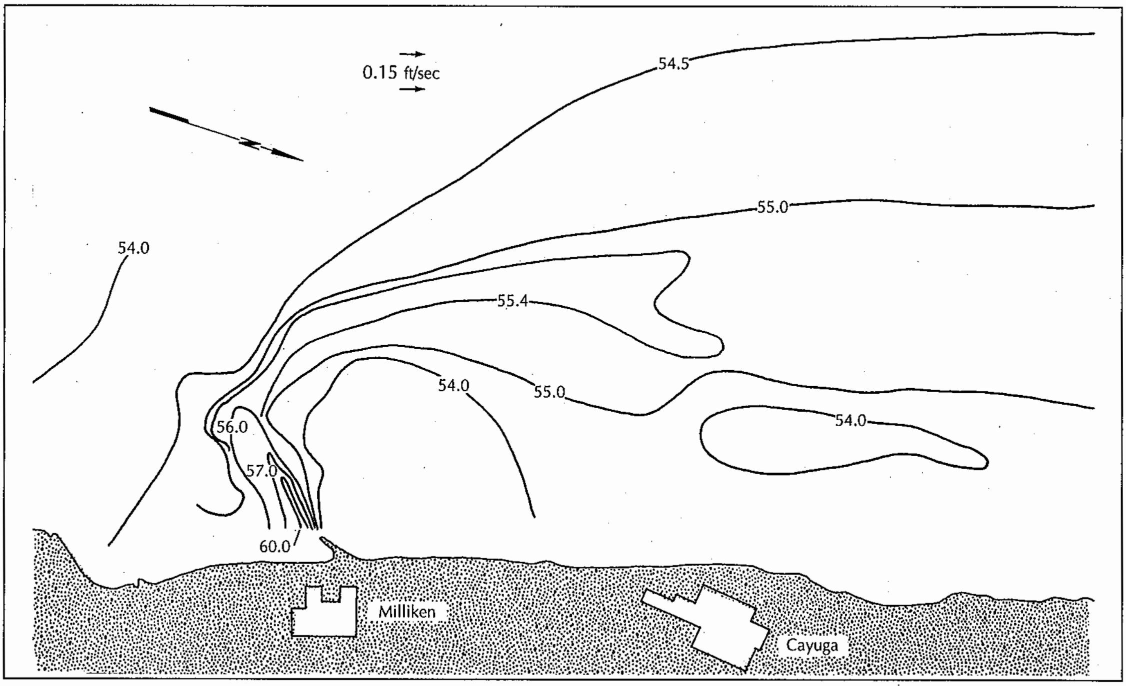

FIGURE 8. Thermal discharge plume at Milliken Station.

surface temperatures, dye dilution studies to evaluate mixing and temperature data acquisition from moving boats were undertaken by many researchers and laboratories, including Alden. Drogues were used to determine overall flow patterns at a site (see Figure 9).

Because of the multitude of experts required for environmental impact studies, engineering firms expanded the hiring of biologists and other scientific specialists. Fish larvae and fish became a concern. Intakes for once-through cooling water systems were modified or enlarged so that some fish could swim away. However, plants wanting to use once-through cooling (still the least costly) were confronting limits on several temperature-flow related fronts.

Large steam electric stations require substantial condenser cooling water flows in order to maximize plant efficiency. The less flow cooling the condenser, the greater the temperature rise (up to the limit set by environmental regulations). The higher the discharge temperature, the greater the mortality of the species that are unable to move away. However, there would be less total larvae entrainment and mortality in the condenser system with the lower flow. All things considered, there may be an optimum temperature rise and flow rate with limits on the maximum discharge temperature and size of the mixing zone.

One aspect of the thermal discharge problem that penalized nuclear power plants was their overall lower plant efficiency compared to steam electric stations using natural gas, oil or coal. A nuclear power station might have an overall thermal efficiency of about 32 percent, compared to 37 or 38 percent for other steam electric plants that can operate at higher temperatures. Also, coal- or oil-fired plants release a significant amount of their waste heat to the air (10 to 15 percent) up their stacks. The combined total effect is that a nuclear plant releases 50 to 60 percent more waste heat in the cooling water per kilowatt generated. The dissipation and dispersion of this heat from a once-through system became a major research and engineering activity at Alden, the Massachusetts Institute of Technology and other places. Cooling ponds to enhance heat dissipation to the atmosphere and diffusers to enhance dilution and other methods were used.

Submerged flow diffusers, used much earlier in sanitary waste disposal, were investi-

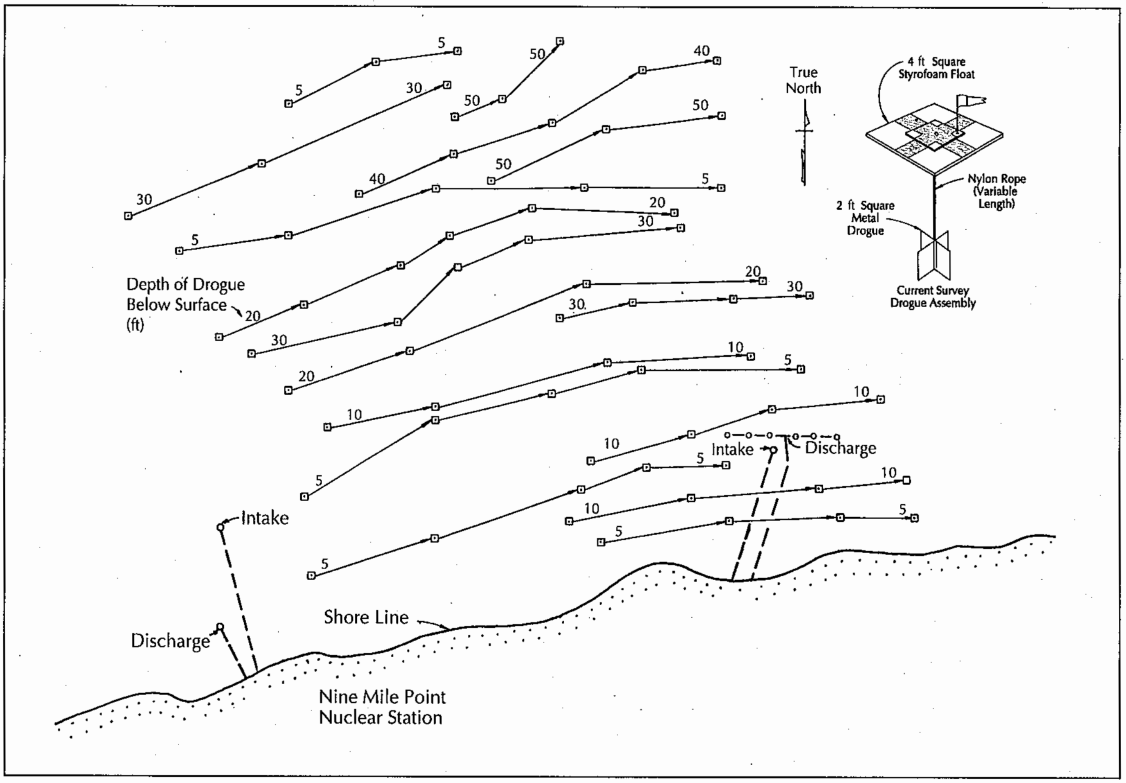

FIGURE 9. Drogue paths near the shore of Lake Ontario.

gated as never before. Some basic work had been done in the past, but each site had circumstances that required physical modeling. Probably the first diffuser to operate at a power station was at the Tennessee Valley Authority's (TVA) Brown's Ferry Station in 1971. There, pipes were half-buried in the Tennessee River so that the plant discharge could mix with available flow. Rapid dilution would result, such as the case where a condenser temperature rise of 35°F was reduced to a peak surface temperature of 3°F.

Another early diffuser was modeled at Alden in 1969 for the James A. FitzPatrick Nuclear Power Station on Lake Ontario. The model included the plant intake, a tee diffuser and sufficient area to measure temperatures outside of the near field mixing zone (see Figure 10). Here, a 31.5°F condenser temperature rise had to meet a 3°F surface temperature limitation outside of a mixing zone. This goal was attained via a discharge tunnel in rock having twelve diffuser nozzles attached.[10] This plant required complete environmental impact studies and field verification of surface temperatures, as did all plants that followed. Regulatory agencies were not just satisfied with results from physical or mathematical model studies, but were also requiring field measurements to substantiate the models.

Thermal Modeling

Not all utilities concurred that nuclear power was the answer to the large power needs of the future. In the early 1960s, a power company contracted with the laboratory to construct models of the mega power projects Chalk Point (see Figure 11 on page 19) and Morgantown. Both of these projects would generate electricity using fossil fuels. Around the same time, other power companies were contemplating nuclear plants at Indian Point on the Hudson River, at Calvert Cliffs on the Chesapeake Bay and at Peach Bottom on the Conowingo Reservoir on the Susquehanna River.

The Chalk Point thermal model in 1962 was a first in many ways, and it served as a major learning experience for the laboratory staff and

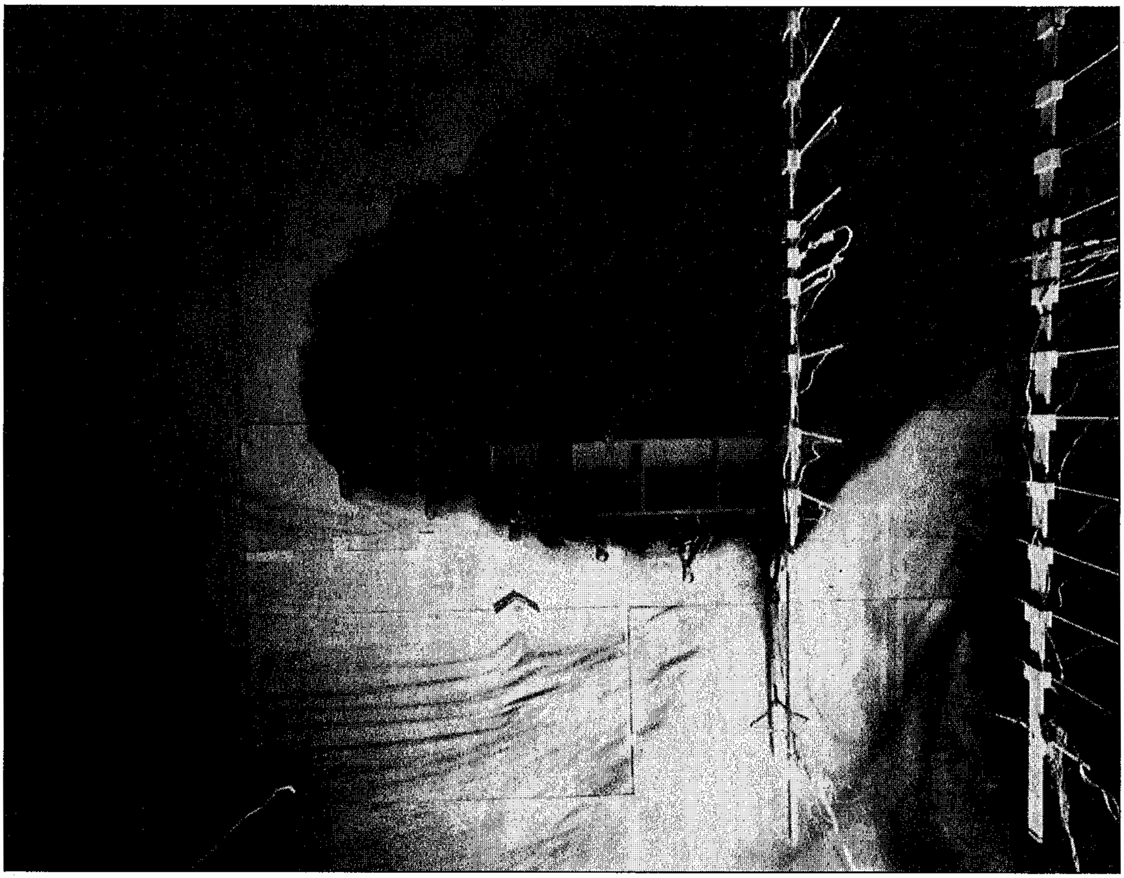

FIGURE 10. Dyed thermal plume from model diffuser for FitzPatrick station (0.7 ft/sec current).

engineers associated with thermal problems. First, the model was built indoors with the intention of minimizing wind and solar effects. This highly distorted, tidal model had two purposes: reduce recirculation of condenser discharge by a suitable arrangement of the inlet and discharge structures; and, investigate the distribution of warm water in a section of the river downstream where oyster beds constituted an important industry. This model reproduced approximately 14,000 feet of the Patuxent River at a 1:300 horizontal scale. As far as it is known, Chalk Point was the first thermal model to ever attempt to predict surface temperature patterns over such a wide area. A 24-point strip chart recorder logged the temperatures measured by thermocouples. (Later models would use 10 or 20 times the number of temperature sensors.) Control of the atmospheric temperatures within the building was rudimentary, but attempted, and the entire concept of using a distorted model to simultaneously predict mixing and surface temperature patterns would be found lacking in the 1970s.

From this initial substantial effort, and as more and more was learned about this type of modeling, the laboratory gained a national reputation in this specialization. The laboratory would have a major impact on many of the proposed major steam electric plants and numerous developments in modeling would occur. As in earlier and in later times, the ability to take on large projects, and change with the times, resulted in the opening of whole new areas of work.

All of these power projects were faced with rapidly evolving environmental laws that were promulgated by the Water Quality Act. Each state had its own requirements for thermal discharges or, as it was sometimes called, pollu-

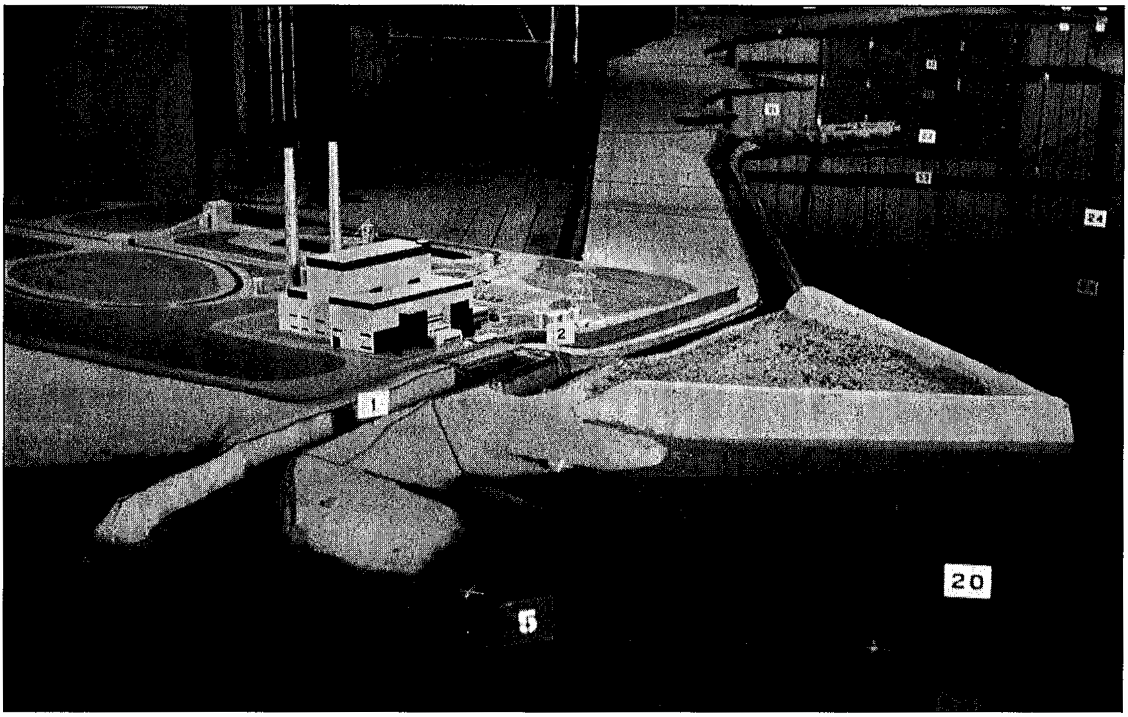

FIGURE 11. Chalk Point thermal discharge model.

tion. Mixing zones, stratification and maximum allowable temperatures became common terminology. Entrainment of organisms, fish and many other environmental issues had to be considered in site selection. Project delays and greatly expanded engineering studies, coupled with high general annual inflation of up to 14 percent for several years in the mid 1970s, caused plant costs to dramatically increase. Elimination of once-through cooling and the installation of cooling towers at some plants caused retrofitting problems as well as further increased costs that were passed along to the customer. Cooling towers had their own special environmental studies. With all of these factors coming together, and numerical/analytical thermal modeling in its infancy, numerous utilities wanted very large-sized thermal models to predict the temperature impact on the receiving body of water. These studies were required for a discharge permit and plant operation. In most states, until a plant became operational, the engineering and construction costs could not be passed on to the consumer.

The laboratory faced a dilemma when models of mega projects were contracted to be built almost simultaneously. Models having a large area had been constructed before, but many of these proposed models were so large that they filled an entire building. For reasons concerning continuous testing, scaling criteria, wind effects and similitude, the models had to be constructed indoors. Up to this time Alden had designed and built all models using laboratory personnel. In fact, with the exception of the Director and his secretary, nobody was exempt from any and all jobs needed to be performed at the laboratory. A shortage of personnel made this approach impossible. The solution was obtained by hiring an outside construction company to erect new light industrial buildings and to house the models.

Due to Allen's foresight in acquiring a very large piece of property, the laboratory was somewhat unique in having the space to ultimately add nine major buildings for thermal models. Most of the thermal model buildings were 90 feet wide and varied in length up to 270 feet (for the Peach Bottom model). Other buildings were also expanded during this period. The laboratory hired engineering personnel to design the models, obtain the data for the topography templates, design the required structures and supervise the model construction. In the mid-1960s, staff at the laboratory substantially increased in number and areas of expertise. Previously, two or three engineers assisted the Director and Assistant Director in all phases of teaching and client research. By the end of the 1960s, a greatly expanded engineering, technical support and construction/crafts group existed.

Thermal modeling was in its infancy and not much was known about its similitude aspects. There were two major areas of concern. The first was the mixing and the temperature rises that occurred near the station discharge, called the *near field*. The second was the *far field*, where surface heat transfer to the atmosphere and dispersion were of interest. For many early models, near-field and far-field temperature patterns were predicted by physical models. Hooper and Neale had researched the problem and concluded to build distorted models — that is, these thermal models had a vertical scale that was different than the horizontal scale. Research indicated that distortions of greater than 10:1 might lead to problems and should not be used. It was also felt that since the atmospheric conditions within the model building were the same, or more severe due to a lack of wind, the model would produce reasonable and conservative results. By about 1969, it was determined that near-field mixing had to be determined in undistorted models. Temperatures that were influenced by far-field phenomena were best determined with analytical models. Surface temperatures near the mixing zone, near and intermediate field, were determined in physical models. Some distorted models had calibrated temperature patterns at the plant discharge so that overall temperatures could be evaluated.

Due to the size of the models and the fact that some models simulated time-varying field conditions (currents), it was impossible to use hand techniques to measure the temperatures. Data were acquired using thermocouples attached to 24-point recorders that printed on continuous rolls of paper. Ten such recorders were employed on some models, and each recorder printed a temperature every 2 seconds. Needless to say, tons of paper evolved from all the tests. Not being able to process all the information with the existing staff, Hooper hired twelve local women to transcribe data from the recorder rolls to plots of the project area. Isotherms were then plotted by the engineers in charge of the project. The staff size at this time (mid-1970s) was the largest during the laboratory's entire history, reaching approximately 85 people.

There were some interesting developments in the first thermal model tested. Strange thermal data began appearing at various intervals. A variety of explanations were broached but none were satisfactory. Hooper and Neale met with Professor Newell regarding the problem. They finally concluded that erroneous results were coming from the thermocouples acting as a large antenna and picking up electrical signals from a nearby commercial radio station. Electrical but non-thermal shielding was provided on the thermocouple tips to remedy the situation. Furthermore, because the studies were trying to measure small temperature differences, a reference temperature for the thermocouples had to be more stable than was being furnished by the recorders. Specialized spark welding techniques combined with probe insulation produced probes without temperature drift. Once these two problems were solved, data acquisition proceeded as planned. While now taken for granted, the development of fast-responding, stable (characteristics not changing with time) and accurate thermocouples constituted major achievements in thermal discharge modeling.

Model Computerization

The Morgantown model was built in 1965 and tested in 1966. It used six recorders with 144 thermocouples that simulated about 14 miles (1:400 horizonal sale) of the Potomac River. When the Peach Bottom Project's owner terminated that study, recorders were moved to the Morgantown model. A few months later, after data acquisition had begun on the Morgantown model, the Peach Bottom model had to be reopened for a few months to obtain information requested by the regulatory agencies. At this point a crisis existed because all recorders owned by the laboratory were being utilized.

Two solutions existed. The simplest seemed to buy ten more recorders at a total cost of $20,000. The other solution was to embrace the fledging computer industry and acquire a computer. The decision was not easy. Problems of interfacing and programming loomed large. The software and hardware to do this job did not exist. Many meetings were held, and finally a graduate student, Russ Vickery, convinced Hooper and Neale that he had sufficient knowledge and ability to make the system work. A mini-computer was purchased for the same price as it would have cost to buy the recorders.

Computerization of thermal models was a continuously evolving process as the technology for computers and instrumentation changed. Initially, the 24-point strip chart recorders simply recorded the signal from the temperature transducer (usually thermocouples but sometimes thermistors). Later, signals were amplified by the strip chart system for an on-site data logger that stored data on magnetic tape. The tape was processed by computer, programmable calculator or taken to WPI's computer facilities where the data were reduced onto final plots. The long process of hand transcribing data was eliminated.

Another advantage of the computer was the ability to obtain more model temperature data by increasing the number of thermocouples (measuring points) without increasing the data acquisition hardware. Once stored, the data could be quickly analyzed and evaluated, as well as easily averaged to obtain representative values. Final isothermal plots that had taken weeks to obtain were now available in a few days. Decisions to re-run tests or to augment test data for completed tests could be made more quickly.

The only major drawback to these initial computerization efforts was that programming in those days required keypunching a card for each command and debugging this "software" was a long and tedious process.

Alden had entered into the computer age somewhat by chance, but the benefits opened the eyes of the administrators, who saw the value of this type of data acquisition. In later years, better computers were acquired and plotting capabilities became available on site. With such equipment and flexibility it was possible, starting in the 1970s, to run a test in the model and, in a few minutes after completion of the test, to walk up to the main laboratory building and obtain a preliminary copy of the isotherms plotted on a site plan. Two to three hundred probes continuously measured surface temperatures while others recorded temperature profiles. Ambient air conditions, sump temperatures and other conditions were monitored by an operator in a computer room. All of the probes could be scanned in 30 seconds or less, and the accuracy of the measurement and conversion process was ±0.1°F.

Velocity Measurements

Calibration (adjustment) of these large models required velocity measurements in the field. These measurements were then checked against the model. Velocity measurements were difficult to obtain in the models because the water moved through them slowly. For some models, propeller-type current meters were employed. In some cases, these meters were designed and fabricated by Professor Newell, who also designed thermistor-type velocity probes. These probes usually had problems with temperature compensation, and a considerable amount of time was spent trying to solve the problem. Newell was successful on some models. The principle method of velocity measurement was a time-lapse photographic method that utilized birthday candles mounted on small floats moved by the model currents. Sometimes the floats had a drag cruciform mounted at some distance below the float to obtain velocities at a required depth. A camera would be mounted above the model in a darkened room, and a black paddle would be rotated at constant speed in front of the camera. The camera shutter would be opened, and a time exposure would be made of the candles. Using a reference length on the model and knowing the speed of the motor allowed the interrupted streaks on the photograph to be measured and referenced to model velocity.

The time-lapse photographic method was later refined. The birthday candles were sometimes replaced by small light bulbs. In the late 1980s, data were acquired by a digital image-processing tracking system. In this technique, a video camera with a wide-angle lens was

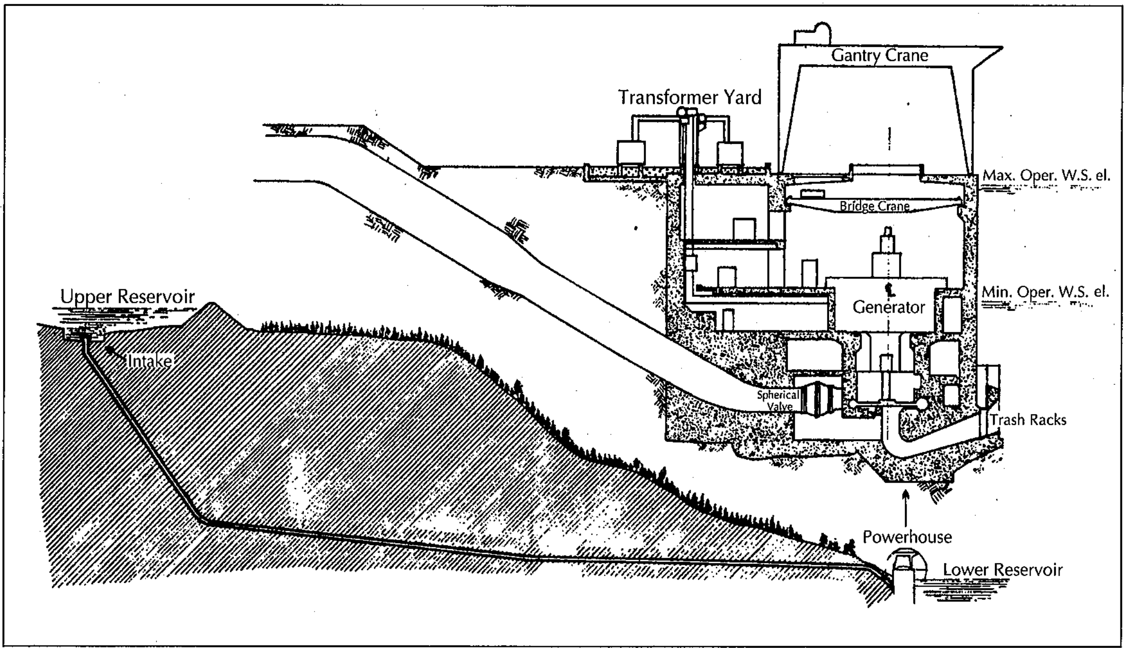

FIGURE 12. A typical pumped storage plant layout.

mounted approximately 15 feet above the model. Initially, a digital background image was taken of the model that included two known locations to be used in scaling the photograph. Candles were then placed in the model, and the video camera would take digitized images over time. These images were transmitted to the computer where the velocity and direction information was processed. The computer also compensated for lens distortion. The computer was interfaced with a CAD system and the velocity vectors were plotted on a map of the area surveyed. Thus, this system gave finished drawings within minutes of running the test.

Similar studies were conducted for a number of power utility companies. A study of a nuclear power plant at Lake Norman, North Carolina, included (besides the thermal study) a study of the time taken for nuclear material to travel to various parts of the reservoir in case of an accidental release. The study was accomplished using rhodomine WT as a tracer and a fluorometer to measure the time for the material to arrive at different locations.

Pumped-Storage Plant Testing

Most of the steam electric plants studied had capacities of approximately 1,000 megawatts or larger. Putting plants this size on line, whether they are fossil- or nuclear-fueled, can present operational problems since these plants cannot easily operate with large power swings and cannot shut down and start up within a short time frame. One of the solutions to this problem is to incorporate a pumped-storage hydroelectric power station. The pumped-storage plant acts as a "storage battery," and the project usually includes an upper and lower reservoir (the term reservoir being used loosely) connected by a penstock in which a machine that acts as a pump or a turbine is located, depending on its direction of rotation (see Figure 12).

The object of the plant is to generate power during high power requirement periods by having stored water flow from the upper reservoir to the lower reservoir. Conversely, during times of low power demand when fossil-fuel plants are producing excess power, water would be pumped from the lower reservoir to refill the upper reservoir. The pumping-generating cycle can be designed to operate on a daily, weekly, monthly or yearly basis. In practice, the pumped-storage plants are run to maximize the efficiency of the power system regardless of the plant's design cycle. In some cases, the reservoir's level can vary 50 to 100 feet, causing design problems not normally encountered in run-of-the-river hydro plants.

Besides meeting peak power demands, these hydroelectric plants provide a rapid startup reserve capacity in the event that an operating unit elsewhere in the system shuts down. Also, they have the ability to start up in a so-called "black start" condition. This condition occurs when there has been a major blackout (such as the one that occurred in the fall of 1965 in the Northeast).

Pumped-storage projects are not new but date back to 1892 in Europe. This country's first pumped-storage facility was the 22 megawatt Rocky River Plant on the Housatonic River in Connecticut in 1927. It has been in continuous operation and has one 33,000-horsepower Francis turbine directly connected to a synchronous generator and two separate 8,100-horsepower centrifugal pumps, each connected to their individual motors. Starting in the 1950s, and especially in the 1960s and 1970s, 35 pumped-storage plants were built in the United States with a total generating capacity of 18,000 megawatts. The laboratory performed numerous model studies on these projects. In fact, of the 15 largest operating pumped-storage projects in the country (with a generating capacity of 14,035 megawatts), Alden conducted various studies on two-thirds of them.

Most of the pumped-storage studies initially involved the upper reservoir and the potential, as the level dropped, for vortex formation at the intake that could cause air ingestion, surging and vibration of the pump-turbine. Other potential problems associated with severe vortexing were decreased efficiency of the machine and reduced available head.

Testing at Alden of pump storage intakes for vortex activity began ironically (because it was never built) with the Cornwall Plant on the Hudson River in about 1962. The design engineers sponsored a very involved study where numerous different types of intakes and anti-vortex devices were evaluated. Much experience was gained, and a modest effort was even made to evaluate scale effects on vortex formation. Prior to this model, the laboratory had been involved with various hydro intakes in the 1950s, and earlier hydro work where reservoir levels remained fairly constant. So it was only natural that major design firms would bring their hydraulic concerns to Alden. As in other areas, model testing techniques developed as more experience was gained.

The Cornwall and Cabin Creek (Colorado) models were built indoors in tanks at relatively small scales — 1:74 and 1:100, respectively. The Cornwall model was primarily concerned with vortices, while for Cabin Creek, at over 11,100 feet elevation, most interest was in ice being sucked into the intake. There was concern with flow patterns in close proximity to the intake, and vortex activity was noted during the first test. Slabs of ice (paraffin in the model) were drawn to the racks at minimum operating levels.

Some of the pump-storage models were built indoors and others outdoors. As larger buildings became available, the trend was to go indoors to get away from wind and weather. As time went by, the significance of model settling time, wind-induced currents, surface tension and other factors became more clear. A large indoor model was built for the Jocassee Project (on the Keowee River in South Carolina), and velocities at the rack were a major concern because of potential trash rack failure (see Figure 13).

Overall and transient flow patterns that develop in reservoirs with large drawdowns became more of a concern, particularly when an intake was well out in the reservoir and not at the end of a channel. For the Kinzua Project (on the Allegheny River in Pennsylvania) in 1966, the entire reservoir and intake were simulated in an outdoor basin. Test records indicated that possibly for the first time an attempt was made to classify vortices in terms of type or strength — *i.e.*, air withdrawn, sticks or leaves "sucked in," or ice pulled in. Testing was conducted with ice on the model. Previously, vortices were described in terms of dimple, air drawing or other general terms. By 1968, when a covered intake was developed for Blenheim Gilboa (on Schoharie Creek in New York), a #1 to #5 vortex strength (type) scale had been developed and this scale was modified a few years later to include a dye core vortex. The resulting Alden #1 to #6 vortex scale has been generally accepted by hydraulic engineers and

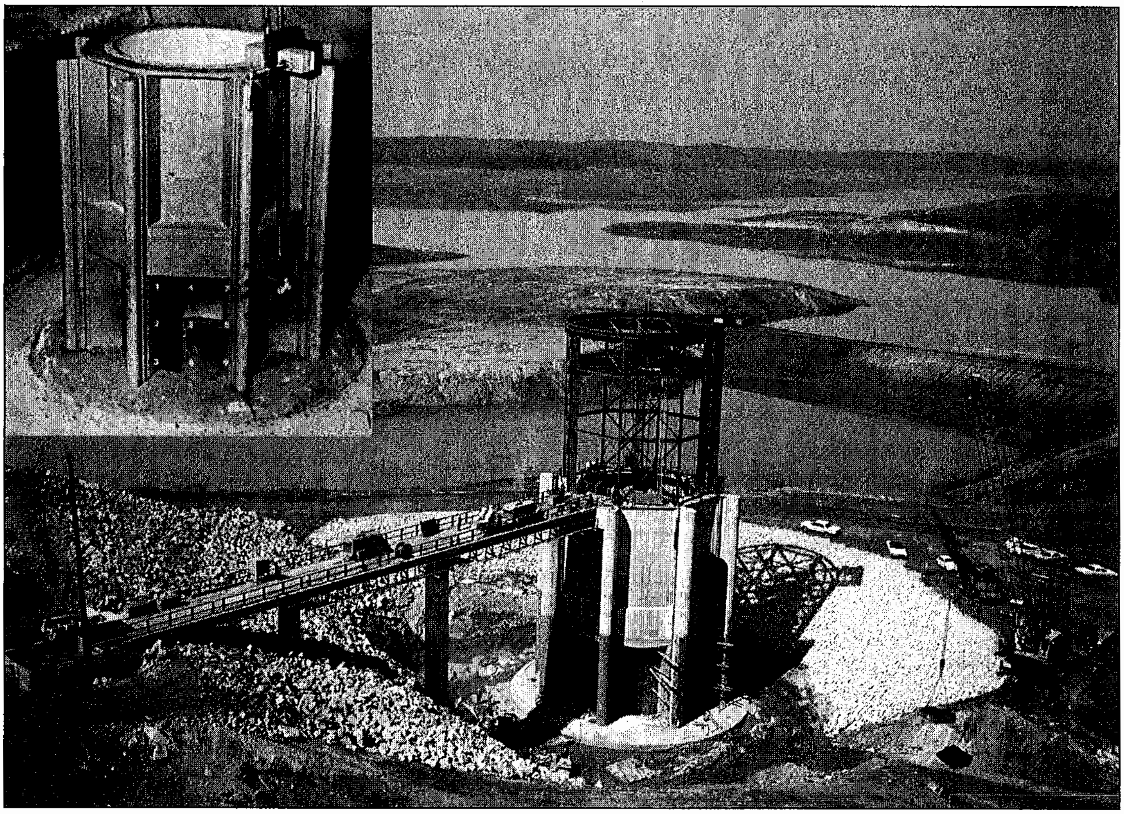

FIGURE 13. Jocassee/Keowee prototype intake, with model (inset).

is included in the newest (1998) standard on pump intake design issued by the Hydraulic Institute (see Figure 14).[11] Now, it is also normal practice to model as much of the reservoir as is practical to obtain overall flow patterns, and model the intake operation continuously during drawdown. If necessary, flow patterns are forced at the model's boundary based on a large-scale overall model. (The Cornwall Project was retested in 1973 with the entire reservoir modeled.)

Alden was the first to identify (classify) the different types of vortices with a numbering system. Later, in order to better compare designs, vortex type was augmented by the length of time the particular vortex persisted in an attempt to indicate the potential seriousness of any problem. Finally, instrumentation sensitive to rotating flow was developed (see Figure 15). A straight-vaned propeller meter (now called a swirl meter) was installed in the model penstock. Electrical pickups would send signals to a meter recording the number of revolutions the meter turned. The first models recorded only revolutions. Later, a timing mechanism was added and total revolutions or revolutions per time period could be obtained. When it was found that the direction of rotation of the vortex can change, even during a short period of time, the pickup was redesigned to indicate the number of clockwise and counterclockwise rotations. From the swirl meter, the swirl angle of the flow (an indicator of the strength of flow rotation) was determined.

With numerous studies being done for pump intakes for large steam electric stations, this same surface vortex classification was used to describe vortices entering pump bellmouths. Later, a submerged vortex-type scale was developed. The evaluation of vortices at intakes has been an on-going Alden activity that has led to numerous publications and the advancement of hydraulic knowledge. Bear Swamp (on the Deerfield River in Massachusetts), one of the early pump storage intakes evaluated by the laboratory in 1973, has

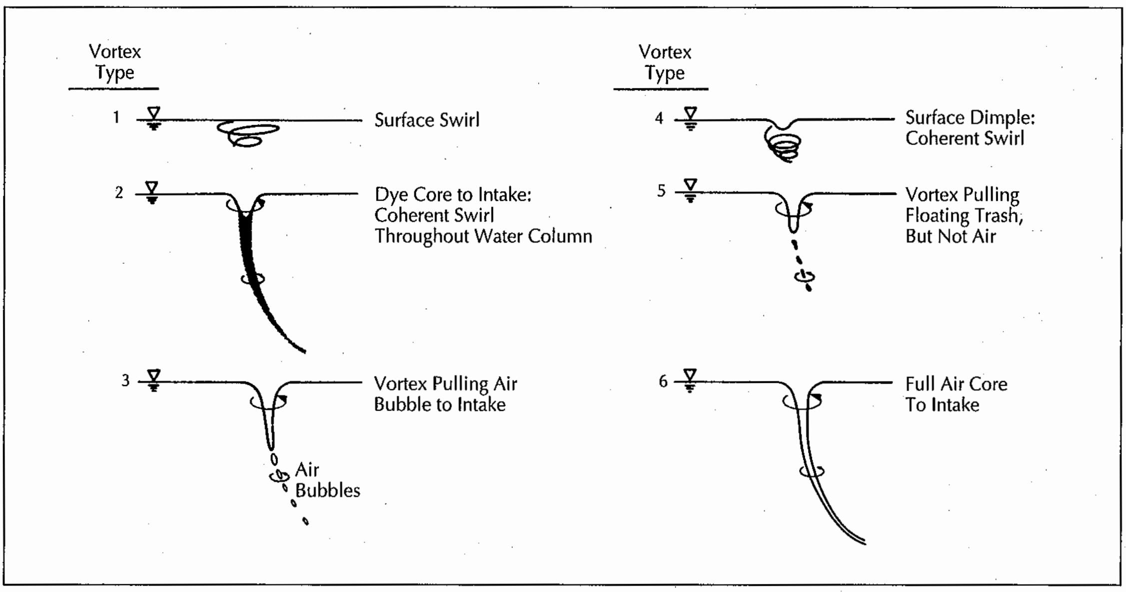

FIGURE 14. Vortex intensity scale developed by Alden in the early 1970s.

had prototype-to-model vortex comparisons.[12] Many model studies became involved with trash rack issues.

In the case of the Smith Mountain Project (on the Roanoke River in Virginia), an interesting story evolved not from the intake model (which came after the project was operational) but from the field. Shortly after the plant had gone on line in 1965, divers were sent down to investigate the upstream part of the arch dam. At some point when the divers were near the intake, they were told to check the trash racks. "What trash racks?" came the reply. "We're standing inside the intake pipe." The trash racks were ultimately found at the bottom of the reservoir looking like someone had cut them off with a torch. An investigation found that the structure had been designed to operate as an intake without considering velocity patterns when pumping. During the pumping mode, intake model tests showed that a high-velocity jet went through the trash rack with resulting severe vibrations and trash rack failure. Upon investigation, other plants had similar problems and failures. Ultimately, there was considerable effort by designers of trash racks to minimize flow-induced vibration problems. Such a discovery increased the number of studies at Alden, where plexiglass model structures were evaluated with flows in both directions. The outcome on several projects was to use gradually tapered structures that facilitated a more uniform flow distribution during the pumping mode. For some plants, racks were omitted.

Another interesting aspect of the Smith Mountain study was an apparently successful attempt to confirm model velocity test results in the field. Based on model velocities, the racks

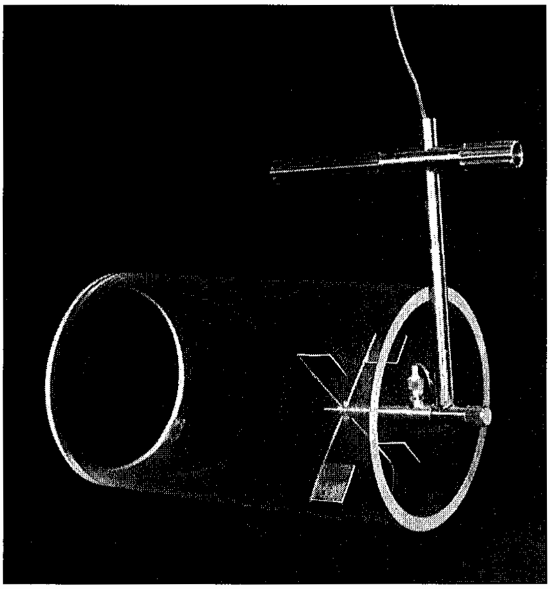

FIGURE 15. A swirl meter.

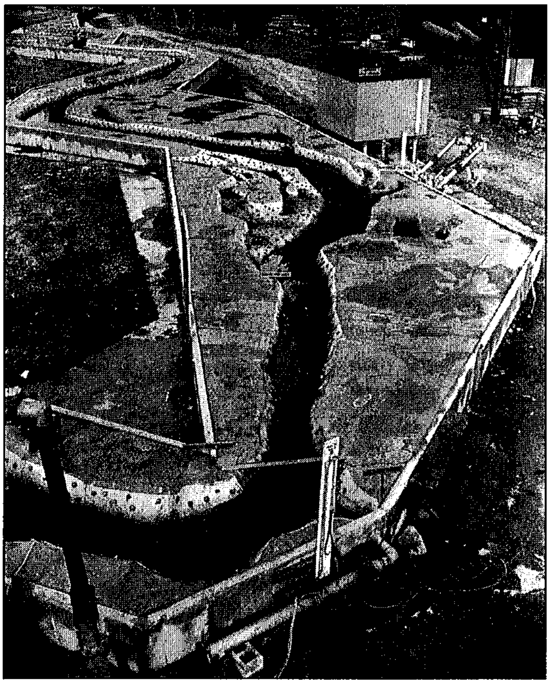

FIGURE 16. Outdoor model of the lower reservoir for the Northfield Mountain Pumped-Storage Project.

were redesigned. Bars on the prototype rack were instrumented with 13 yaw (two-dimensional) velocity probes — six for measurements during pumping and seven for generating. Strain gauges were also installed to measure torsional and bending stresses. This instrumentation was installed on racks 150 feet below the reservoir surface. Since the pressure at the holes on the probe is a function of velocity magnitude and direction, the probes had to be calibrated before being installed. This calibration was done in a 24-inch test section. A portion of the rack was installed with a probe and the angle of the rack could be varied (equivalent to changing velocity direction) and calibration curves were developed for the field measurements. Under very difficult field conditions, the prototype measurements verified the jet effect in the pumping mode.

For some pumped-storage stations, there was concern with vortex formation at the lower reservoir in the pumping mode. For other studies, there were concerns about mixing, stratification, scour and turbidity in either the upper or lower reservoir.

The Parr Hydro Project was different in that it involved the V.C. Summer Nuclear Station, located on the relatively constant level upper reservoir of the Fairfield Pumped-Storage Plant (on Frees Creek in South Carolina), and a hydro station at the downstream end of the lower reservoir. A thermal study combined the operation of the nuclear station as well as the operation of the pump-storage facility. For this project, the major concern was the thermal discharge by the pump-storage plant when it generated and discharged heat from the upper reservoir to the lower reservoir. A detailed model of the pump-storage intake structures was conducted to minimize mixing and reduce velocities at the trash racks in the pumping mode.

Another interesting study was for a pumped-storage project called Prattsville, which was to utilize the existing Schoharie Reservoir (in New York) as its lower reservoir. The purpose of the study was to evaluate Prattsville's pumping and generating cycles on the natural temperature stratification and turbidity of Schoharie Reservoir. The mixing data from the model study were also used in an analytical study to predict the final temperature stratification in the reservoir due to solar input and meteorology.

At the western end of the reservoir, water is withdrawn through the Shandaken Tunnel to Esopus Creek and utilized to supply drinking water for New York City. A maximum of 650 million gallons per day flows through the tunnel. Since the reservoir is highly stratified in the summer and cooler waters are required for the tunnel to satisfy environmental concerns in Esopus Creek, it was desired to minimize temperature mixing in the reservoir during the generation phase of the pumped-storage plant. Increasing the turbidity during the same phase was also to be minimized.

Since it was not possible to model the silt at the bottom of the reservoir, it was decided to obtain velocities in many different parts of the model reservoir and use this information in the analytical model. The velocities were obtained by three methods: using an electromagnet current meter, photographically documenting the movement and manually timing floats over a known distance.

The system used to create the thermal stratification in the model consisted of a series of

TABLE 4.
Cost of Power & Inflation

Year	Consumer Price Index (1982-1984 = 100*)	Annual Average Change in Consumer Price Index (previous 5 years)	National Average Residential Price of Electricity— Current Dollars (cents/kWh)	National Average Residential Price of Electricity— 1987 Dollars (cents/kWh)
1960			2.5	
1970	38.8	4.6	2.1	6.3
1975	53.8	7.8	3.5	7.1
1980	82.4	10.6	5.4	7.5
1985	107.6	6.1	7.4	7.4
1990	130.7	4.2	7.8	6.9
1991	136.2	4.2**	8.1	6.9
1993	144.5	3.0***		

*Annual averages of monthly figures. **Change since 1990. ***Average for 1992 & 1993. Ref. 2.

4-inch PVC pipe with 0.125-inch holes spaced 3 inches apart. The pipes went around the periphery of the model near the maximum elevation waterline. For a thermal test, the sump water was mixed to obtain constant temperature. This water was pumped into the model to a level below that required for the test and allowed to settle to eliminate any movements. Water heated to the desired temperature was then dribbled into the model from the holes at the bottom of the PVC pipe. Due to buoyancy, the heated water spread over the entire model and created the desired stratification. One of the results of these tests showed no significant breakdown of the stratification during the pumping mode. Conversely, there was some mixing during the generating mode.

Not all pumped-storage studies were limited to vortex problems. In the case of the Northfield Mountain Project on the Connecticut River in Massachusetts, a complete distorted scale model (see Figure 16) of the lower reservoir was built to study steady-state and transient movement of the flow in the river during both the pumping and generating phases of the operation. This river model was adjusted and calibrated based on extensive field tests. Ultimately, a computerized/analytical model was developed that included plant operation for that section of the river. For the late 1960s, it was a notable accomplishment, reflecting the rapid growth in mathematical modeling. A physical model was built to study the bifurcation in the piping system located in the penstock inside the mountain. A third physical model on this project examined the performance of the surge tank. This information was input to the analytical model of turbine operation. Another physical model on the same project studied the operation of bascule gates. And, finally, since the upper reservoir was to be constructed with an intake that could some day provide water from the upper reservoir at Northfield to Boston's Quabbin Reservoir, a model of a section of Quabbin Reservoir was built. This model studied the retention of the water in a dammed section of the reservoir for purification purposes. (The water supply tunnel has never been built due to various unresolved jurisdicational and environmental issues. Furthermore, with Boston conserving more water, the need does not exist yet.)

Mega Plant Slowdown

The age of building mega power plants lasted more than two decades. During that period a number of things occurred that brought to a halt the frenzied rush to build large electric generating facilities. The oil embargo of 1973 and 1974 dramatically raised the price of crude

TABLE 5.
U.S. Nuclear Power Growth

Year	Operating Reactors	Nuclear Reactors Planned	Net Summer Capacity of Reactors (1,000 megawatts)	Average Capacity Factor of Nuclear Plants	Portion of Total Electric Generation (%)
1965	6		0.8		0.3
1970	18		7.0		1.4
1973	42	116			
1975	54	111	37.3	55.9	9.0
1976		101			
1977		74			
1980	70	11	51.8	56.3	11.0
1981		11			
1985	95		79.4	58.0	15.5
1990	111		99.6	66.0	20.5
1991	111		99.7	70.2	21.7
1993	109				21.2

Ref. 2

oil for power stations. This increase propelled nuclear proponents to advocate building nuclear power plants due to the nuclear cost advantage over fossil fuels, in addition to the independence from foreign oil. It was predicted that imported oil would eventually cost $100 per barrel. (As of this writing, it is about $15 to $20 per barrel, and gasoline today is cheaper, after inflation, than in the early 1960s.) At the time of the embargo, many power stations were in the process of converting to oil as a buffer against the scarcity of natural gas brought about by federal regulation.

Some mega plants, especially the nuclear plants, began to experience significant problems so that electric utilities were financially threatened and some went bankrupt. One problem was the perceived threat of thermal pollution. By 1973, it was estimated that 50 percent of the United States' fresh water supply was being used for cooling purposes. Opposition to nuclear plant construction, new regulations and extensive environmental studies caused significant delays in building, resulting in huge cost increases due to the high interest rates and inflation of the time (see Table 4 on page 27), particularly from the early 1970s into the mid-1980s.

In the late 1960s and early 1970s, a nuclear power station could be constructed in six to seven years. Construction and licensing time would eventually double, and some plants would never go on line or their fuel would be switched. In the late 1960s, capital cost for a nuclear plant ranged between $90 to $200 per kilowatt. Now, the cost of a 500-megawatt gas-fired plant costs about $700 per kilowatt, and an 850-megawatt oil-fired plant can cost more than one billion dollars, if it were to be built. Because of the reduced power demand and great financial risk, smaller stations, often gas turbines, are now being built.

As Table 4 shows, residential power cost in the early 1970s was about the same as it had been in the 1950s and 1960s, actually in a declining trend. In absolute terms, the cost per kilowatt hour quadrupled over 20 years, keeping pace with inflation.

Accidents further reduced the public's confidence in nuclear power. In 1975, a fire occurred at the Tennessee Valley Authority's Brown's Ferry Nuclear Plant. Four years later, a loss-of-coolant accident at the Three Mile Island Plant in Pennsylvania further eroded public confidence. The final blow to the nuclear industry came in 1986 when the Soviet Union's accident at Chernobyl (Ukraine) released tons of nuclear waste to the atmosphere. These wastes were carried by the wind throughout the world. By the end of 1982, the electric utilities had shut down nuclear projects with expenditures reaching $15 billion. It was also in 1982 that the U.S. unemployment rate would reach 10.8 percent, the highest since 1940. A year later the worst bond default in the history of the country occurred in Washington State when a nuclear consortium failed to meet its financial obligations. Table 5 illustrates the growth and demise of the nuclear industry in the 1970s and 1980s. From 18 operating reactors in 1970 to a peak of 111 in 1990, the large contribution of nuclear power to total electric generation represented a major saving in all other fuels. At the present time, about 21 percent of all electric generation is nuclear-fueled. However, the problem of storing and processing radioactive waste still remains unsolved.

Issues such as conservation, the closing of energy intensive industries, reduced need of power, national recession and the cost of meeting environmental regulations placed mega plants on hold. A final blow was that state regulatory boards would not automatically agree to rate reimbursement. Every effort will be made to extend the life of these large plants. Nuclear plants are licensed for 40 years, and some effort will be made to extend their life. The large pump-storage plants and the hydro plants that were upgraded may be operating 100 years from now.

Flow Measurement

Since its inception, Alden has had strong ties to flow measurement. This commitment to accurately measure large flows was demonstrated by the installation of a Venturi meter, a 50,000-pound weigh tank and numerous large weirs in the original laboratory in 1894 and thereafter. This equipment had served the laboratory well over the years up until World War II. After the war, as power plants became larger, flow meters to measure steam and water also became bigger in diameter with increased Reynolds number (the ratio of inertial forces to viscous forces). It soon became evident that gravity-supplied test lines from a pond would not meet the future flow calibration needs of the laboratory and its clients. The two biggest drawbacks of the original system were lack of pressure and lack of consistency in water temperature throughout the year. Because of the large sums of money involved with various aspects of flow measurement, it is desirable to have a total accuracy of ±0.5 percent or better.

In the first fifty years of operation, flow meter calibrations were not a significant source of work or income at Alden, but the connection to the flow meter industry was important. Infrequent calibrations were made on flow meters for utilities. As early as 1926, the laboratory was calibrating Venturi meters and controllers. In 1929, Venturi meters 12 inches and smaller were being calibrated for boiler feed lines. Later studies would determine calibration total loss coefficients when the flow was regulated by controller gates, and tests of the controller for constant discharge under a gradually dropping head (see Figure 17). In those early days, the flow meter calibration facilities were utilized primarily to calibrate flow meters that were used to measure flow in the models.

The very first facilities with gravity flow were incapable of producing the required higher cavitation free flows in pressure differential type meters, such as Venturi, nozzle and orifice meters. The lower winter temperature of the pond water caused a twofold change in viscosity of the water from that of the summer. This difference meant that the same meter calibrated in the winter would have a maximum Reynolds number only half of that obtained in a summer calibration. Because the meter would often be used in a plant with still higher Reynolds number, there was concern about the accuracy of the calibration at the higher plant flows. One impetus for large flow meters was to optimize the "heat rate" of a steam plant to get the maximum power, and this gradually occurred over time.

The calibration facilities at the laboratory have been used to accomplish the following goals:

- Calibrate meters of all types so that for a signal output, often pressure, the customer would accurately know the flow;
- Calibrate meters at a sufficiently high flow (high Reynolds number) so that the

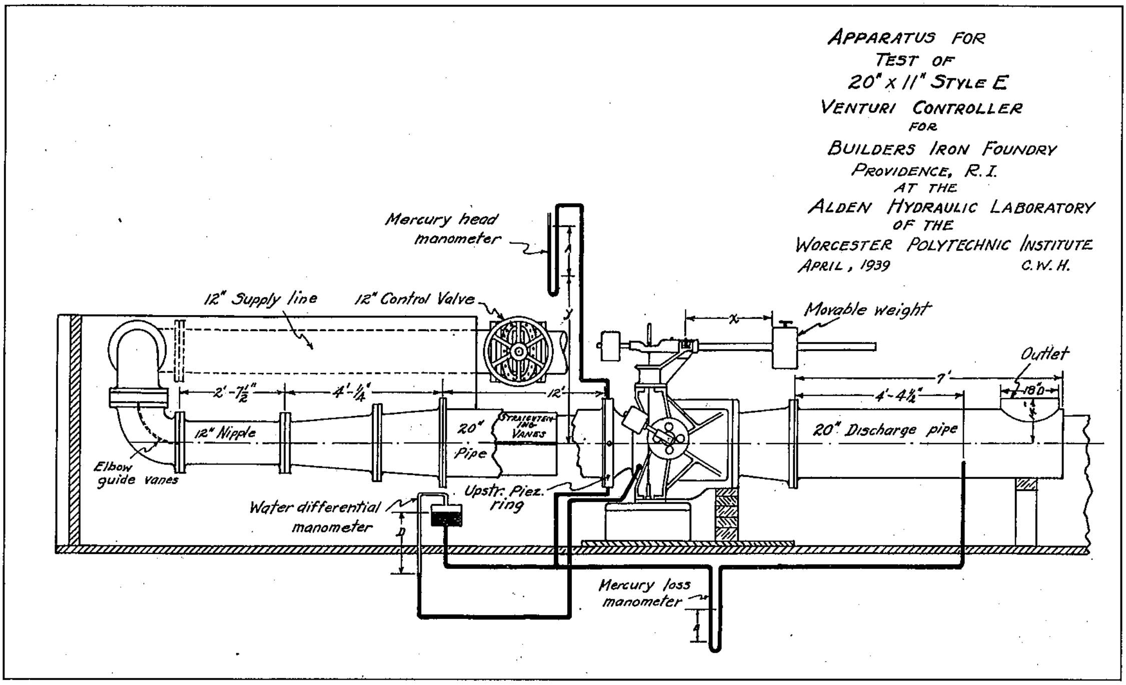

FIGURE 17. Dropping head (flow calibration).

meter, when operated at an even higher flow, would give accurate flow measurement;

- Calibrate meters to see if they meet a manufacturer's accuracy for flow measurement;
- Calibrate meters that will be installed in non-typical situations where high accuracy requires the approach geometry of piping be present for the calibration; and,
- Test various flow-related equipment such as valves and strainers for head-flow characteristics.

One of Hooper's favored areas, and one in which he had special expertise, was flow measurement. With plant sizes increasing in the 1950s, flow measurements began to be more important in power production. Electric utilities concerned with the efficiency of their plants began sending more of their flow meters for calibration at Alden. An activity that had previously involved a few commercial meter calibrations a year increased to a few meters a month, and the meters kept increasing in size.

Many calibrations on Venturi meters, Dall tubes and Kinneson nozzles were performed after World War II. Calibrations were performed using the 50,000-pound weigh tank or the 36-inch Venturi as the primary method of measuring the flow. The flexibility of the original 50,000-pound weigh tank facility was rather limited. The pipeline was fixed at each end, and the meter to be calibrated had to be piped between these two fixed ends. Due to limited funding, the laboratory had only a few threaded flanges in various pipe sizes up to 12 inches in diameter. The piping procedure became one of finding the correct length of piping plus the meter to exactly fit between both fixed ends, putting flanges on the pipe (making sure that the threads were properly greased so they would come off easily) and installing the piping for testing. This procedure was used until 1959.

At that time, Hooper noticed an advertisement in a magazine for a device called a Dresser coupling. This device allowed for some flexibility in the length of a pipeline. Hooper consulted for some time with Neale on the advisability of obtaining such a device to increase the efficiency of piping meters into the test line. After much soul-searching regarding the financial aspects of this purchase, it was decided to buy a 3-foot long, 12-inch Dresser coupling. At the onset it was clear that this purchase improved the efficiency of the piping operation and simplified the method of assembling the test piping. Today, there are hundreds of such Dresser-type devices of all sizes being used at Alden in numerous types of applications. Needless to say, the decisions to acquire these fittings were not as long or as soul-searching as for the original fitting.

Along the same line, in the early 1950s the laboratory used C.M. Allen's 20-inch slide rule and a mechanical Friden adding machine to extract the square root of a pressure differential that is required when calibrating a flow meter. The slide rule was used to approximate the square root. That number was multiplied by itself on the calculator to see if it resulted in the exact pressure differential. If the result was not correct, the slide rule number would be changed slightly and the procedure repeated until the answer was precise. This process was time consuming when numerous values had to be determined for averaging. One day Hooper saw an ad for a Friden calculator (a mechanical machine run by electric motor) that, besides adding, subtracting, multiplying and dividing also took the square root. The cost of the machine was $1,600. Because of the increase in the number of calibrations being performed, Hooper decided that the calculator would pay for itself in terms of time saved.

Some of the early calibrations after World War II were made on an electromagnetic flow meter. The operating principle for this type of meter is that a conductor moving in a magnetic field produces a voltage. The meter consisted of a pipe surrounded by an electrical magnet. With a flow of conductive fluid through the pipe, a voltage was created proportional to the flow rate. Alden water was found to have sufficient conductivity to test such meters.

The Nuclear Navy

One of the military/industrial growth areas in the United States as the result of the Cold War was related to the demands of the nuclear navy. In 1954, the first atomic-powered submarine, the Nautilus, was launched. Flow meters used aboard naval ships began appearing at the laboratory in the late 1950s for calibration from the primary suppliers of meters for nuclear-powered ships and submarines. All of the large meters in this program were calibrated at Alden, giving the laboratory the distinction of having calibrated flow meters aboard all nuclear submarines in the U.S. fleet.

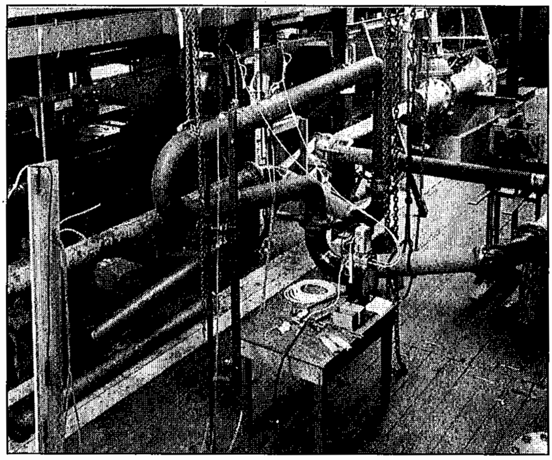

FIGURE 18. Complex approach piping required for an accurate meter calibration (1960s).

Because of cramped quarters aboard ships and submarines, the amount of straight piping upstream of a meter was limited. A long, straight approach is desirable for predicting meter accuracy without a specific calibration with the approach pipe included. In addition, the meters were built with large beta ratios (ratio of throat diameter to pipe diameter) to minimize the pressure loss through the meter. Both factors necessitated that these meters be tested with duplicated upstream pipe. One such test setup of a 24-inch meter came off the side of the main penstock, took a 90-degree turn and went down at an angle into the basement of the laboratory. Considerable effort in piping this configuration in the original laboratory was required for each test. Reproducing complex large piping has become a commonplace activity that very few facilities can accomplish (see Figure 18).

One of the strangest test programs in the calibration area involved the "sail" of a submarine. A sail is the conning tower that stands up from the long body of the submarine. A complete full-size sail was cut off a submarine and sent to Alden. It contained an internal orifice plate and screens to filter seawater. The sail was installed in the brook outside the original labo-

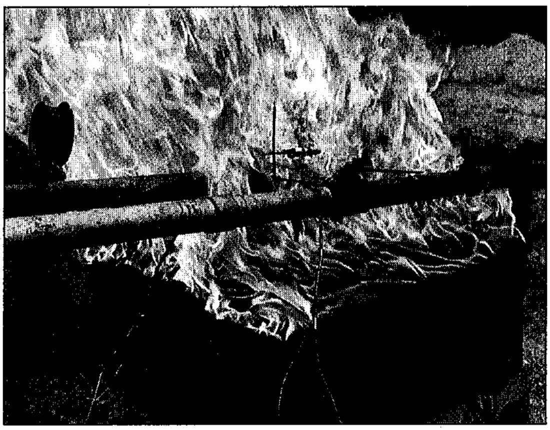

FIGURE 19. An example of a burn test on a valve.

ratory. Piping was brought from the basement test line to the sail, which had been modified to accept the piping. After the orifice calibration had been completed, tests were performed to determine whether seaweed or other type of seaborne debris could be backflushed off the screens. Fifty-gallon drums of various seaweed and other material were shipped to Alden.

The material was dumped into the basement test line and flowed into the screen. Backflushing the screens was done by re-routing the flow. Unfortunately, most of the seaweed would only weave itself in the holes of the strainer and become more firmly attached to the strainer. From the results of these tests, the Navy decided to redesign the strainer plate to include a device that would clear the woven seaweed.

Valve Testing

The nuclear navy has been responsible for other activities conducted at Alden. In the 1950s a number of check valves were evaluated for performance. The pressure losses were determined versus the valve clapper position with the valve installed in the flow-through direction. For the reversed-flow direction tests, the valve was installed in a line with a calibrated, homemade propeller-flow meter. The flow meter output, the position of the flapper as determined by a potentiometer, and the pressure in the pipe adjacent to the valve obtained by strain gauges glued to the pipe were all measured by an electric recorder. From this record, the flow, flapper position and pressure could be plotted versus time.

In one of the reversed-flow tests, the steel cover on the valve was replaced with a clear acrylic cover so that the movement of the clapper could be observed. The test began by introducing a steady flow through the valve with the clapper held wide open by means of a wire. When the wire was released, the clapper immediately shut with a resulting loud noise, followed by a sudden fountain emerging from the top of the valve. There were hurried movements to try to protect the electrical instruments and to run up two stories to reach the control valve at the upstream end of the pipeline. The pressure built up by the sudden valve closure had created a conical hole with a base diameter of approximately 6 inches in the acrylic cover. It was the last time that clear covers were used for this type of testing.

Another test on a check valve was performed to study the performance of the valve on flow reversal. For this test, water from under the building was pumped through the valve into the surge tank of the main penstock. The pump was then shut off and allowed to coast while the flow decreased and finally reversed. The instrumentation was similar to the previously mentioned test except that the motor speed was also recorded. A dash pot had been installed on this valve to regulate closure time of the flapper. The client had suggested that the first test be done with the dash pot set to maximize the time to close the flapper. With everything in place, the pump was started, allowed to reach steady state and then shut off. The flow began to decrease and it finally reversed. The reverse flow kept on increasing until a loud noise occurred, accompanied by a 6-foot movement of the pump and pipeline, followed by water coming out of a separation in the line upstream of the valve and also flowing from the top floor where the pipeline had also separated. By the time the valve at the surge tank had been closed, practically everyone in the building was soaking wet. The ultimate result of this series of tests showed that the check valve operated much better without a dash pot since the weight of the clapper shut the valve just before flow reversal and minimized pressure build up at the valve.

Many sizes of check valves and other types of valves (such as globe, roller control and steam isolation) were studied, many of which were used onboard naval ships. Included in the studies was a 26-inch fiberglass model of a main steam isolation valve. Parts of the valve were capable of being removed or changed to compare the pressure drop through the valve with different interior configurations.

Besides the growth in work for the naval program after the war, the chemical industry also experienced significant growth. One company started producing a new product called a ball valve. The simplicity and ease of operation of this valve made it an instant hit in the chemical industry. Alden performed many tests to determine pressure drop through many different size and models of these valves. Other valves, such as butterfly valves, were also tested for this company. One type of valve test was termed a "burn" test. This test consisted of submitting a valve, instrumented with thermocouples, to a fire for a specified period of time. The test setup was rather basic, but the valve was exposed to a fully developed fire (see Figure 19). After the test, the valve was subjected to pressure and the leakage measured. The valve was then recycled a number of times, pressure re-applied and leakage again checked. Afterwards, the valve was dismantled, a visual inspection was conducted and a record made for each part of the valve.

Growth of the Fluid Meter Industry

Flow meter use was not restricted to naval applications. A number of companies used meters for control or monitoring control systems. Many of these meters were calibrated at Alden prior to installation in plants throughout the country and, sometimes, overseas. In the early days, these systems were electromechanical in nature, but they later became computerized.

Relatively new types of meters were coming into the market during the 1950s. One meter, the Gentile tube (a shortened Venturi-style meter) drew immediate attention because of the meter's advertised insensitivity to upstream flow conditions, its low pressure loss and its high pressure differential signal — all very desirable meter characteristics. Alden seemed to be suddenly deluged with requests to calibrate many different-sized meters of this type for a variety of customers. After the initial onslaught, the rush subsided and very few such meters were received.

Six to ten months later, telephone calls began arriving about "poor" calibrations. Because of the advertising, customers had Alden calibrate the meters in straight upstream piping. However, in all cases, the meters had been installed with complicated upstream piping, such as two elbows out of plane or a 180-degree elbow directly upstream of the meter. In reality, recalibrations of the meters with the proper upstream configurations proved that the meters were unable to perform according to advertised specifications.

Alden started calibrating in the 1950s large turbine meters up to 16 inches in diameter. Initially, the meters were used primarily to measure oil flow in various Middle East countries. Later, when the space program started, these meters were used to measure various fuels and liquids pumped into rockets. With the advent of the nuclear power plants, Alden also calibrated flow meters, most of which were 12 inches in diameter or larger.

Laboratory Expansion

With the increase in calibration activity in about the mid-1950s, thought was given to improving the flow capacity of the laboratory's test lines. The first improvement was the addition of a 20-inch header for the test line leading to the 50,000-pound weigh tank. The second improvement was a 6-inch centrifugal pump. This 900-gallon-per-minute pump with a head of 70 feet augmented the flows for most meters less than 8 inches in diameter and was an important asset in calibrating small meters.

A big increase in capacity was achieved when the laboratory obtained four surplus marine diesel engines. Two of the engines were rebuilt using spare parts scavenged from the other two engines and, in some cases, from making new parts. The two diesels were then coupled to two centrifugal pumps of ancient vintage, one being a 1919 DeLeval pump. The flow capacity of the lines used at the time was increased from approximately 13 to 22 cubic feet per second.

At the beginning of the 1960s, Hooper realized the need to expand the laboratory due to increased model studies and flow meter calibration work. In June 1961, he listed the laboratory's future planning needs as follows:

- Increase undergraduate and graduate instruction;
- Strengthen the following areas of work: flow metering and calibration, surface waves on structures, ballistic missiles, density currents in rivers and reservoirs, sediment transport, beach erosion, and air pollution;
- Invite the Civil and Mechanical Engineering Department staffs at WPI to complement the Alden staff; and,
- Enlarge the facilities to include test facilities, offices for students, staff and library.

Five months later, Hooper recommended the construction of a three-story 144- by 48-foot building to be located between the existing laboratory and a pipe shop. To fund it, he suggested approaching the Trustees of the Alden Fund, since either they or Alden himself had been directly involved in every laboratory expansion. It was also mentioned that the proceeds of the $50,000 Thompson Fund, established by G.I. Alden and named after the first WPI president, and the $175,000 added to it by the Trustees of the Alden Fund could be used, as it had been, for maintenance of existing buildings.

The matter seemed to lay dormant in 1962. In January 1963, Hooper proposed a ten-year program to WPI. The gist of the program was similar to his 1961 appeal except that the term "immediately" appeared before the suggestion to expand the facility and staff. In May 1963, a proposal was sent to the Trustees of the Alden Trust Fund requesting $60,000 for additional staff and $24,000 for architectural and engineering fees to plan a new building.

Plans for the new building were drawn and a preliminary estimate for the cost of the new modern facility was $1 million. It was decided to approach the Federal Office of Education to obtain one-third of the funding, with the remaining two-thirds to be supplied by the trust fund. The proposal, sent to the government in July 1965, also included proposals for instruction as well as for the new facility. Funding was finally secured for the new building, consisting of a $700,000 gift from the Alden Trust and a $361,000 grant from the U.S. Department of Health, Education and Welfare. Eventually, the Alden Trust gift was over $1 million. Other gifts were also received.

As with most construction projects, this building met with cost overruns. When the total cost approached $1.4 million, WPI President Storke sat down with Hooper and the new building's architect and said he would not tolerate any more overruns. If any overruns were found, the overrun amount would be divided in half between the architect and Hooper. The architect's half would eliminate something in the office or library areas. Hooper's half would eliminate something or some equipment in the laboratory area. As the result of this compromise, the main floor calibration laboratory area opened without a traveling crane, a water filtering system and only half of the top floor in the laboratory wing that had been originally planned for the facility.

The modern facility was divided into three parts: office area, auditorium or lecture hall, and test wing. The office area was a two-story 130- by 41-foot area with a library, administration offices and two classrooms on the top floor, and 20 graduate student offices, four staff offices, and a complete photographic section on the bottom floor. The photographic area included four rooms for developing and printing photographs and a large room used for drafting, assembling reports, etc. The 41- by 37-foot auditorium was equipped with oak tables and chairs on staggered levels, making easy viewing for everyone. A modern projection booth, sound equipment and two motor-operated projection screens were provided.

The 140- by 60-foot test wing was primarily devoted to flow measurement. It contained a 250,000 gallon sump underground. The test floor had two 72-foot-long, 36-inch-diameter test lines, a 6-inch test line, 100,000-pound and 10,000-pound weigh tanks, four pumps and a diesel generator with 750-horsepower capacity (see Figure 20). The largest flow in the facility is 44 cubic feet per second (19,750 gallons per minute). The system was also designed to pump the excess heat from the diesel engine to the sump water to keep it high enough to achieve the highest Reynolds numbers possible. Water flow calibration was determined by

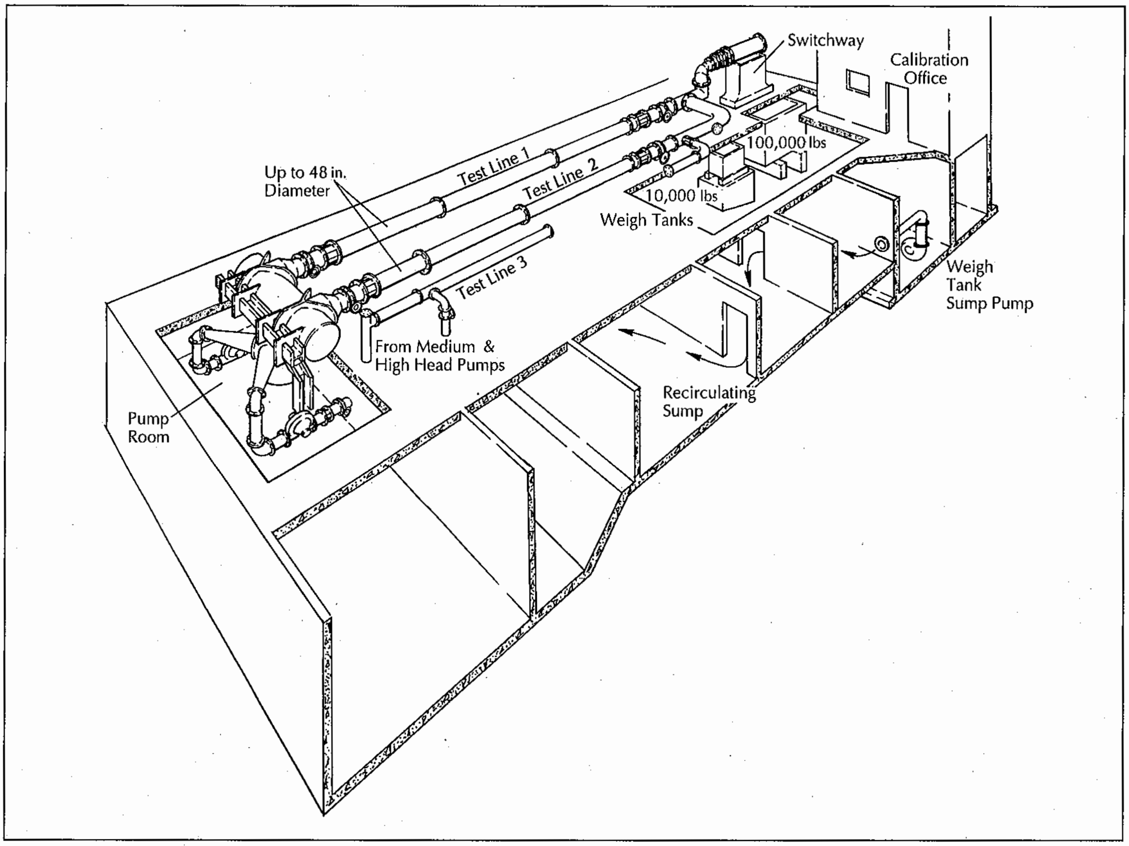

FIGURE 20. Overall view of the Alden calibration test facility.

measuring the weight of the flow over an elapsed time. Half of the second floor of the test wing was finished to supply room for student test facilities. Later, the other half was completed, furnishing offices, a conference room and a dining area for employees.

The flow features of the new facility placed Alden into the very forefront of calibration facilities throughout the world. The accuracy and Reynolds number capability for large meters in the 12- to 24-inch range were comparable to the government-run facilities in East Kilbride, Scotland, and in Delft, The Netherlands. When designed in the mid-1960s, the facility was capable of attaining the maximum Reynolds numbers of many power plants in the United States. However, the large nuclear plants and some fossil fuel plants would later require testing at even higher Reynolds numbers. An analytical study of the design of such a "High Reynolds Number Test" facility was later performed by Alden, but funding could not be obtained for building this expensive facility.

On May 22, 1968, the formal dedication of the new laboratory took place. The dedication was also accompanied by the announcement of Hooper's retirement. After a nationwide search for a qualified candidate to head the laboratory, the decision was made to name Lawrence C.

TABLE 6.
Growth at Alden

Year	Budget	Number of Staff
1928	$ 30,000	6
1938	$ 45,000	8
1948	$ 80,000	12
1958	$225,000	25
1968	$650,000	47

FIGURE 21. Aerial view of Alden facilities (1968).

Neale the new Director of Alden Research Laboratories. Alden's growth during Hooper's tenure is listed in Table 6. Figure 21 shows an aerial view of the test facilities at Alden in 1968.

Modern Flow Meter Calibration

While the laboratory was being expanded, Hooper was directing the precise calibration of the 100,000-pound Toledo scale. This process was quite involved. A special state-of-the-art scale was purchased with the hope of directly weighing 50-pound (nominal) weights and adjusting them until they were 50 pounds ±3 grains. (There are 7,000 grains per pound, and 3 grains are roughly equivalent to 3 BB pellets.) The scale was so sensitive it would register a change if someone clapped or walked in the room. Finally, this scale was used as a "comparative" scale. The weights were compared to a 50-pound weight traceable to the Bureau of Standards, and adjusted. These weights are still used, and their calibration has never needed further adjustment. At the time, Hooper was attempting to attain a scale accuracy of better than ±0.05 percent (50 pounds in 100,000 pounds) — far removed from the "good old days" when 55-gallon drums filled with concrete were used to calibrate the original 50,000-pound scale.

After the weights had been calibrated, a number of calibrations were made on both weigh tanks to check their accuracy and repeatability. The goal was to have a flow-measuring accuracy of about ±0.25 percent or better, which is a world-class standard for measuring large flows. In February 1970, the scales were calibrated for the last time before starting flow meter calibrations. Since May 1969, four 20-inch condensate flow nozzles had been sitting in the laboratory yard waiting to be calibrated in the new facility. As soon as the tank calibrations had been completed and the electrial wiring finished, the meters were piped into the new test lines and tested. The piping was not easy since the crane rail system had not been installed. Immediately after this job, I-beams and hand-operated chain falls were put up above each of the two test lines.

After the facilities were put into operation, Hooper expressed the feeling that there might not be enough work for the new facility. Little did he know that in the years following his death in 1977, there would be a continuous demand for calibrations and related test work in not only the new calibration laboratory but that the calibration lines in the original laboratory would also have a full schedule.

The first Dall tube (a shortened and modified Venturi meter with less loss and a higher differential pressure) tested in the new facility revealed an interesting phenomenon at the higher Reynolds numbers that could be tested. When this type of differential head flow meter was calibrated in the old laboratory, the discharge coefficient, the quantification of which was the whole purpose of calibration, would appear to become constant at the Reynolds numbers then available. Sometimes at the highest Reynolds number, the coefficient seemed to tend to be slightly higher than indicated by a constant flat line. This difference was attributed to possible cavitation in the meter throat. Tests in the new facility showed that the discharge coefficient in fact did increase and eventually flattened out at a higher value at the higher Reynolds numbers attained in the new calibration loop. Because of this shift to higher values, the Dall tube was used less frequently in new applications and eventually was replaced by other low-loss meters based on the Venturi principle.

One of the first studies, other than a flow meter calibration, conducted in the new test wing was a full-scale air flow study on an 880-megawatt nuclear reactor cavity. The study was to determine the cooling air flow distribution between the concrete and the insulation panels surrounding the reactor. Of particular importance was the air flow around pipes that penetrated the concrete and insulation panels.

With the opening of the new laboratory coinciding with the initial operation of many nuclear plants in the United States, many flow meters were sent to Alden for calibration. Hundreds of meters to be used at nuclear facilities were calibrated at Alden. (It is interesting that in the 1980s and 1990s, some of these same meters were returned to Alden for re-calibration after being cleaned and/or re-worked.) During this time period, the nuclear industry found that flow meter interiors were becoming fouled, thereby changing their calibrations, sometimes by as much as 4 percent. The meters at the time were being used to set the power outputs of these plants. Due to the fouling problems, the utilities were in a quandary. On one hand, the Federal Nuclear Regulatory Council had established fines and penalties for plants exceeding their license limitation at any time. On the other hand, the utilities needed to generate the maximum power to recover their large investments in the plants. Removal of the meter from the power station would cause a shut down. It became important to calibrate the flow meters at frequent time intervals during normal outages.

Meters of all sizes and types from a fraction of an inch to 72 inches in diameter have been calibrated at Alden. The heaviest meter test section calibrated weighed 15 tons.

Over the century of its existence, Alden has been at the forefront of flow meter testing and calibration. Throughout the years, the laboratory has calibrated practically every type of flow meter manufactured and used throughout the world in a variety of industries. It is estimated that approximately 5,200 commercial flow meter calibrations have been performed at Alden, with more than 80 percent of them performed in the last 25 years. The thousands of calibrations, some repeated after a number of years, attest to the accuracy of Alden's tests and the confidence of clients.

GEORGE E. HECKER *was appointed Director of the Alden Research Laboratory in 1975, when it was part of WPI, and became President in 1986 when Alden was separately incorporated. Prior to joining Alden in 1971, he worked for Stone & Webster in Boston and for the Tennessee Valley Authority before that. With more than 35 years of experience in solving flow problems using physical models, analyses and field studies, he has published widely and has served on many national professional committees. He has degrees from Yale and the Massachusetts Institute of Technology.*

ALBERT G. FERRON *was employed at Alden for 35 years. He also was an Adjunct Associate Professor of Mechanical Engineering at WPI. Upon his retirement from Alden in 1992, he was Vice President of the Flow Meter Calibration Section. Currently, he is employed at the University of Massachusetts Medical School in Worcester, continues as an Adjunct Associate Professor in WPI's Department of Civil & Environmental Engineering and is active in many community projects.*

BRUCE J. PENNINO *is Professor of Civil Engineering Technology at Springfield Technical Community College. Formerly, he was a Research Engineer at Alden for many years. He has a B.S.C.E. from Bucknell University and a M.S.C.E. from Colorado State University. He has over 30 years of civil and hydraulic engineering experience, and is a registered professional engineer in Massachusetts.*

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