AN INTRODUCTION TO THE POSSIBLE ROLE OF CAVITATION IN THE EROSION OF WATER CHANNELS

EDMOND W. HOLROYD, III**

Received 20 October 1989; Revised 10 January 1990

Abstract

The process of cavitation in water has been involved in the damage of many types of man-made structures. Shock waves and water jets caused by the collapse of cavitation bubbles can clean, dent, or even Pulverize materials of many types, including concrete and metals. The physics of cavitation damage is reviewed. Flow speeds greater than 30 m/s appear necessary for cavitation damage, but thereafter the damage potential can increase rapidly, perhaps at rates proportional to the sixth power of velocity. Major damage can occur with flow depths of only a few meters. Damage potential decreases with flow depth because increasing pressures make it less likely that internal water pressures can be dynamically forced to become less than the vapor pressure of water. Cavitation damage is greatly lessened as the air content of the water is increased, suggesting that cavitation damage is unlikely to be found in "white water" rapids. The roughening of water channel surfaces also decreases cavitation damage by slowing the flow speeds and thereby increasing flow depths for constant flow discharge. Damage initiated by cavitation can provide opportunities to accelerate the rates for normal erosion processes as water plunges into the holes created by cavitation.

Cavitation Damage at the Glen Canyon Dam in 1983*

After a winter of near-normal snowfall in the basin of the Colorado River the snowpack was rapidly increased by spring storms in 1983. The record snow pack was then subjected to abnormally warm conditions, causing a rapid melt. The result was flooding in many portions of the Colorado River Basin. In response to the unusual flow of water into the system of dams and reservoirs, water had to be released rapidly from reservoirs to make room for the new water that was soon to arrive. In addition, the height of the Glen Canyon Dam spillway gates, near Page in northern Arizona, was increased by over two meters to create additional storage capacity. These measures were sufficient to limit the damage by the flood waters to the spillway tunnels at that dam.

Water was initially released past the Glen Canyon Dam through four bypass tubes, later through the left spillway, and sometimes through right spillway as well. The dam is shown in Figure 1 spanning a narrow canyon cut into the Navajo sandstone formation. Behind it is Lake Powell. In front of the dam is the water plume from the four bypass tubes and the larger flow through the left (when looking downstream) spillway tunnel. Flows through the left tunnel began on 2 June, at rates of up to 571 m^3/s (20176 ft^3/s). After about 24 hours at the high rate, rumblings were heard from the tunnel. An inspection showed that damage characteristic of a process known as cavitation was occurring in the 12.5 meter diameter spillway tunnels. Flows were reduced for about a week, but the coming flood waters necessitated a resumption of high water flows, peaking briefly during a test at 906 m^3/s. Concrete and rocks torn from the tunnel walls could be seen being ejected by the high flows. In late July flows were reduced below 100 m^3/s. A histogram of the total hours at the several flow rates during June and July 1983 is shown in Figure 2. Lesser flows were released through the right tunnel during that period.

Later inspection of the tunnels revealed large caverns* excavated through the one-meter thick reinforced concrete liner and up to nine meters into the sandstone rock. Figure 3 shows a view looking downstream into the largest cavity (10 m deep, 12 m wide, 37 m long). The ladder and the workmen help provide a scale. Boulders as big as automobiles were excavated by the water from the bedrock and some of them remained in the tunnel downstream of the damage. The largest, which had to have been lifted out of the 10 m deep hole, is visible at the top of Figure 3 blocking part of the 12.5 m diameter tunnel. Others are seen in Figure 4 at the exit of the tunnel known as the "flip bucket."

The vertical profiles of the left and right spillway tunnels are shown in Figure 5. The full profile of the left spillway tunnel is shown in Figure 5a from the spillway gates at the upper left to the "flip bucket" at the right. (The flip bucket is a curving profile at the end of the spillway that launches the water into the air. The energy of the water is then dissipated when it falls into a filled plunge pool in the river.) The right tunnel has a similar profile but a shorter length in the horizontal portion. The damage in both tunnels occurred in the region of the dashed box in Figure 5a. The damage locations and extents are indicated by the dotted shading along the bottom of the profiles of the right (b) and left (c) tunnels. The extent of damage to the side walls is shown by the dashed lines. It was found that the damage was initiated by a process known as cavitation and enlarged by erosion.

Understanding the Process of Cavitation

Cavitation is the creation of gaseous phase bubbles in a liquid as a result of a decrease in pressure. The creation of the bubbles themselves is relatively harmless. If they choke the flow in confined conduits, like tubes, then the blockage is more of a nuisance. It is the *collapse* of bubbles that can cause structural dam-

***The details are from Falvey, 1990; Bureau of Reclamation, 1984; personal discussions with Bureau of Reclamation engineers and examination of internal newsletters, drawings, and exhibits.**

****Edmond W. Holroyd, III, Ph. D., 8509 W. 63rd Ave., Arvada, CO 80004-3103.**

***Editor's Note: For readers interested in cavern formation in limestone see Williams, E. L. and R. J. Herdklotz, 1977. Solution and deposition of limestone in a laboratory situation II. *CRSQ* 13:192-99.**

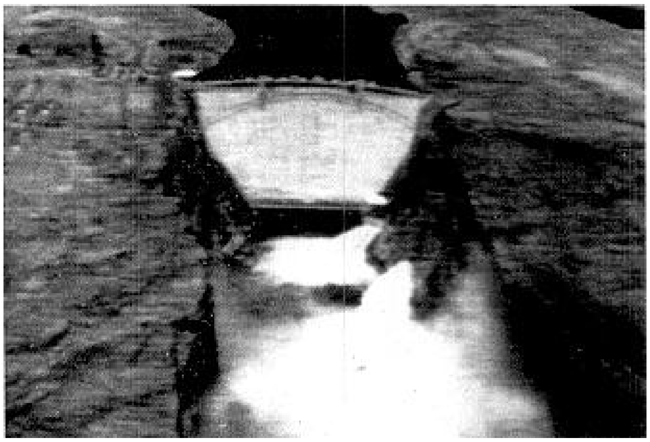

Figure 1. An aerial view of the Glen Canyon Dam of northern Arizona during operation of the by-pass tubes and the left spillway. A highway bridge spans the canyon in front of the dam. (From Bureau of Reclamation video)

age to surfaces that are in contact with the liquid. The collapse will cause powerful shockwaves and possible minute jets of water that impact the solid surfaces. Though the collapse of the bubbles is actually the opposite of the creation of vapor cavities, the term cavitation tends to be used to refer to the entire process.

Severe structural damage, comparable to that at Glen Canyon Dam, had occurred in 1941 to the Arizona spillway of Hoover Dam. As a result, the Bureau of Reclamation began studies of the cavitation process about a decade later. While cavitation damage at the Glen Canyon Dam in 1983 was the largest observed at structures designed and operated by the U.S. Bureau of Reclamation, damage occurred at other facilities during that flood season and at other times. The Bureau conducted extensive studies to be able to understand the conditions under which cavitation damage might occur, to predict the location and severity of damage, and to design corrections to prevent future damage to the water conveyance structures. Falvey (1990) suggests that water heads (indicating the energy available from elevation changes) in excess of about 45 m and flows in excess of 30 m/s are suspect for the potential for producing damage to structures by cavitation.

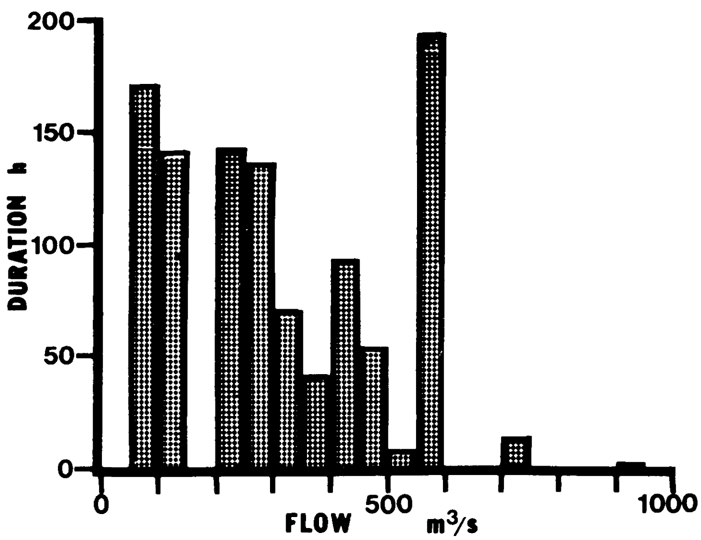

Figure 2. A histogram of the total hours at the several flow rates during June and July 1983 for the left spillway of the Glen Canyon Dam.

It was found possible to control the curvature of spillways in the design process so as to minimize the possibility of cavitation damage. But redesigning and modifying structures that were already constructed was potentially too expensive. It was eventually found that the injection of air bubbles into the water flow stopped the damage under normal operating conditions. The bubbles provided nuclei, or sites, on which water vapor cavitation could grow. They then caused a major reduction of the speed of sound in the water, limiting the shock wave pressure intensities generated by the bubble collapse. Finally, the total collapse of the bubbles, containing vapor surrounding a core of air, could not be possible. After the vapor had condensed back to liquid, the air core of the bubbles acted as a shock absorber or cushion to eliminate the high pressures of total collapse. It was also found that a uniform roughness lessened damage by increasing the boundary layer thickness and decreasing the flow velocity at the bumps that would ordinarily initiate cavitation.

The Bureau then summarized its experiences with cavitation by producing a monograph (Falvey, 1990). It thoroughly explores the state of knowledge of cavitation as it relates to the water conveyance structures typically built and managed by them. For a more detailed treatment of the basic concepts of cavitation, Falvey recommends Knapp, *et al.* (1970). Part of this paper is a review of the Falvey monograph?

I will digress from a strict discussion of cavitation at numerous points. The purpose is to relate the process to other phenomena which may be more familiar. Necessary equations are found in the Falvey monograph, though some of the more important are reviewed in the Appendix. One of the computer programs supplied with the monograph was run, first on the Glen Canyon Dam tunnel profile, where damages were measured, and then on several other profiles, man-made, artificial, and natural. These computer model runs gave guidance on the possibilities of cavitation damage to water channel surfaces during flow conditions greatly exceeding those experienced during the 1983 floods. The results of these simulations will be presented in a subsequent article.

The Vapor Pressure of Water

While cavitation can occur in many liquids under the proper conditions, the Falvey monograph and this paper are restricted to cavitation in water. For a more comprehensive study in the change of phase between

*Along with the text, giving all relevant equations and some calibrations using actual structures, the publication includes a set of 5.25 inch floppy disks for use on an IBM compatible microcomputer. The original program code is provided in FORTRAN. One piece of software receives as input a nominated initial flow condition and structural profile. The output is a table of flow conditions throughout the structure, including parameters relating to cavitation. Some of the outputs can be graphs of a few parameters. Additional programs provide guidance for profiles having a constant cavitation index, for design of aerator slots for injecting air bubbles into the flow, and for estimating the damage index from a record of historical flow conditions.

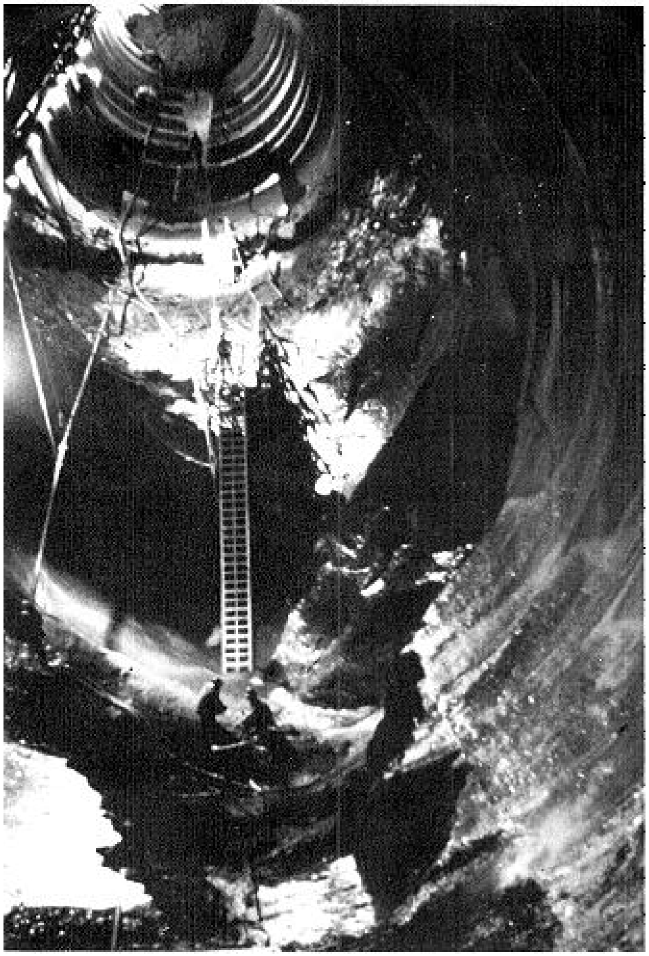

Figure 3. A view of the greatest cavitation-initiated damage in the left spillway tunnel of the Glen Canyon Dam, near Page, Arizona. The tunnel diameter is 12.5 meters; the ladder into the 10 m deep hole and the workmen provide additional scales. The largest surviving water-excavated boulder partly blocks the tunnel at the top of the view. (Photograph by Bureau of Reclamation)

liquid and vapor for water and the interaction of the phases of water with air, the reader can consult one of numerous standard textbooks in thermodynamics and physical meteorology (e.g. Byers, 1959). The concept of vapor pressure is vital to the understanding of cavitation processes. The brief descriptions below are not intended to convey a complete explanation of the process.

The saturation or equilibrium vapor pressure of water is the gaseous pressure of water vapor in equilibrium with a flat water surface at the same temperature. It is normally measured in the absence of other gases, but as described by Dalton's law, the presence of most other gases does not affect the water vapor pressure. In a mixture of gases and vapors, the total pressure is the sum of the partial pressures (or vapor pressures) of each gas. The vapor pressure of water increases with temperature, as described by Clausius-Clapeyron equation and is presented in numerous tables, such as in List (1963). That relationship is graphed in Figure 6a from -50°C through the normal melting and boiling points to the critical point at which the distinction between vapor and liquid vanishes. For interest, the vapor pressure of water above a flat ice surface is also presented in Figure 6a, while that for the liquid surface is extended to temperatures at which water is supercooled (colder than 0°C but still liquid). The vapor pressure is presented on a linear scale between -25 and 50°C in Figure 6b to provide more easily readable values for normal environmental temperatures. Figure 6c presents the difference between the vapor pressures over supercooled water and over ice, using the short scale in the bottom center.

Water boils at the temperature at which the vapor pressure equals the total atmospheric pressure. As the atmospheric pressure is decreased, as at higher elevations, water boils at lower temperatures. The boiling temperature of water can be increased by increasing the pressure in the vessel containing the water and vapor, as in a pressure cooker. The production of work by steam engines is done by the conversion of heat to steam (vapor) pressure.

Water (liquid) can also be made to change to the vapor phase by reducing the atmospheric pressure to below its vapor pressure at a given temperature. Water (liquid) can be made to evaporate if it is in contact with air whose water vapor partial pressure is less than the vapor pressure of the water at that temperature. Hot water evaporates more rapidly into the dry air than cold water because the higher vapor pressure of hot water creates a steeper vapor gradient, and therefore diffusion rate, at the air-water interface. The evaporation of water causes a transfer of energy from the liquid water to the water vapor in order to give the vapor molecules sufficient kinetic energy to escape from the liquid. The liquid is thereby cooled by the evaporation.

These effects can be illustrated in an interesting laboratory demonstration. A dish of water is placed in a Bell jar connected to a vacuum pump. The pump is then turned on, reducing the atmospheric pressure in the jar. When the pressure is reduced to and below the vapor pressure of the water, it will "boil" vigorously. The observed process is really cavitation, involving the decrease of pressure, rather than heat induced boiling. If the jar is continuously pumped,

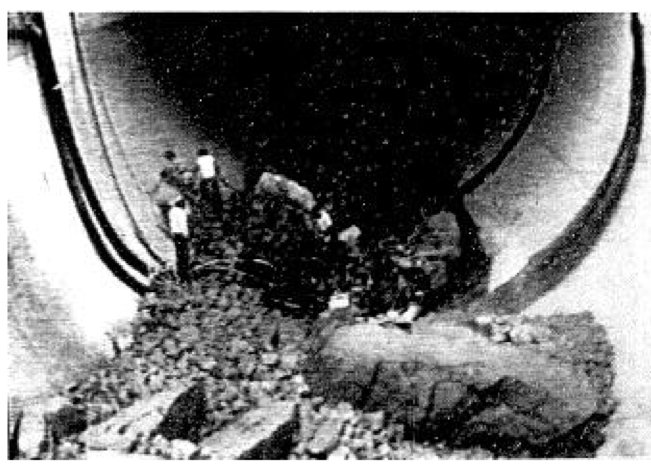

Figure 4. Other large boulders were excavated by the water and deposited at the end of the left spillway tunnel. The 12.5 meter diameter of the tunnel and the workmen provide a scale. (From Bureau of Reclamation video).

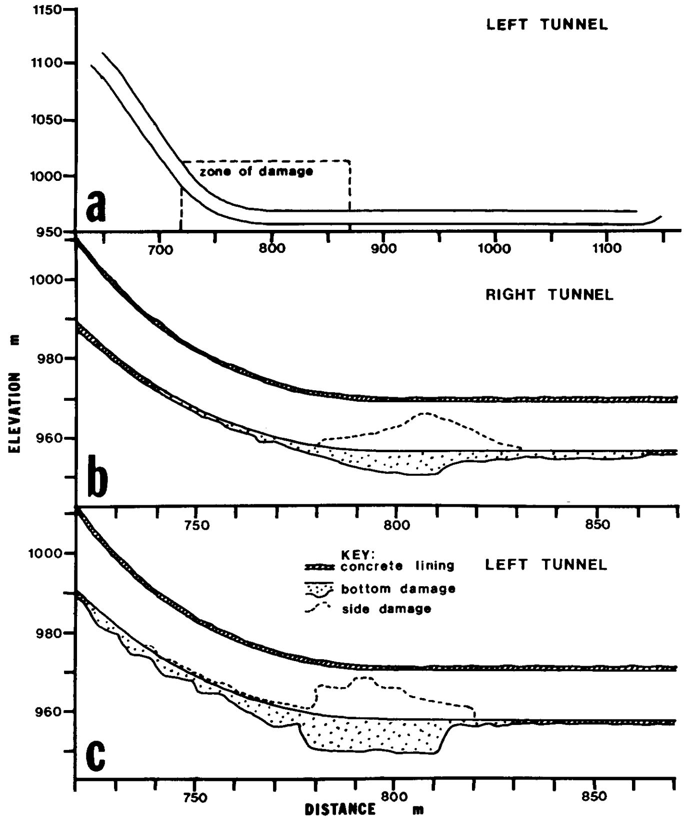

Figure 5. The vertical profile (a) of the left spillway tunnel of the Glen Canyon Dam. The damage extents and locations for the right (b) and left (c) tunnels are indicated by the dotted shading. The side wall damage extent is shown by the dashed lines.

eventually the dish of water is chilled so much by evaporative cooling that it freezes to ice.

Air is saturated with water vapor if its partial pressure of water vapor is equal to the vapor pressure of water at the temperature of the air. It is unsaturated if the partial pressure is less and supersaturated if it is greater. Water can be evaporated into unsaturated air. Evaporative cooling during the process is responsible for the operation of swamp coolers used for cooling in dry climates. It is also responsible for the cool air associated with summer showers (Holroyd, 1986) and the downbursts that have caused aircraft to crash.

The opposite of evaporation is condensation. Meteorologists can measure and describe the water vapor content of the air by the concept of "dew point" or "frost point." They are the temperatures at which water vapor will condense if unsaturated air is chilled. When a surface is provided that is colder than the dew (or frost) point of water in the air, then some of the vapor will condense out of the air until the vapor that remains adjacent to the surface has the pressure equal to the vapor pressure of water at the surface temperature. The condensation will be as ice if the surface is both colder than 0°C and the surface can nucleate the formation of ice; otherwise only supercooled water will be deposited on such a cold surface.

The difference between the two vapor pressure curves in Figure 6a, for vapor above ice and above supercooled water and graphed in Figure 6c, is responsible for the growth of most snow and therefore for much of the precipitation that falls to earth, even in the form of rain. Vapor molecules near the surface of an ice particle are at a lower vapor pressure than the water molecules near any surrounding supercooled water droplets. This pressure difference drives the water molecules from the liquid droplets to condense from the vapor onto the ice. The molecules can go from liquid to vapor to ice; the ice particle need not touch any supercooled droplets to grow larger at the expense of the droplets. Between –10 and –15°C the vapor pressure difference between ice and supercooled liquid is greatest. This may be partly responsible for the -15° peak in the ice crystal growth rate that is coincident with dendritic growth.

The understanding of vapor pressure is also needed for investigations of a possible pre-Flood vapor canopy (Dillow, 1983). In their numerical model of a vapor canopy, Dillow and Baumgardner arrived at canopy temperatures that were colder than the condensation temperatures for the given pressure profiles. The curve in Figure 6a shows the threshold temperature-pressure relation where the partial pressure of water vapor is used instead of the total atmospheric pressure. If the canopy were pure vapor, then the curve of Figure 6a would be exactly the lower temperature limit for the total atmospheric pressure at each altitude. Therefore their hypothesized canopy could not have existed by natural processes. Even so, their postulated total water content of the canopy (think "stratosphere" for those not familiar with the canopy theory) was only twice the water content of a saturated canopy. For a first attempt, that is encouraging; it could have been off by a factor of a thousand. Refinements of their model would be encouraged.

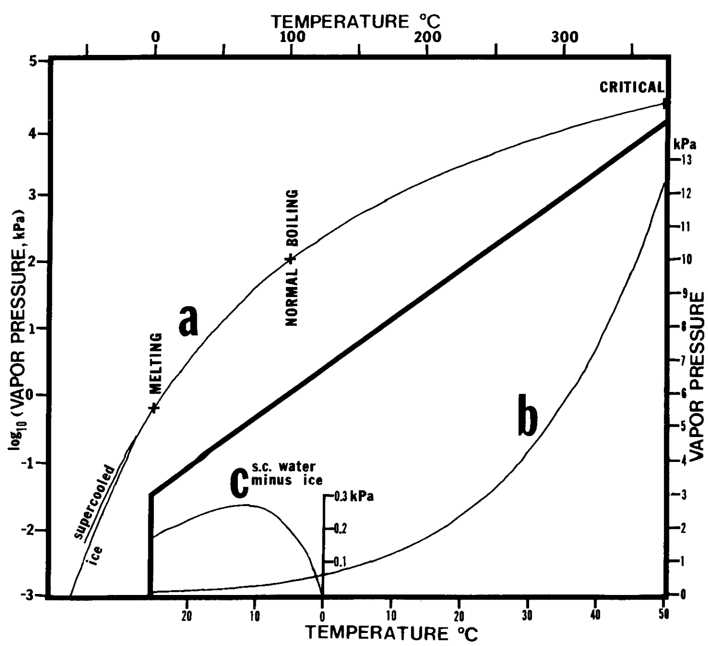

Figure 6. The equilibrium pressure of water vapor over water and ice surfaces. Curve (a) gives the entire temperature and pressure range for liquid water using the scales at the left and top. Curve (b) enlarges that portion of the range more appropriate to environmental temperatures using the scales at the right and bottom. Curve (c) shows the difference between the vapor pressures over supercooled water and over ice using the scales at the bottom and lower center.

This description of vapor pressure has been too brief to give full understanding of the concept. It has also digressed into other subjects not specifically related to cavitation. The purpose has been to show how vapor pressure is related to many other processes of interest. Creationist subjects that can involve water vapor pressure include cloud and precipitation physics for producing the pre-Flood mists, the rains of the Flood, the snows of any ice age after the Flood, and current weather phenomena; the structure of any vapor canopy whose collapse contributed to the Flood; the cavitational assist (the subject of this paper) to erosion processes during and after the Flood; the physics of superheated waters for hydrothermal deposit and dissolving of minerals; and the role of steam in the pressures of volcanism.

The Mechanism of Cavitation

As mentioned above, the difference between boiling and cavitation is that boiling involves the vaporization of water by the addition of heat to water; cavitation is the vaporization of water as a result of the decrease of pressure in the water. The pressure at any point within a fluid is the sum of static and dynamic pressures. Static pressure is generally from the weight of all of the fluid above that point, including the atmosphere. Dynamic pressure is the additional contribution, positive or negative, that results from the movement of the fluid. Positive dynamic pressure is similar to the pressure of the wind or of water flow against a stationary object. Negative dynamic pressure occurs, for example, in the air above the curved wing surface of an aircraft causing it to fly.

The cavities produced by pressure decrease need not be of pure water vapor; other gases may be present. Gaseous cavitation occurs when cold water is warmed, forcing dissolved air to come out of solution and form bubbles. Gaseous cavitation is also observable when the pressure is reduced by opening a container of a carbonated beverage and bubbles of mostly carbon dioxide are formed. Similarly, the reduction of pressure as a diver rises from deep water causes the formation of bubbles of nitrogen gas in his blood, leading to the bends. All of these are examples of cavitation.

Cavitation is the mechanism by which ultrasonic cleaners operate. The sound waves not only cause the pulsation of the boundaries of bubbles (if any) injected into the water, but may so reduce pressures at the water interface with a solid object that bubbles of pure water vapor rapidly form and collapse. The rapid fluctuation of bubble surfaces touching the object provides the forces to flush the contaminating substances away from that surface.

On several occasions this author has flown in an unpressurized aircraft to altitudes above 20,000 feet (6 km) where the atmospheric pressures were 30 to 40 kPa. (All crew members and passengers were breathing through oxygen masks.) By creating a strong sucking action inside my closed mouth I could feel the saliva bubble as cavitation was produced by the reduced pressure. The sucking created a pressure in my mouth less than the 6.3 kPa vapor pressure of water at 37°C. Apparently my mouth is not strong enough to initiate cavitation against atmospheric pressures in excess of 40 kPa at lower elevations.

The concept of sucking is perhaps helpful for understanding the initiation of cavitation in water. Ship propellers are subject to damage by cavitation. While the screw action creates increased pressures on the aft side of the propeller, where it pushes against the water, a decreased pressure occurs on the fore side of the propeller. That pressure decrease, for hard-working propellers, can be sufficient to vaporize water. The propellers then become severely pitted and lose efficiency.

Dynamic pressure decreases also occur in water valves, pumps, and gates that regulate the flow of high speed water. Figure 7 illustrates the cavitation damage done to a steel valve surface 25 cm in diameter. The irregular pitting and sharp edges are indicative of cavitation rather than ordinary erosion, which would have produced striations and smooth bumps. Concrete and rock do not have as much strength as steel to resist the damage of cavitation.

Part of Bureau of Reclamation's studies of the cavitation processes were conducted in a vacuum chamber with scale models. By greatly reducing the atmospheric pressure on the model, cavitation could be achieved with low flow velocities. Figure 8 shows the bubbles produced by an obstruction. The damage occurred downstream (right) where the bubbles fade away.

Damage from Cavitation

The bubble formation itself does not create the damage of cavitation. It is the downstream collapse of those bubbles, where pressures are restored in excess of the vapor pressure, that can subject solid surfaces to shock waves and water jet impacts. Falvey (1990) summarizes two methods that may be involved. Bubbles that collapse within the water send out shock waves. As these shock waves encounter another bubble, they subject it to a pressure increase that is likely to cause the collapse of that bubble as well. The newly collapsed bubble adds its energy to the shock wave. In this manner the bubbles collapse in phase and together create a shock wave of large amplitude. The mechanism is similar to the operation of a laser, in which the emission of light from individual atoms is triggered by the passage of the light wave front past the atom. When the shock wave produced by the

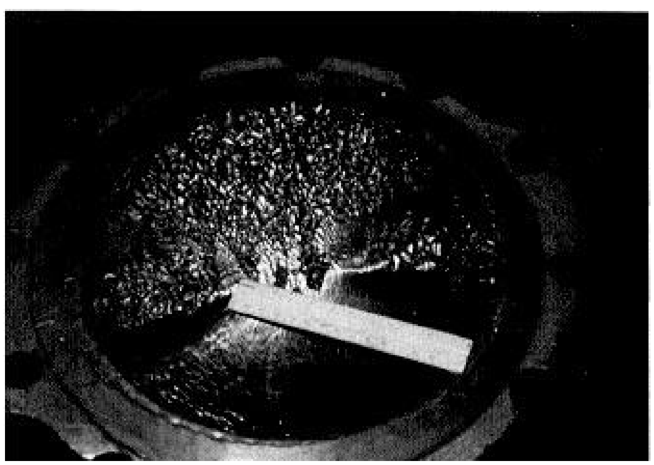

Figure 7. Cavitation pitting in the steel surface of a valve. A 15 cm (6 in) ruler provides a scale.

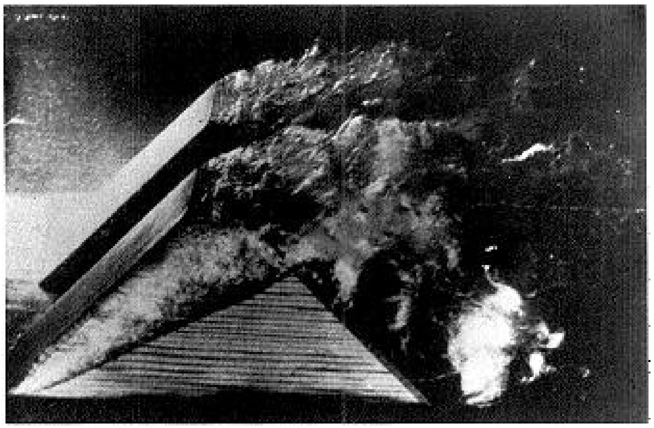

Figure 8. The turbulence and vortices downstream of an obstruction cause the production of cavitation bubbles in this scale model. The greatest surface damage occurred where the bubbles vanished. (Photograph by Bureau of Reclamation)

collapsing bubbles reaches a solid surface, even if there are no bubbles there, they strike the surface with a considerable force. The present theory suggests that the magnitude of the pressures that are generated can exceed 200 times ambient pressure.

The other mechanism for damage is for bubbles in contact with a solid surface when they collapse. The contact gives the bubbles a slight to major asymmetry. The dynamics and wave mechanics of the collapse cause a water jet to be initiated on the bubble surface opposite the solid surface. Naude and Ellis (1961) examined the process. They showed high speed motion picture frames of such a collapse, but the photographic technique can only show a dimpled bubble surface and not the jet itself. Their jets pitted aluminum with a yield strength in excess of 300 MPa, or 3000 times normal atmospheric pressure.

The bubble collapse dynamics, at slower speeds for an air bubble in sea water at the upper air-water surface has been illustrated in Woodcock *et al.* (1953) by a series of photographs, one of which is copied in Figure 9. The water surrounding the bubble parts first at the solid surface. Surface tension and wave mechanics then cause a rapid flow of water around the inner surface of the bubble to converge at the point of the bubble farthest from the solid surface. The convergence causes a mound and then a jet of water to rebound from that convergence point towards the interface surface. In this figure the jet fragments at its tip into several water droplets. In the collapse of a cavitation bubble at a solid surface, the jet strikes the solid at high speed. That speed is considered to be near sonic (>1400 m/s) speeds. The summary in Falvey (1990) suggests that additional laboratory and theoretical work is still needed for both mechanisms of proposed damage initiation.

Falvey (1990) gives some preliminary indications of the relative strengths of some materials in terms of the amount of time to achieve the same amount of damage from cavitation. Reinterpreting those approximate values to a relative scale gives concrete—1, polymer concrete—42, aluminum or copper—80, plain carbon steel—286, stainless steel—2000. In this review some values for granite, sandstone, shale, and limestone would have been desired, but the concrete value might approximate that for limestone. There is an obvious need for laboratory calibrations for various rocks.

Indicators of Cavitation

In order to anticipate possible cavitation damage to man-made structures while still in the design phase, it is helpful to have some predictive capability based on known physical principles. Once structures are built, it is additionally helpful to have some guidelines for recognizing cavitation-initiated damage while it is still small in extent. Some of the descriptive equations given in Falvey (1990) and important to an understanding of cavitation in practical water flow conditions are given in Appendix I.

There are three numbers among the equations that are used to describe several aspects of the cavitation process: the cavitation index, the cavitation damage potential, and the damage index. It is challenging for those who do not use the terms regularly to distinguish between them. Their definition equations are repeated in Appendix I.

The cavitation index has as its numerator the difference between the ambient water pressure and the vapor pressure of water at its particular temperature. Water will vaporize into bubbles to prevent this difference from becoming negative. Therefore shallow water (small static pressure) is more likely to produce cavitation than deep water. Hot water is also easier to cavitate because of its higher vapor pressure. The denominator is the ambient kinetic energy of the water and therefore is proportional to the square of the water velocity. Low ambient water pressures and high water speeds make the cavitation index a small number, approaching zero. The smaller the index, the easier it is for some bump in the water channel to create a local eddy that results in the vaporization of

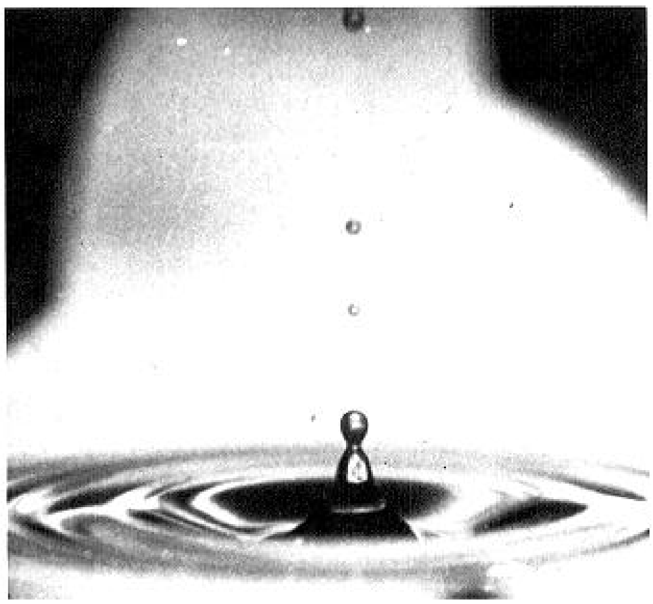

Figure 9. A water jet reduced by the asymmetric collapse of a 1.0 mm diameter air bubble at an air-sea water interface. The photo from Woodcock et al. (1953) was taken by C. F. Kientzler with an exposure time of 30 microseconds. The smallest droplet diameter was 0.09 mm. A similar jet may strike a surface in contact with a collapsing cavitation bubble.

water into cavitation bubbles. The cavitation index is therefore an estimate of how easy it is for cavitation to be initiated.

The second number is the damage potential. It addresses the question, given that cavitation is likely to occur at a location, of how strong the damaging forces will be. Falvey points out that the damage potential is inversely proportional to the cavitation index and appears to be proportional to the sixth power of the water speed. Using the flow conditions for the threshold of cavitation as a reference, the damage potential number is defined, as in Appendix I, by comparing actual flow values with the reference values. The damage potential was crudely calibrated in the monograph by comparing actual damage at several dams with the theoretical damage potential numbers. Values of damage potential for "incipient," "major," and "catastrophic" damage are given as 500, 1000, and 2000, respectively. The damage at Glen Canyon Dam was considered to be "catastrophic." It is the behavior of the damage potential that will be examined in a subsequent article.

The third number includes a time factor to estimate the degree of damage. If a flow produces a high but brief damage potential, there will not be as much destruction as if the condition was sustained. Furthermore, cavitation damage appears to be somewhat self-limiting. Surface damage will produce a roughening that will slow the water and increase the boundary layer thickness, increasing the cavitation index and lessening the damage potential. Cavitation damage also makes the solid surface recede from where the bubbles were collapsing, thus reducing the shock pressures at the surface. Large excavations of the solid surface, as illustrated in Figure 3, fill with calmer water and shield the surface from the stronger flows. It is then that ordinary erosion replaces cavitation as the damage mechanism.

To express both the time factor and the self-limiting nature of cavitation, Falvey defines the damage index. It multiplies the damage potential by the logarithm of elapsed time at the particular flow condition. Some of the terms are cumulative to account for the effects of previous flow conditions. Using the same three threshold names, values of the damage index are crudely calibrated at 5000, 10,000, and 20,000 for incipient, major and catastrophic cavitation damage, respectively.

The equations for the growth and collapse of bubbles of various air contents are not presented here. As with boiling, nuclei are needed for bubble initiation. These can be microscopic air bubbles. The collapse equations indicate that the radius of the bubbles decreases rapidly, which contributes to the generation of shock waves. The pressure intensity of an example, as estimated for a distance of about two initial bubble radii from the collapse center, is about 200 times the ambient pressure of the region. The shock wave propagates at the speed of sound in water (about 1400 m/s). The addition of air bubbles into the water lowers the speed of sound in the surrounding water to at or below the speed of sound in air (about 340 m/s). This effect significantly decreases the shock pressure intensities at the solid surface.

Falvey summarizes theoretical cavitational characteristics for a variety of general flat and curved profiles of water channels. A variety of surface irregularities, both into the flow and away from it, and of several geometrical shapes were investigated. Concrete structures do not remain smooth, even if so constructed. There may be displacements along joints as slight settling occurs. Water seeping through cracks in the concrete can rapidly create calcite deposits similar to stalagmites during periods in which the structures are not in use. Many observations and experiments relating to such deposits are summarized by Gish (1989). Normal erosion, dissolution, and freeze-thaw damage can change the surface texture of the concrete. While bumps in a smooth surface are likely origin; for cavitation, it was found that uniform roughness could create a thicker boundary layer and decrease the damage from cavitation.

Cavitation damage can be recognized by its texture, locational symmetry, and origin. Part of the damage is caused by a pressure wave that travels at the speed of sound in water, typically 10 to 40 times the flow velocity. Other damage may be caused by minute water jets aimed directly at the solid surface. Therefore the damage appears to be formed by a source that is perpendicular to the surface. Cavitation damage in metal is pitted irregularly rather than striated (Figure 7). Damage to concrete consists of loss of the matrix, including shapes which look like crevices and worm holes, and a polishing of the aggregate. Perhaps a water hammer phenomenon also occurs in some of the holes. Erosion of concrete, however, by sand-laden water, polishes both the aggregate and the matrix. Freeze-thaw damage breaks both the aggregate and the matrix. Cavitation damage always occurs downstream from its cause and never propagates upstream. Surface irregularities that cause cavitation are left intact and can be inspected upstream of the damaged area.

A bump (it can also be an offset into or away from the water stream) creates a flow disturbance that results in a dynamic pressure decrease sufficient to create cavitation bubbles, as illustrated in Figure 10. These bubbles collapse downstream and damage the nearby surface. Prolonged damage produces another flow disturbance, more bubbles, and more damage. The surface downstream of a bump can thereby develop a chain of craters. That was the form of the damage upstream of the largest hole in the Glen Canyon Dam left spillway, as illustrated in Figure 11. This series of holes was about 3 m deep and 6 m wide. They made a series of small waterfalls at the time the scene was recorded.

Sometimes the flow geometry creates longitudinal vortices, with reduced central pressure (like tornadoes and aircraft wing-tip vortices in air, and like gurgling whirlpool drainages in water). Longitudinal motion in the form of a pair of counterrotating vortices is produced by water flowing in a circular tube that is itself smoothly bending, like where the Glen Canyon spillway tubes change from steep descent to nearly horizontal flow and also in the flip bucket at the end of the horizontal section. In cross section, water initially descends in the center and rises at the edges. This is partly the cause of the U-shaped cross section of the water being thrown into the air by the left flip bucket in Figure 12. The same shape of vortices can be seen,

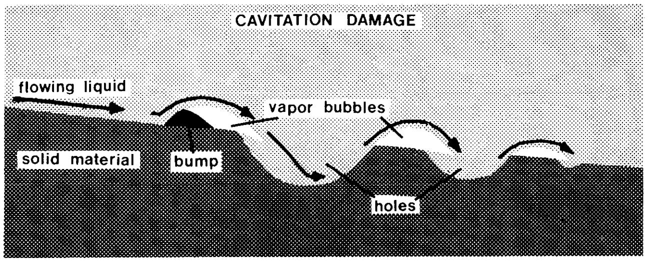

Figure 10. Cavitation damage can occur to a solid surface by the formation and collapse of vapor bubbles downstream of a bump. Large holes can cause more downstream cavitation and damage.

though vertically inverted, in a steam or smoke plume emitted by a smokestack into windy air. Cavitation damage created by such longitudinal vortices will not have exact origins, like surface bumps, to identify them.

Once a hole is started by cavitation, the flow of water begins to be diverted into the hole. High velocity water will impinge on the downstream end of the hole, creating higher pressure there compared to the ambient pressures. The high pressure water typically finds minute cracks and forces them to enlarge. The destructive process then changes from cavitation to normal erosion as large chunks of material are ripped out of the surface of the water channel. Whereas pitting from cavitation tends to be at random locations, erosion tends to be more organized and striated.

Surface roughness, however, is of considerable practical interest. Falvey mentions that very smooth concrete surfaces can be made with rugosities of 0.015 mm by pouring the concrete into special steel forms. Rugosities of 1.5 mm would represent the other extreme for rough plywood forms and misaligned construction joints. Such an increase in rugosity by a factor of 100 reduces the damage potential by a factor of 3.2 in one example. While isolated irregularities initiate cavitation, uniform irregularities reduce it. Natural channels will have large roughnesses and therefore less potential for cavitation damage.

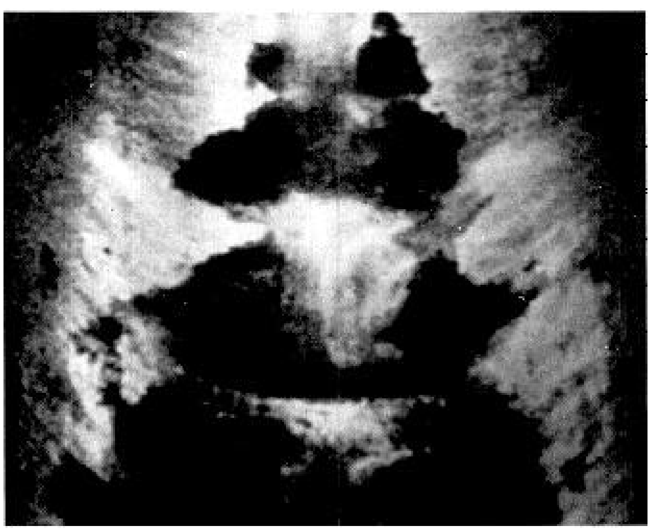

Figure 11. The first cavitation-induced holes in the left spillway were a series in which each one triggered the formation of the next. They were about 3 meters deep and 6 meters wide. (From Bureau of Reclamation video)

Falvey presents an entire chapter on the design of aerators for the purpose of introducing air bubbles into water flows. The air bubbles reduce the sonic velocity in the mixture. It has been found that cavitation damage varies inversely with air content of the water at mole concentrations between 8 and 20 x 10^{-6}. At about 0.07 moles of air per mole of water, cavitation damage is completely eliminated. The Bureau of Reclamation's solution at the Glen Canyon Dam was to create an air slot part way down the spillway tunnel. It can be seen in Figure 13 as the dark ring at the top of the view. A man can be seen standing beside a small stream of water in the tunnel and beside dripping water from the ceiling of the tube. He is standing near the former location of the holes of Figure 11. After construction of the air slot the spillway was tested at water flows greatly exceeding those which caused the catastrophic damage of 1983. There were no traces of any damage after these tests. So the solution of creating an air slot was highly successful and will prevent any more damage from cavitation in the future.

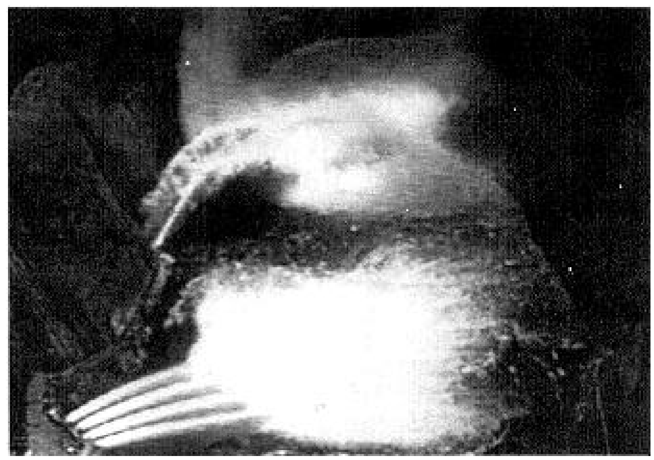

Figure 12. A view downstream at the Glen Canyon Dam showing water flowing from the four by-pass tubes (foreground) and the left spillway tunnel (background). The circular cross section of the spillway tunnel and the circular vertical curvature at the water exit cause a U-shaped profile to the water, as revealed by the shading in the water plume. (From Bureau of Reclamation video)

This effect of air bubbles is of vital importance in dealing with natural water channels. Any channel irregular enough (boulders, ledges, sharp turns) to create "white water" by its turbulence is unlikely to be damaging its channel bed by cavitation. There is too much air mixed into the water. It is the high speed clear turbulent flow that is damaging.

Discussion and Conclusions

The process of cavitation is generally familiar to our experiences but rarely recognized. Engineers are more likely to recognize its presence, especially when they must design equipment to avoid damage from cavitation. The physics of cavitation involves numerous phenomena with which we can relate in our common experiences, the most important of which is the physics of water vapor. As considered in this paper, cavitation is the creation of water vapor bubbles within liquid water by the reduction of pressure

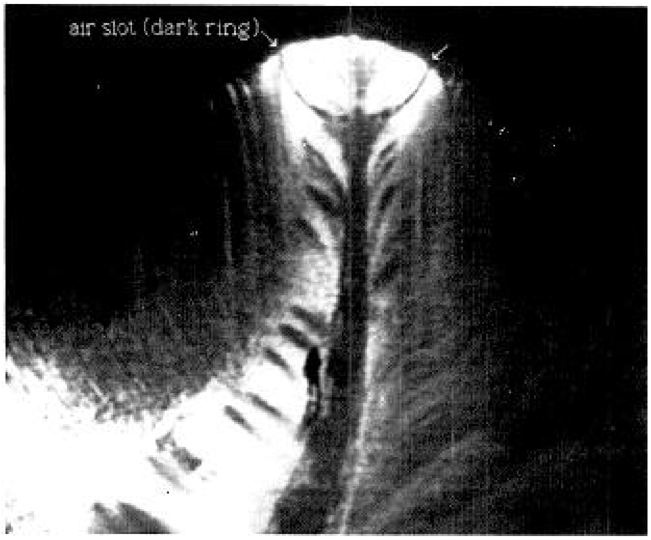

Figure 13. The air slot constructed in the left spillway tunnel of the Glen Canyon Dam is seen as the dark ring at the top of the view. By reducing the speed of sound in the water and somewhat by providing a cushion of air bubbles the new slot now prevents cavitation damage in the spillway by greatly reducing the speed of sound in the water. (From Bureau of Reclamation video)

to the vapor pressure of water at the temperature of that water. The term cavitation has been erroneously extended to include the damaging processes associated by the collapse of those bubbles.

The process of cavitation damage relating to water conveyance structures was explored with the help of a monograph on cavitation and the accompanying software packages. The monograph findings have been summarized above; the software simulations are being left for a subsequent article. Variables of particular importance during the process of cavitation are the head of water (energy available from elevation changes), water depth and speed (affecting the static and dynamic pressures), water temperature (affecting the vapor pressure), surface roughness, material strength, and especially air bubble content.

The thesis of Paiva (1988) also addressed the process of cavitation in catastrophic flows. It is mostly a theoretical work paralleling parts of the Falvey monograph. He discussed several related phenomena that appear to be worthy of further investigation. Among them is mentioned the possibility that the pressure fluctuations during bubble collapse might achieve a frequency that resonates with the natural frequency of the bedrock. If that happens, then the rock would disintegrate rapidly. But Falvey suggests that typical cavitation frequencies are greater than 10 kHz and that rock frequencies are less than a few Hz. It would be useful to establish these frequencies more precisely.

Paul M. MacKinney has been wondering if the cavitation damage in 1983 at the Glen Canyon Dam created detectable seismic vibrations. Falvey (private communication) mentions that the Army Corps of Engineers tried to detect cavitation seismically at the Hoover Dam in 1983. Their measurements located the tunnel, but the communication did not mention the magnitude of the vibrations.

Hot water cavitates more readily than cold water, so large water flows heated by volcanic activity are candidates for destruction of the landscape by cavitation processes. One might investigate if the process of hot water cavitation could have caused the rapid breaching of the Vulcan's Throne lava flow that temporarily plugged the Grand Canyon in the geologically-recent past.

None of the present theoretical work addresses what happens if the vapor bubbles coalesce into large bubbles. It would seem reasonable that forces of collapse would operate over a greater distance (bubble radius) and release a greater energy. Perhaps it might result in greater surface damage.

The boulders shown in Figure 4 are similar in size and texture to those found in the conglomerate at the bottom of the Tapeats sandstone in the Grand Canyon. This is the first layer above the Great Unconformity, and the boulders of the conglomerate appear to have been formed from the underlying rock species. Yet the Great Unconformity is widespread flat surface. From where did the boulders come? To move them in from elsewhere would have required large, widespread flows of water approaching the conditions (the computer simulations indicated about 40 m/s speeds) that created and moved the boulders at Glen Canyon Dam. Those conditions were also conducive to the processes of cavitation.

There is much opportunity for further research into numerous phenomena related to the process of cavitation. But even with the present knowledge and actual experience it appears that the rapid destruction of rock by the process of cavitation can greatly assist the process of normal erosion in removing rock from water channels during truly catastrophic flows of water. Thousands or millions of years are not necessarily needed for the carving of some valleys and canyons if the process of cavitation becomes involved.

Acknowledgments

The author first became sensitized to the possible role of cavitation in catastrophic floods while attending the First International Conference on Creationism (Holroyd, 1987). While Austin (1986) briefly mentioned cavitation in an article about erosion at Mt. St. Helens, one of the other conference attendees, Paul M. MacKinney, was championing the process and possible effects of cavitation during the Flood in the private conversations during breaks and mealtimes and in a short presentation one afternoon. It is therefore in response to the interest of Mr. MacKinney that this present introductory study was initiated.

The contents of this article have been greatly improved through discussions with many people. The greatest help came from the engineers of the Bureau of Reclamation, who also provided draft copies of the Falvey monograph beginning in mid-1988. The comments of Paul M. MacKinney, Steve Austin, and Duncan C. Blanchard have been helpful. Dr. Blanchard provided Figure 9 and a copy of the Naude and Ellis article showing the actual collapse of cavitation bubbles at a solid surface.

Parts of this study were funded by interest from the contributions to the Creation Research Society Laboratory Fund (1306 Fairview Road, Clarks Summit, PA 18411). Image processing software for the microcomputer system was made available by MicroImages, Inc., 201 N. 8th, Suite 15, Lincoln, NE 68508-1347.

Appendix I. Equations of Cavitation

Some of the equations given in Falvey (1990) important to an understanding of cavitation in practical water flow conditions are reviewed. The monograph can be examined for the rest. Steady state water flow can be described by the Bernoulli equation in the form,

$$v^2_0/2 + P_0 + Z_o g = v^2/2 + P + Z g \qquad (1)$$

where = density of water
v = flow velocity
P = absolute pressure
Z = elevation
g = gravitation acceleration constant,

and the subscript o refers to an upstream flow location. The equation can be rearranged to a dimensionless form that introduces the pressure coefficient or Euler number, C_P:

$$c_P = 1- (v/v_0)2$$
$$= [(P+ Z g) - (P_0 + Z_0 g)]/(pv^2_0/2) \qquad (2)$$

When the pressure is reduced by turbulence or vortices to the vapor pressure, P_v, of the water, then the onset of cavitation is reached. This threshold is represented by the cavitation index, σ:

$$\sigma = -C_P \text{ at } p = p_v \qquad (3)$$

The vaporization of water will prevent the pressure from lowering below P_v. For negligible elevation difference between the reference and sample locations, this can simplify to:

$$\sigma = (P_0 - P_v)/(pv^2_0/2) \qquad (4)$$

This cavitation index is mostly a function of the ambient pressure and the flow velocity. For the perturbation caused by an abrupt obstruction extended into the flow, σ = 1.8 is the threshold for the first bubbles. The computer model of the left tube of the Glen Canyon Dam gave σ = 0.1 near the points of severe damage under high flow and smooth surface conditions. Cavitation is more intense as σ decreases towards zero as either the ambient pressure is decreased or the velocity is increased.

The Falvey monograph indicates that cavitation damage is inversely proportional to the cavitation index and approximately proportional to the sixth power of the velocity. He introduced the term, D_P, damage potential, as

$$D_p \propto [1/\sigma - 1/\sigma_r][v/v_r]^6 \qquad (5)$$

where σ_r, is the cavitation index and v_r is a reference velocity for the initiation of damage. He gives some approximate damage potential thresholds for incipient, major, and catastrophic damage as D_P = 500, 1000, and 2000, respectively.

As damage actually occurs, the surface is eroded away. Water flow is diverted somewhat into the resulting cavity. Large surface cavities may cushion the flow of water into them. But ultimately the surface recedes away from the location at which cavitation bubbles are collapsing. For steady flow the amount of further damage that can be done by cavitation lessens with time. To express this relation Falvey also introduces the term D_i, damage index, as

$$D_i = D_p \ln(t - t_O) \qquad (6)$$

where t is the time and t_O is a constant of integration set to –1 for the start of operation of a structure. For later times and differing flows,

$$t_O = t_C - \exp(Di/D_P) \qquad (7)$$

where t_c is the cumulative time of operation of the structure, D_i is the damage index at the end of the previous discharge, and D_P is the damage potential for the next discharge. Therefore the damage index combines both the intensity of the flow (damage potential) and the passage of time. For the same three damage categories, incipient, major, and catastrophic, D_i = 5000, 10000, and 20000, respectively.

References

CRSQ—Creation Research Society Quarterly

Austin, Steven A. 1986. Mount St. Helens and catastrophism in Walsh, R. E., C. L. Brooks and R. S. Crowell, editors. Proceedings of the First International Conference on Creationism. Volume I. Creation Science Fellowship. Pittsburgh. pp. 3-10.

Bureau of Reclamation. 1984. Challenge at Glen Canyon. 27-minute video. Denver.

Byers, Horace Robert. 1959. General meteorology. McGraw-Hill, New York.

Dillow, Joseph C. 1983. The vertical temperature structure of the pre-flood vapor canopy. *CRSQ* 20:7-14.

Falvey, Henry T. 1990. Cavitation in chutes and spillways. Bureau of Reclamation. Denver.

Gish, Duane T. 1989. More creationist research (14 years) —part I: geological research. *CRSQ* 25:161-70.

Holroyd, Edmond W., III. 1986. Some notes on the timing of precipitation and the thermodynamics of afternoon showers. *CRSQ* 23:8-10.

________________ 1987. International Conference on Creationism. CRSQ 23:174-76.

Knapp, R. T., J. W. Daily and F. G. Hammitt. 1970. Cavitation McGraw-Hill. New York.

List, Robert J. 1963. Smithsonian meteorological tables. Sixth revised edition. Smithsonian Institution Publication 4014. Washington, D.C.

Naude, Charl F., and Albert T. Ellis. 1961. On the mechanism of cavitation damage by nonhemispherical cavities collapsing in contact with a solid boundary. *Journal of Basic Engineering* 83:648-56.

Paiva, Clifford A. 1988. Cavitation in macro-fluvial processes and the implications for geologic time. Masters Thesis, Institute for Creation Research, El Cajon, CA.

Woodcock, A. H., C. F. Kientzler, A. B. Arons, and D. C. Blanchard. 1953. Giant condensation nuclei from bursting bubbles. *Nature* 172:1144.

QUOTE

Since Sartre also argues that man's goal is to become God, self-psychology often can be interpreted as a commercialized American packaging of much of European existentialism.

Vitz, Paul C. 1987. Secular personality theories: a critical analysis in Burke, T. J. editor. *Man and Mind: A Christian Theory of Personality.* Hillsdale College Press. Hillsdale, MI p. 90.

INDEX TO VOLUME 26 OF THE CREATION RESEARCH SOCIETY QUARTERLY

S

T

V

W

ARTICLE AND BOOK REVIEWS

LETTERS TO THE EDITOR

QUOTE

Leaving the institution of kingship aside, young sociologist Jean-Pierre Dupuy from the Ecole Polytechnique presents (in *Ordres et desordres*, Paris, 1982) a complementary thesis. Modern society's crisis should be explained by the fact that it recognizes no reference-system beyond and above itself, so that the citizen acknowledges no transcendental source of authority or ordering principle. Everybody being equal like gas molecules in a container, the constant agitation appears to be the only "law," motivating each molecule to rise to the top. This is what classical authors used to call "anarchy," the end-product of democracy's inherent logic.

Molnar, T. 1987. Crisis. ***Modern*** Age 31:215.