CANYON LEGACY

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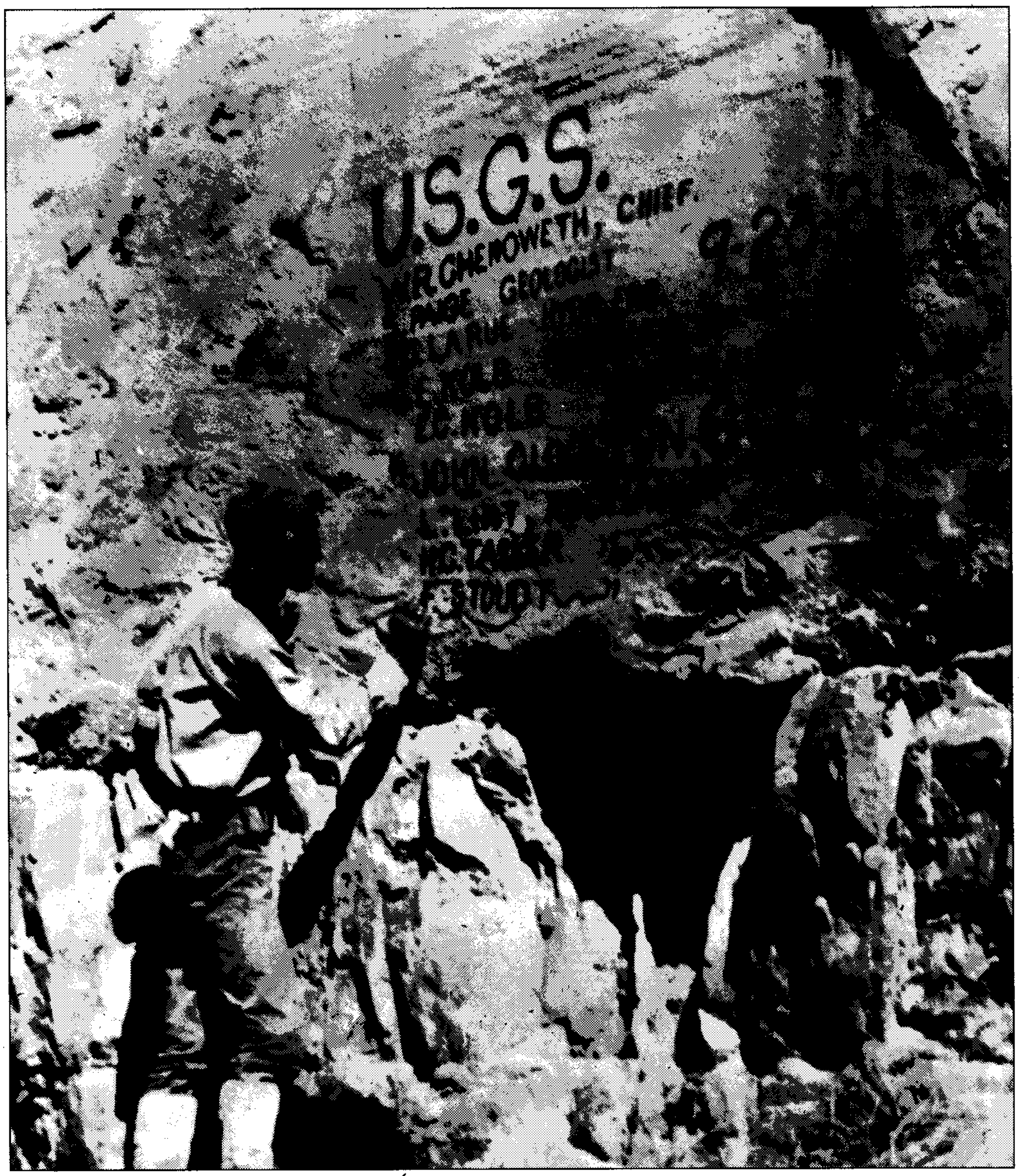
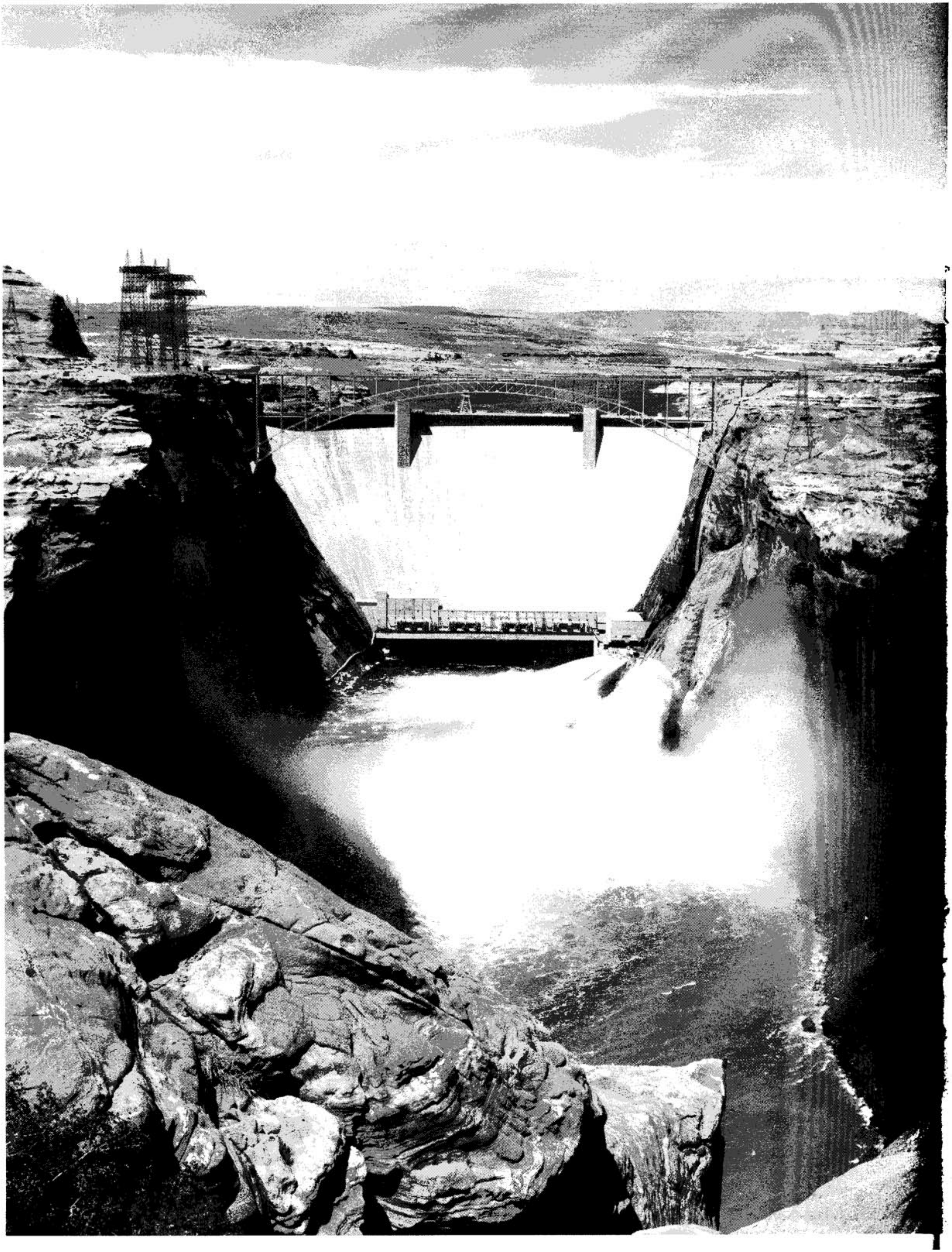


Designs on the river...

Stories of man's efforts to harness and ride the Colorado



THE 1983 FLOOD

How the Glen Canyon Dam held up under the impact of cavitation

by John Keys,
Former Commissioner
U.S. Bureau of Reclamation

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The picture at left was taken of Glen Canyon Dam in 1983. Photograph courtesy the U.S. Department of Interior, Bureau of Reclamation, Upper Colorado Region. Photo by Joe Dahilig.

In 1983, El Niño conditions produced exceptionally heavy snowfall over the Upper Colorado River Basin. The resulting snow pack, with early hot weather, led to record runoff into Lake Powell. The reservoir rose quickly, requiring maximum releases of water through Glen Canyon Dam's power plant, river outlet works, and spillways. Cavitation in the spillways during these releases caused significant damage to the spillways and their linings. The resulting repairs, installation of "air slots," and the development of better runoff forecasting methods have strengthened the dam and enhanced management of water in the Colorado River.

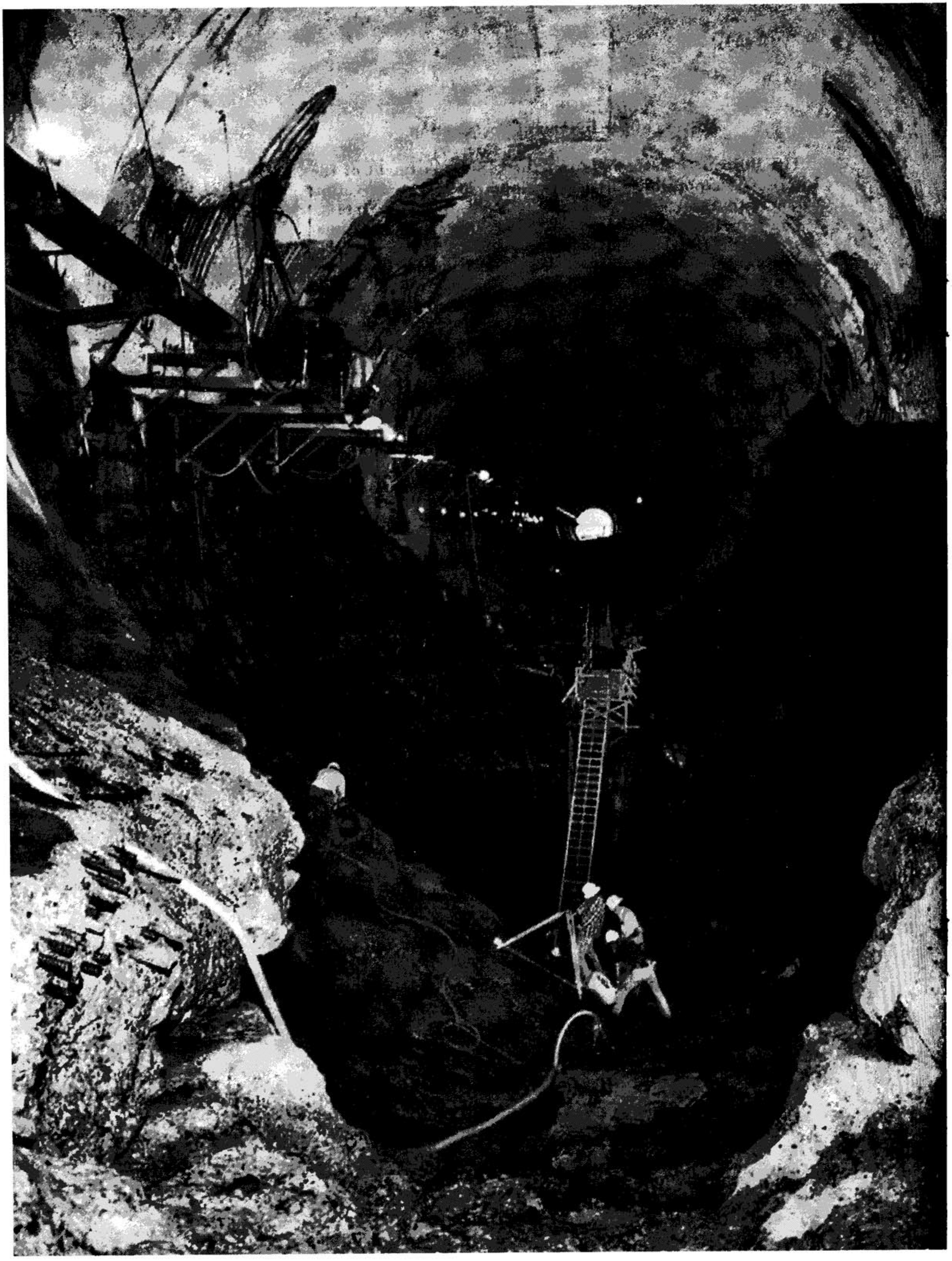
GLEN CANYON DAM

Glen Canyon Dam was constructed on the Colorado River near Page, Ariz., from 1957 to 1964 by the Bureau of Reclamation, a part of the Department of the Interior. The dam is a concrete arch-gravity dam, rising 710 feet from the river bed. (Note: That's more than two football fields high.) It creates Lake Powell which will hold 26.2 million acre-feet of water at a full-pool elevation of 3,700 feet above mean sea level (MSL). This volume includes 24.3 million acre-feet of active live storage and 1.9 million acre-feet of dead storage below the sill of the outlet gates. An acre-foot is 325,850 gallons or enough to cover an acre with water one foot deep.

The reservoir is a unit of the Colorado River Storage Project. Its main purposes are storage replacement for upstream water development, meeting downstream requirements under the Colorado River Compact of 1922, producing hydroelectric power, and providing recreational opportunities.

There are four ways to release water from Lake Powell through Glen Canyon Dam to the Colorado River below the dam: through the power plant, the river outlet works, and two spillways. The power plant can pass about 31,500 cubic feet per second (cfs) at full capacity. The water is discharged into the after-bay in the river. The river outlet works—four eight-foot diameter jet flow valves on the left side of the dam—can pass about 17,000 cfs of water into a plunge pool on the left side of the after-bay.

Glen Canyon Dam has two spillways, each 41 feet in diameter, that were tunneled through the sandstone walls on each side of the canyon. These tunnels descend steeply to the river level below the dam and were



designed to handle a discharge of 180,000 cfs. They were originally lined with three feet of concrete, but they were expected to be used rarely and only for short periods of time. Two radial gates control the flow of water into each spillway. When water is released into the spillway, it drops several hundred feet to the elbow section. (See figure below.) From there, the water flows horizontally for about 1,000 feet through the lower tunnel. When the water leaves the spillway tunnel, it hits a "flip bucket." A flip bucket is a water ramp, like the bottom end of a ski jump, that is designed to dissipate the tremendous energy of the flow by cascading it into the air, allowing it to fall into the Colorado River.

Glen Canyon Dam is an arch-gravity dam. That means it combines the characteristics of an arch dam with the characteristics of a gravity dam. An arch dam transfers a large portion of the weight of the water behind it into the walls of the canyon on each side. A gravity dam transfers the weight of the water into a downward vector that should hit the canyon floor within the middle one-third of the footprint of the dam. Glen Canyon Dam combines those characteristics; it uses the most favorable of each. Its bulk or weight and shape alone are not quite able to transfer the weight of the water into the middle one-third of the footprint, but the combination of the two gives it added safety factors.

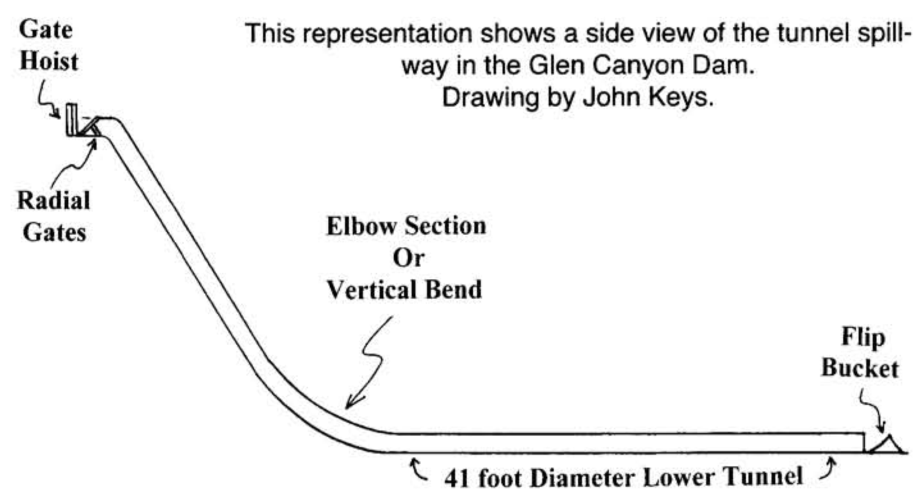
THE FLOOD

In late September 1982, a five-day storm saturated the Utah, Colorado and Wyoming mountains. That storm was followed by a hard freeze that sealed the moisture in the ground. The remainder of the 1982-1983 winter was fairly normal with a January 1 forecast for Colorado River runoff of 112 percent of normal (for the April-to-July period), and a March 1 forecast of 96 percent of normal.

IN THE COLORADO RIVER BASIN, ALL TRIBUTARIES FLOWED AT FLOOD STAGE, WITH ALMOST ALL STORAGE FACILITIES FILLING AND SPILLING...

In April and May of 1983, the Upper Colorado River Basin and most of the Intermountain West received heavy wet snowfall, resulting in a runoff forecast of 131 percent of normal on June 1. Then prolonged hot weather arrived in the area. This sudden warming produced rapid runoff in rivers and streams all over the West. There was significant flooding around Utah Lake, along the Wasatch Front, and in Salt Lake City and its suburbs. It also caused the Thistle Slide in Utah's Spanish Fork Canyon, which took out a major highway and rail line in the center of the state.

In the Colorado River Basin, all tributaries flowed at flood stage, with almost all storage



This representation shows a side view of the tunnel spillway in the Glen Canyon Dam. Drawing by John Keys.

Tunnel Spillway Side View Glen Canyon Dam

The photograph at left shows the large hole caused by damage to the left spillway. The hole was located just below the vertical bend in the spillway. Photograph courtesy the Bureau of Reclamation.

facilities filling and spilling, including Strawberry Reservoir on the Strawberry River, Morrow Point and Crystal reservoirs on the Gunnison River, and Flaming Gorge Reservoir on the Green River.

On the Colorado River, Lake Powell collects flows from the Colorado, Green, White, Yampa, Duchesne, Gunnison, Dolores and San Juan rivers. With all of these tributaries flowing at flood stage, Lake Powell inflows increased from 35,000 cfs on May 20 to a peak of 111,500 cfs on June 29. These flows raised the water surface of Lake Powell to a record level of 3,708.34 feet MSL where it contained 26.4 million acre-feet of water. Instead of 131 percent of normal runoff, the actual runoff in the Colorado River above Glen Canyon Dam was 210 percent of normal.

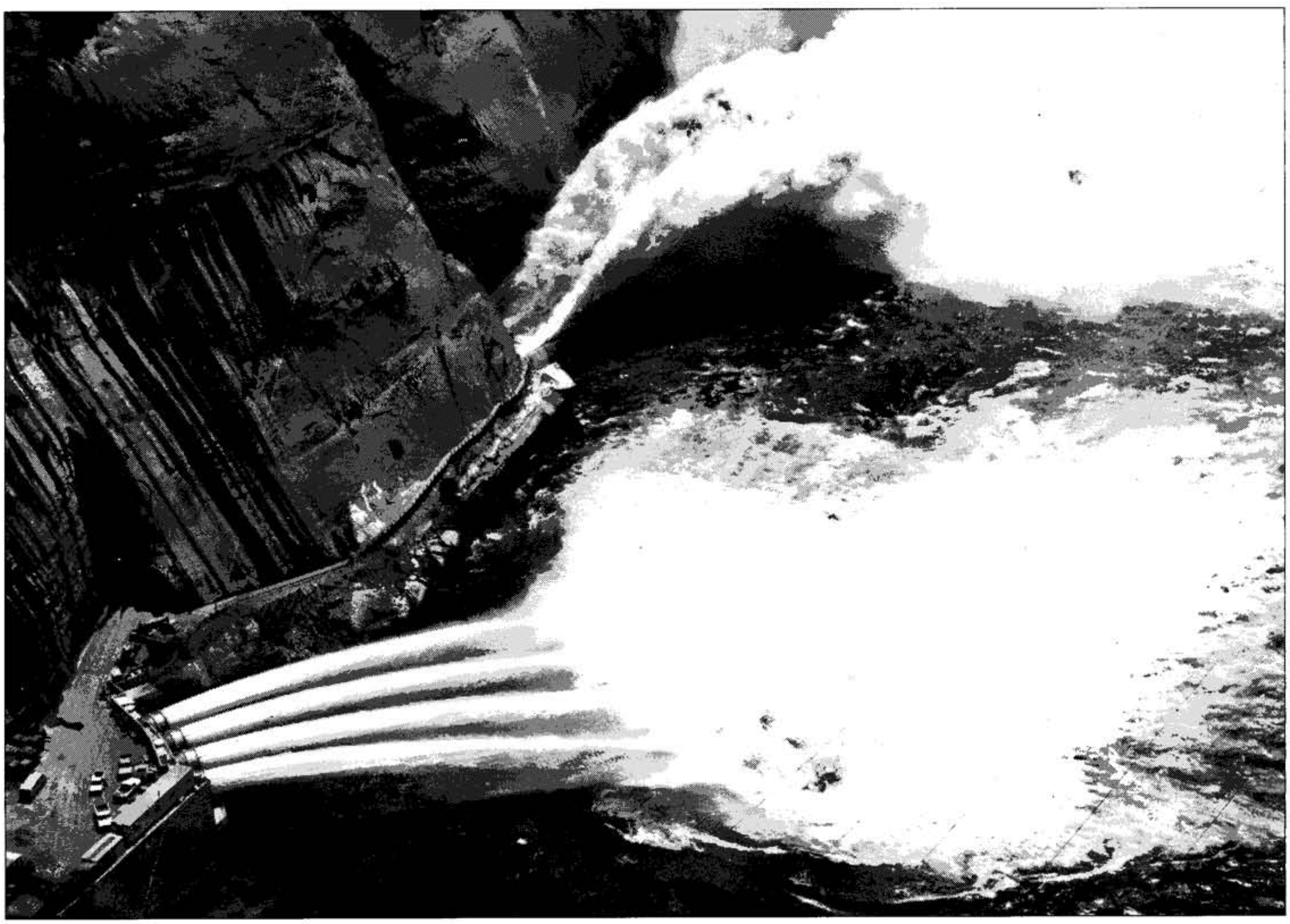
The photograph below shows the left spillway and river outlet works in operation at the Glen Canyon Dam in 1983. Approximately 17,000 cfs of water is being discharged. Photo by Joe Dahilig, courtesy Bureau of Reclamation, U.S. Department of the Interior.

GLEN CANYON DAM OPERATIONS

With nearly all tributaries of the Colorado River flowing at record levels and at or above flood stage in early May 1983, Bureau of Reclamation operators at Glen Canyon Dam opened the wicket gates of the power plant to run the facility at full capacity (31,500 cfs) and make room for the heavy runoff. In early June, with Lake Powell still rising, the river outlet works were opened to release more water (15,000 cfs), the left spillway gates were opened to begin spilling water, (10,000 cfs to 20,000 cfs, and later to 32,000 cfs), and temporary plywood panels were installed on top of the spillway gates to increase the storage capacity of the dam's reservoir.

The primary concern was not that the dam would be over-topped, but that the water would rise above elevation 3,700 feet and flow over the top of the spillway gates. Early on, agency officials had made the decision to not use the right spillway but to hold it in reserve for emergency use.

In mid-June, the inflow to Lake Powell rose to nearly 100,000 cfs. With the power plant, river



outlet works, and left spillway all in operation, almost 75,000 cfs of water was being passed through the dam. But the reservoir was still rising. Then cavitation (see sidebar) reared its ugly head. On June 6, deep rumbling noises were heard coming from the left spillway, the spillway discharge developed an orange tint, and chunks of concrete and sandstone were observed in the flow.

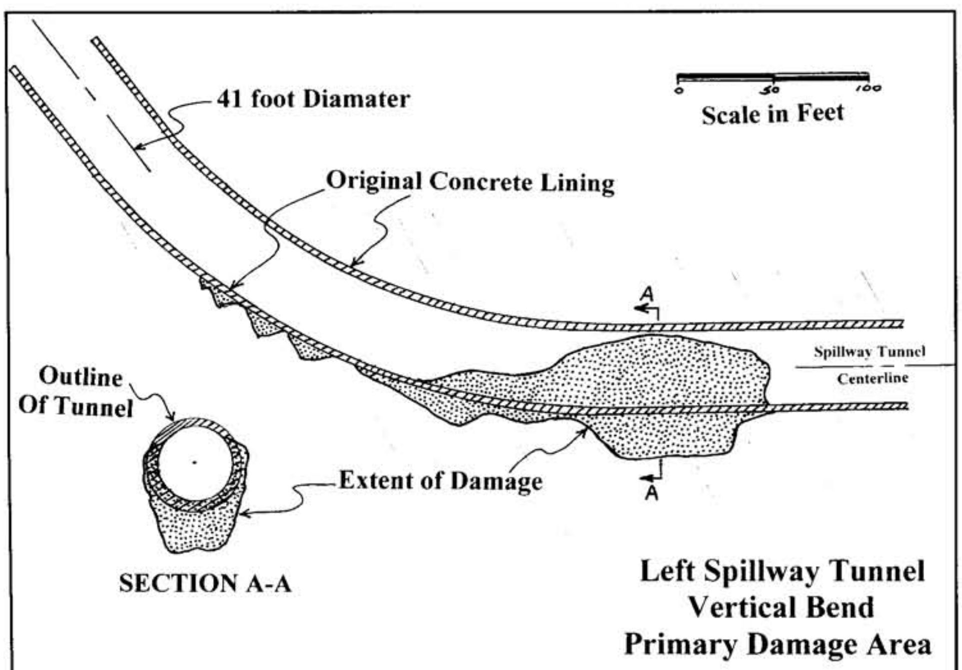
With these obvious signals of damage, the left spillway was closed for an inspection. A cart was lowered into the spillway. Almost 600 feet down the tunnel inspectors observed large holes completely through the three-foot-thick concrete lining. Some of the holes actually extended into the sandstone, and reinforcing bars from the concrete were twisted and broken. The cart could go no farther, but a series of large holes farther down the tunnel was observed.

With this information, plans were made for Glen Canyon Dam operations to get through the high runoff season. For a more permanent fix, eight-foot steel flash boards would be installed to replace the plywood flash boards (construction was completed in early July). The power plant and river outlet works would continue to be operated at capacity. And, both spillways would be operated, the left one to carry the most flow and the right one to take some pressure off the left one.

By the end of June, with inflow to Lake Powell at its peak of 111,500 cfs, both spillways were opened. For the next month, several experiments were conducted to determine the proper release rates, but it was evident that cavitation was doing its dirty deeds inside the spillway tunnels. Flows in the right spillway varied from 4,000 cfs to 27,000 cfs, and flows in the left spillway varied from 10,000 cfs to 32,000 cfs.

Finally, Lake Powell peaked at elevation 3708.34 feet on July 14 and began to fall. High releases were continued into early August to take pressure off the spillways and their gates. Flows through the spillways were shut down in late July.

The representation below shows damage to the left spillway that occurred in 1983 on the Glen Canyon Dam. Drawing by John Keys.



What is Cavitation?

Cavitation is a hydraulic phenomenon where fast-moving water is diverted or thrown upward by small obstructions, creating vapor cavities or small vacuum pockets under the flow and against the wall of the conduit (pipe, canal, or river bed).

These vapor cavities or vacuum pockets are microscopic in size, but many may be formed by the same small obstruction. The cavities collapse with destructive force, digging holes into the surface on which the water is flowing. The holes are enlarged and deepened by continued cavitation and flow. After one hole is formed, a leap frog action is initiated, causing further cavitation holes to form downstream of the first one.

In early spillway designs, cavitation was almost certain to occur. The solution in those days was to manage the system to almost never spill water, and when there was a spill, to limit the spill to very short periods of time. Then if cavitation damage happened, it would be repaired.

Research in the 1950s through the 1980s found that the installation of air slots in a spillway would eliminate cavitation. Tests showed that when high velocity water crossed the air slots, a cushion of air bubbles would be introduced on which the water would ride through the remainder of the spillway. The size and placement of the air slots depended on the size of the conduit and the volume and speed of the water.

This air slot technology was not available during the design and construction of Glen Canyon Dam.

OTHER DOWNSTREAM OPERATIONS AND PRECAUTIONS

With the high releases of water through Glen Canyon Dam, many precautions were taken to protect people and property downstream.

Hoover Dam and Lake Mead, about 300 miles lower on the Colorado River, were operated to handle the increased inflow of water. All law enforcement officials, state officials, and local governments were briefed on initial high water and flow conditions, and all were regularly updated on conditions and plans. And the National Park Service continually provided flow information and conditions to river outfitters and private parties floating the Colorado River through the Grand Canyon.

DAMAGE AND REPAIR

Throughout the entire period of high flood releases, the eight power plant units and the four hollow-jet valves of the river outlet works operated around the clock without incident. Inspections after the event showed no damage to any of them. The performance of these units was critical to the successful flow releases at Glen Canyon Dam during the summer of 1983.

In early August, the tunnel spillways were drained and inspected for damage. Access for the inspections was from the downstream flip buckets. From the first look at the left tunnel, it was obvious that serious damage had occurred. The flip bucket contained over 300 cubic yards of concrete, reinforcing steel and sandstone. About 500 feet inside the tunnel, a large sandstone boulder, as large as a good-sized automobile, sat in the middle of the tunnel. Then, there was the damage to the tunnel itself.

ABOUT 500 FEET INSIDE THE TUNNEL, A LARGE SANDSTONE BOULDER...SAT IN THE MIDDLE OF THE TUNNEL. THEN, THERE WAS THE DAMAGE TO THE TUNNEL ITSELF.

Extensive damage had been experienced in the vertical bend of the tunnel. Immediately downstream of the vertical bend, a hole 35 feet deep, 150 feet long, and 50 feet wide had been excavated in the sandstone by the high energy flows. Three-fourths of the tunnel liner circumference had been removed in the area of the large hole. In many other places near the vertical bend, the concrete lining was entirely gone, with reinforcing steel broken off by metal fatigue. A number of other smaller holes in the sandstone had been excavated, as can be viewed in the accompanying photographs and drawings.

Inspection of the right spillway tunnel showed less damage. There was little debris in the flip bucket or tunnel. A large hole was found in the bottom of the tunnel immediately downstream of the vertical bend. The concrete lining had been removed for about 175 feet and sandstone had been excavated up to 12 feet deep. A number of other smaller holes in the lining and sandstone were found.

In late August and early September, repairs to the Glen Canyon Dam spillways began with an urgency. The repairs had to be done as soon as possible in case they were needed again the next year. With the power plant operating at full capacity and the river outlet works discharging at near capacity, the year-long repair began. Guy F. Atkinson Construction Company, headquartered in San Francisco, was

At left, a view of Lake Powell in 1983. Bureau of Reclamation photograph.

selected as the general contractor.

With the spillways drained of water, adit tunnels (openings in the tunnel walls) were bored into the lower sides of each tunnel, near the outlet portals, to allow access to heavy equipment and trucks. The first task was to remove broken concrete, loose sandstone and other debris. Then the tunnels were prepared for new reinforced concrete to fill the holes and reinstallation of the concrete lining. The large hole in the left spillway tunnel actually took 2,500 cubic yards of concrete to fill.

While repairs to the tunnels were underway, final designs for the air slots to be incorporated in the upper portions of the tunnels were completed by Bureau of Reclamation engineers in Denver. These designs called for a four-foot-wide, four-foot-deep circular trench to be cut and lined with concrete about 110 feet down from the upper end of each spillway. With the contractor on site, the construction and implementation of these air slots were made part of the repair contract. This addition would bring Glen Canyon Dam spillways up to state-of-the-art design.

On Aug. 12, 1984, the left spillway, completely repaired and having an installed air slot, was tested with a release of 50,000 cfs. After a few days of testing, the flow was cut off and the spillway pumped dry for inspection. There was no damage. The repairs were sound, and the air slots were deemed a complete success in preventing future cavitation.

The cavitation of 1983 was a "once-in-a-lifetime" event because of the redesign and reconstruction of the spillways.

Construction for the repair of the spillways at Glen Canyon Dam was officially completed in October, 1984. The final cost of those repairs and other work during the flood-control activities was approximately $32.5 million. Offsetting those costs, the steady full operation of the power plant to release more water during that period of time had netted almost $35 million in extra revenue.

The photograph below shows an overall view of the elbow area of the right spillway. The concrete lining was eroded from left to right, and in the center is damage to the elbow area. Photograph taken on Sept. 21, 1983 by Tom Fridmann, courtesy the U.S. Department of Interior, Bureau of Reclamation.

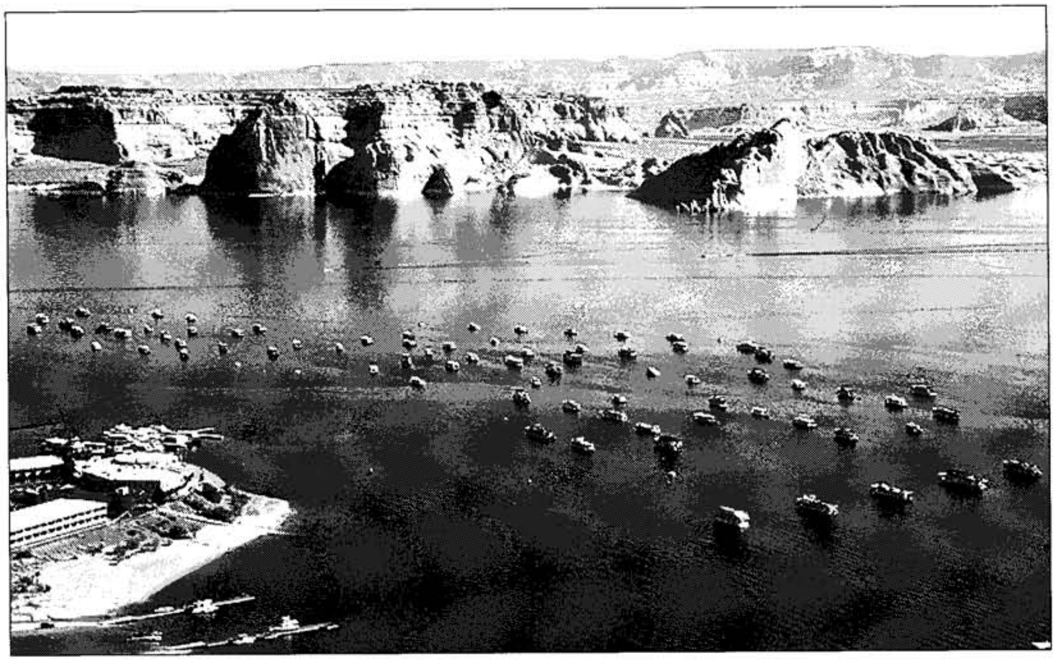
RESULTS

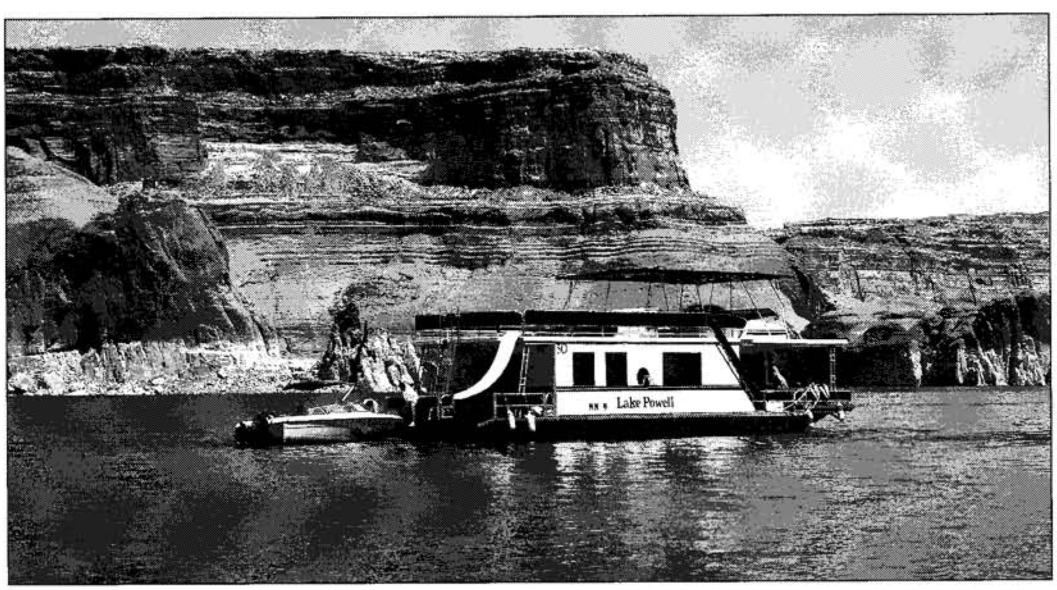
After the surprise incident of the 1983 runoff in the Colorado River Basin (i.e. 131 percent of normal forecast on June 1, followed by an actual runoff of more than 210 percent of normal), it was apparent that runoff forecasting had to be improved.

The Bureau of Reclamation worked in cooperation with the National Weather Service, the Soil Conservation Service (now the Natural Resources Conservation Service), and the states of the Upper Colorado River Basin to devise and implement an improved forecasting system. A new model was developed, new data collection stations were installed, and new procedures were put in place to improve the forecasts and quickly refine the model and its predictions as snowfall in the mountains accumulates. The system has worked well since its development.

The air slot design that was incorporated into the repair and improvement of the Glen Canyon Dam spillways to prevent cavitation has been incorporated in many other spillways of that type across the West. The spillways of Hoover Dam in Arizona and Nevada, Flaming Gorge Dam in Utah, and Hungry Horse Dam in Montana have already been modified. Several others are being planned.

While the events of 1983 at Glen Canyon Dam were tense at times, there was never a real threat to the dam itself. The spillways have been repaired, modified and tested to prevent that sort of action again. The power plant and river outlet works proved themselves while running continuously for almost two years. The dam is still a safe and effective part of water resources management on the Colorado River.





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The pictures at left show the recreational popularity of Lake Powell, with steady marina and houseboat use. Photos courtesy Bureau of Reclamation.