Distinctive Features of Grand Coulee Outlets

Model Tests Disclose Unexpected Low-Pressure and Spray Problems and Lead to Modifications in Conduit Profiles as Well as in Exit and Entrance Details

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With great advances in the size and design of engineering structures, engineers are finding the model laboratory increasingly useful. The laboratory fills a unique need in supplying to a large extent the only substitute for precedents that do not exist. In this paper, originally presented before the Hydraulics Division at the Society's Denver Convention, Mr. Warnock presents concretely the story of the successive surprises encountered in developing outlets for one of the world's greatest dams.

With the development of larger structures, the increased head and larger quantities of water involved have made the problems of outlet design more complex. In the case of one large dam already constructed, an outlet through the spillway developed an excessive seepage leak near the upstream end after operating only a few weeks. Improper shape and position of the entrance had caused severe cavitation and the loss of considerable material in the roof of the conduits. In another case, the spray from the outlets was so excessive as to forbid release of water except in cases of extreme necessity.

In preparing for the Grand Coulee outlets, how were these known faults to be corrected? How were other errors in assumption or design to be avoided? Precedent could be of no assistance. The only expedient remaining was the use of models for a step-by-step design.

At Grand Coulee Dam, sixty 8-ft 6-in. outlets in tiers of 20 each have been provided to release 225,000 cu ft per sec. On preliminary drawings, Fig. 1 (*a*), the outlets were rectangular in cross section (5 ft 8 in. wide by 10 ft 6 in. high), longitudinal in plan, horizontal in section, and unlined. One tier of 20 outlets was at approximately El. 935.00 and the other tier of 20 at El. 1,110.00.

Severe splash and erosion were found to result from this design when it was tested in a 1:120 model representing the complete ultimate development. The jets from the lower tier impinged on the water surface downstream from the spillway bucket, and the upper tier produced practically the same result except that the scour in the river was even more severe. The destructive conditions were extreme, particularly along the riprapped banks of the power-house tailraces, and as a result of this undesirable situation the outlets with horizontal inverts were abandoned.

The outlets were next changed from rectangular to circular in cross section and placed on parabolic paths through the dam (see Fig. 1, *b*) so that the jets would plunge into the spillway stilling pool. The invert of the lower conduits was placed tangent to the spillway bucket, and pairs of outlets were made to diverge in plan to improve the energy dissipation. This became the final design of the lower tier at Grand Coulee except for a later entrance refinement to prevent sub-atmospheric pressures.

While the early studies were in progress, reports came from the Madden Dam on the Chagres River in the Panama Canal Zone, that a portion of the conduit roof in the outlets immediately downstream from the entrance had been destroyed after only a few weeks' operation. Apparently sub-atmospheric pressures and cavitation were produced by an incorrect shape of entrance and by a position of the conduit at an elevation too near the floor of the reservoir.

To avoid a repetition of these conditions at Grand Coulee, a series of entrance investigations was instituted. A cylindrical pressure tank (Fig. 2) 3 ft in diameter and 5 ft long was constructed with concentric distributing cones and a stilling rack to produce approach conditions similar to those in the prototype. A sharp-edged orifice was placed at the downstream end of the tank, and a detailed survey of the jet from this orifice was made with a specially designed instrument. The slope of the upstream face of the dam and the position of the control gates for the outlets had been established previously. With these limitations, and with the surveyed shape of the free jet, a bell-mouthed entrance with a converging elbow was developed. A model was installed in the pressure tank in place of the orifice, and detailed pressure measurements showed that the pressures throughout the

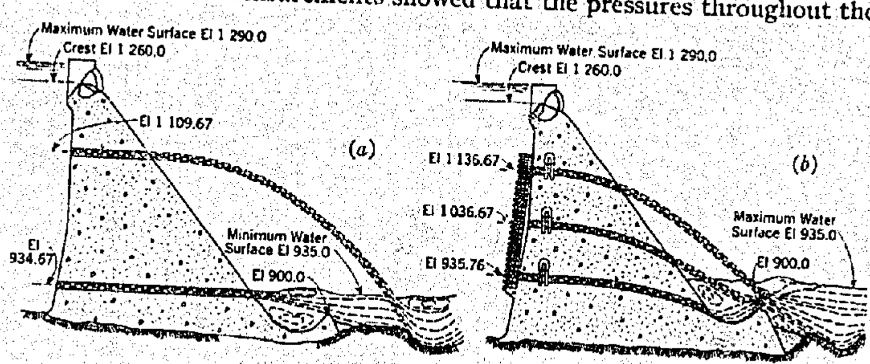

Fig. 1. Early Designs for Grand Coulee Outlets
(*a*) Straight Discharge Caused Prohibitive Disturbances Downstream from Bucket
(*b*) Parabolic Profiles Also Missed Bucket, Produced Cavitating Pressures in Conduits

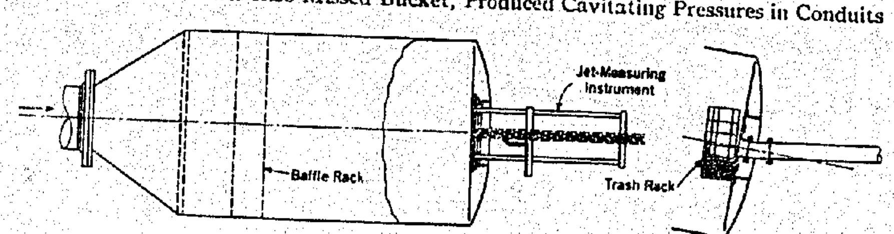

Fig 2. Pressure Tank for Study of Jet and Entrances
Trash Rack for Test of Entrances Designed from Modification of Free Jet Profile

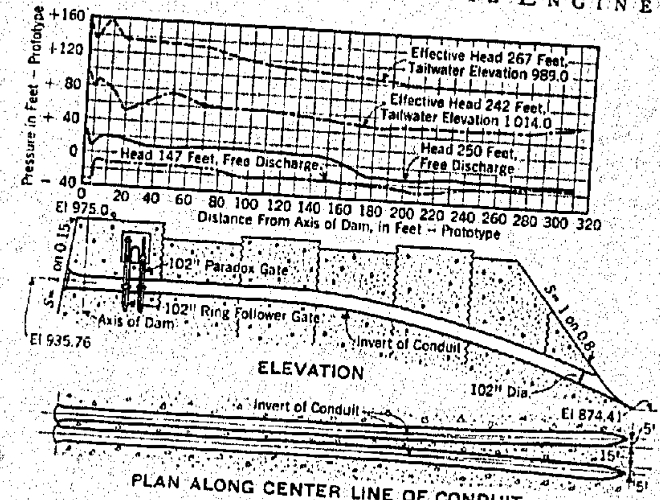

FIG. 3. PRESSURES IN LOWER TIER OF OUTLETS
Conduit Discharges Directly Into Spillway Bucket, Normally Submerged

bell mouth and converging section were above atmospheric.

Since the trashrack structure might affect the entrance pressures, particularly for the lower outlet because of its proximity to the base, a replica was installed in the hydraulic model as indicated in Fig. 2. The tests revealed that the position of the bottom of the trashrack had the most influence while the effect of rib placement was negligible. A decrease in pressure along the top of the entrance resulted when the bottom of the trashrack was moved toward the opening. A position was finally chosen that gave positive pressures in the entrance and a velocity distribution such that no trouble should occur downstream.

"DOWN-PULL" ON GATES ELIMINATED

The acquisition of high-pressure pumping equipment for the study of the outlet entrance for the first time permitted a laboratory investigation of control gates. In the initial tests, made on a model of the Norris Dam penstock inlet tractor gates, the presence of a greatly augmented downward force was noticed when the gate leaf approached the closed position or during the first part of the opening cycle.

The control gates for the lower outlets at Grand Coulee are of two types. The upstream or emergency control is a ring-follower gate operated by a hydraulic piston. The downstream or service control is a paradox roller gate operated by motor and gear train connected to the gate stems. The gate leaves in the two types are fundamentally alike in that each has at the bottom a follower ring which comes into position when the gate is fully open, making the conduit an unbroken passage through the gate section.

In operating the model gate it was found that the force required to lift it at small openings was greatly in excess of the dead weight of the gate. When reversed in position, with the normally upstream face turned downstream, the gate leaf floated and required a downward force to close it. Analysis of the pressure data showed that as the gate leaf normally descended toward the closed position, its top was subjected to full reservoir pressure over its projected area. At the same time, the high-velocity jet passing through the constricted area between the partially closed leaf and the oppositely curved lower surface of the conduit produced a negative pressure over an area essentially equivalent to that subjected to full static pressure above. These two pressures produce a downward force upon the leaf and stem which has become known as "down-pull." Hydraulic balance was reestablished to a large degree by providing a vertical intercommunicating passageway behind the leaf in the gate bonnet and frame. This allows the excess pressure above the leaf to escape into the top of the conduit downstream from the gate and alleviates a condition which in the operation of the prototype would have been the source of much grief.

As yet no studies had been made of the performance of the conduit between the entrance and the exit. A pipe of the correct inside diameter and formed to the proper profile for the lower outlet was installed on the 1:17 model of the entrance and control gates. The pressure gradients throughout the conduit with the correct tailwater were above atmospheric pressure, as had been expected (Fig. 3). However, when the model was operated without the tailwater to simulate conditions in either of the upper tiers, the results were startling. Sub-atmospheric pressures prevailed in the model which, when converted to the prototype, would have caused absolute zero pressure through a considerable length of the conduit. Severe cavitation would have occurred in the prototype, hampering or even completely preventing successful operation. The fact that the frictional losses in the conduit were insufficient to overcome the accelerating force introduced by the slope of the conduit had apparently been overlooked.

Another condition that required further study was the formation of spray on the face of the dam. The canyon-wall outlets at Boulder Dam had demonstrated that the friction of the jet with the surrounding air created a dense spray which was carried up the canyon toward the power house, causing undesirable conditions and some actual damage to the power house doors.

The subsequent redesign of the conduits for the middle and upper tiers at Grand Coulee was therefore based on three objectives: (1) prevention of sub-atmospheric

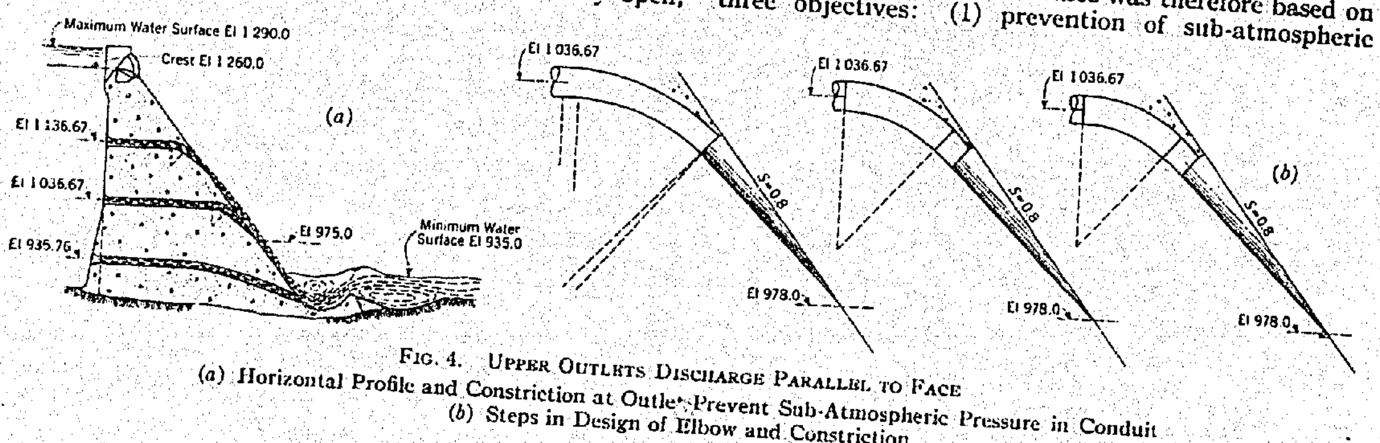

FIG. 4. UPPER OUTLETS DISCHARGE PARALLEL TO FACE
(a) Horizontal Profile and Constriction at Outlet Prevent Sub-Atmospheric Pressure in Conduit
(b) Steps in Design of Elbow and Constriction

pressures within the conduits, (2) minimizing the formation of spray, and (3) minimizing the river-bed erosion.

The ideal solution for the conduit between the control gates and the face of the dam was to bring the outlets through the dam on a horizontal profile and to introduce an elbow at the downstream end, forcing the jets to flow

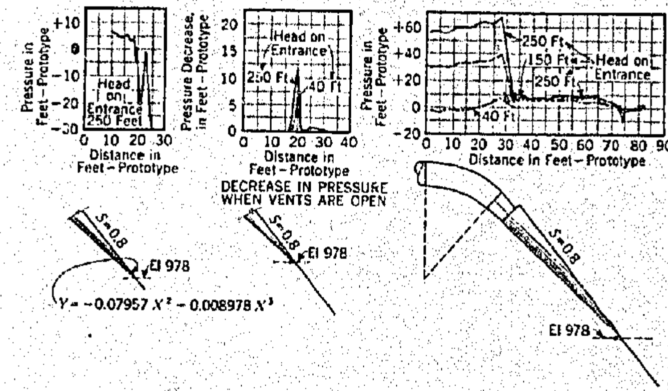

Fig. 5. Unexpected Low Pressures Encountered at Tip of Open Channel Slot

parallel to the face of the dam, as shown in Fig. 4 (*a*). A reduction of area in the elbow would reduce the discharge, decreasing the velocity and increasing the pressure throughout the conduit. With this arrangement, the jets flowing down the spillway face would be less conducive to the formation of spray than those falling freely through the air, and the river-bed erosion would be minimized since the bucket at the toe of the dam would function as an energy dissipator for the outlets as well as for the spillway. The proximity of the elbow to the face of the spillway would be determined by the thickness of material necessary for structural purposes.

If the elbow were omitted, allowing the jet to discharge horizontally into the air, sub-atmospheric pressures would be entirely eliminated. Therefore the problem was reduced to the designing of an elbow with a constriction to maintain the positive pressures in the conduit, and an exit channel in the face of the spillway that would minimize spray and river-bed erosion. Successive stages in the development of this design are illustrated in Fig. 4 (*b*).

Since a sudden change in the alinement of a conduit may cause unfavorable local pressure distribution, the reduction in area in the first trial was effected by converging the crown of the elbow toward the invert. A minimum distance of 3 ft was established between the elbow and the face of the dam to allow for placement of adequate reinforcing steel in the concrete. The invert of the open-channel portion of the outlet was made circular in cross section and carried in tangent to the invert of the elbow.

The pressures in the elbow were above atmospheric, but the discharge was materially decreased. Fins of water formed on both sides of the jet in the upper end of the open trough. The fins were objectionable because of the spray released and because of the unpleasant appearance that would result when all 40 outlets were discharging.

In an effort to prevent the formation of these fins, a long succession of revisions in the shape of the open channel were undertaken. The solution finally obtained comprised a conical constriction symmetrical about the center line. This formed a slight, but definite, break

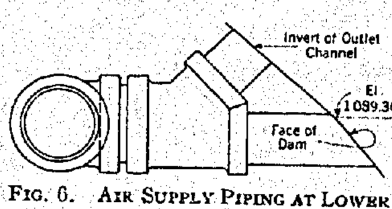

Fig. 6. Air Supply Piping at Lower End of Outlet

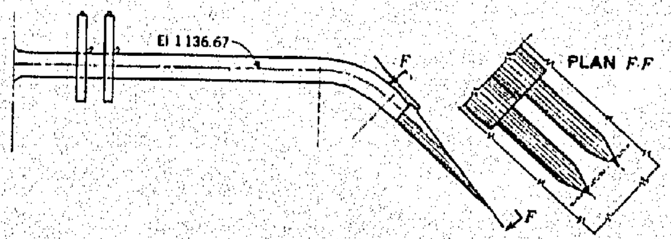

Fig. 7. Final Design with Deflector Over Exit

at the intersection of the frustrum with the open channel. The pressures throughout the conduit were positive for all heads in excess of 40 ft on the center line of the entrance. The sub-atmospheric pressures that will occur when the outlet is operating under a head of less than 40 ft should do no damage in the short period of operation necessary during construction.

Unexpected Disturbances at Outlet Tip

The trough, or apron, portion of the outlets presented a problem of greater magnitude than originally anticipated. As the solution of the elbow and exit channel unfolded, the importance of the shape of the open channel became increasingly apparent. In the case of ordinary open-channel flow, minor surface irregularities are of relatively little importance, but this problem required a discharge surface that would reasonably fit a jet of water with a diameter of 7 ft 9 in. and a maximum velocity of 110 ft per sec. Any non-conformity tending to change the direction of this ponderous jet would result in unfavorable flow conditions. As in the case of the elbow, a step-by-step trial method was used to arrive at the final design.

In the first trial, a slight but distinct break was formed between the cone and the apron and between the apron and the face of the dam. The pressure immediately downstream from the cone was slightly above atmospheric, which was contrary to expectations. However, the complete surprise was the excessively low pressure on the apron immediately above the intersection with the face of the dam.

A number of changes in curvature and profile (Fig. 5) were made in attempting to solve this problem. None was successful. When the solution was found, it was quite by accident. Pressures in the elbow, cone, and upper portion of the channel were satisfactory; the jet of water was stable and undisturbed; the design of the conduit down to the end of the cone had been released to the design department for detailing; the simplicity of the design so far was encouraging. But what was to be done with this one remaining low-pressure condition? It appeared that the optimum design had been reached so far as structural treatment and visual observations were concerned.

One morning, after several weeks of study, the single-leg glass piezometer tubes were being replaced with U-tubes to eliminate the necessity of establishing a new datum plane after each change in the model. During the changing of the rubber connections, it was noted that the pressure downstream from any disconnected tube was increased. Air flowing into the disconnected tube aerated the low-pressure region. Why not install air vents for that purpose?

The air supply was taken from the face of the dam at a sufficient distance on both sides of the channel to prevent the outlet jets from covering the openings. The size of the air conduits was

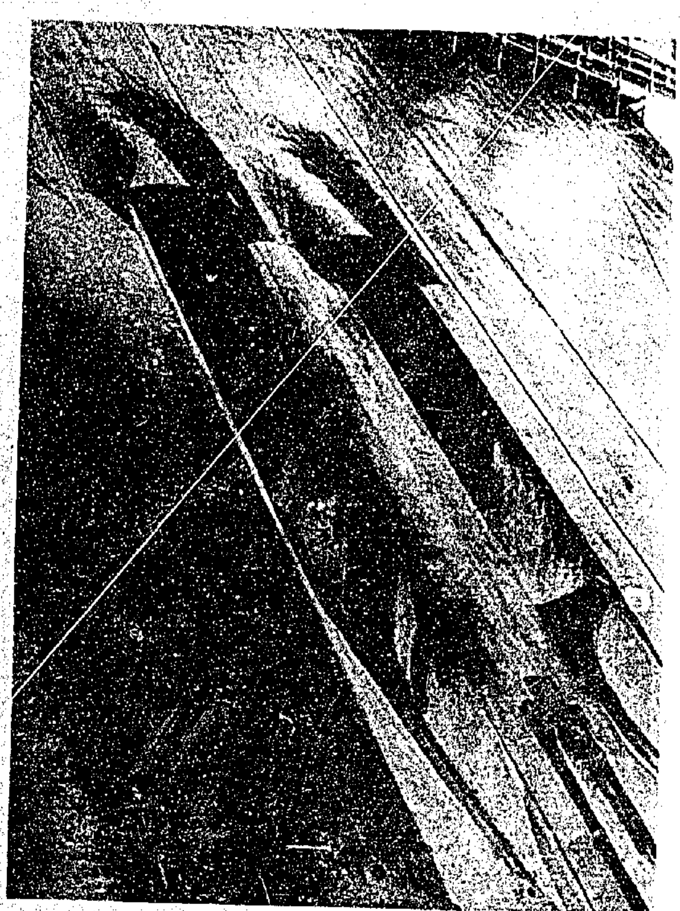

FIG. 8. COMPLETED EXIT PORTALS AT GRAND COULEE
Deflectors at Top; Ventilating Holes Just Discernible at Bottom

determined on the model by trial. In the prototype the header lines have a diameter of 6 in. while the feeder lines are 4 in. in diameter (Fig. 6).

The supposedly final design for the intermediate outlets at Grand Coulee Dam, which was developed under extreme urgency because of the progress of construction, did not have deflectors over the outlets (Figs. 7 and 8), although consideration had been given to the excessive spray from the water dropping into the channel of the outlet. Later tests, however, showed that for the condition in which the spillway operated alone such spray formation would be critical.

To eliminate this, the trajectory of the spillway jet was deflected above the opening in the face of the dam. The raised portion, or deflector, was made parabolic in the direction of flow and was blended into the spillway face by reverse curves.

With the addition of the deflector over the outlet, the thickness of concrete between the cone and the face of the deflector was increased considerably beyond the minimum established at the beginning of the studies as necessary for the reinforcing steel. Advantage was taken of these projections to move the elbow and cone 3 ft horizontally downstream. This change moved the point of intersection between the invert of the channel and the face of the dam up the slope 13 ft, reducing the exposed opening. Construction progress prevented any change in the intermediate outlets at Grand Coulee except the addition of the deflector, but the shortened opening and deflector were adopted for the upper tier in Grand Coulee and all outlets in Shasta Dam.

PROTOTYPE STUDIES PLANNED

The rapid completion of the prototype is expected to provide unusual opportunities for the comparison of field and laboratory work. The photograph, Fig. 9, shows the outlets operating at a recent stage of construction. Piezometer openings have been placed in the lining of the right outlet of block 51 in both the intermediate and upper tiers. A piping system connects these openings to terminal boards conveniently located in the inspection galleries.

Visually, the action of the prototype flow from the intermediate tier thus far observed has corresponded favorably with the model. The intake of air through the vents at the intersection of the apron with the face of the spillway also substantiated the model studies. Although the action of the deflectors with respect to the spillway flow cannot be ascertained until the dam is completed, their location with respect to the outlet jet permits ample inflow of air beneath the deflector. Further detailed comparisons between model and prototype results are to be expected after the dam is placed in regular operation.

The hydraulic laboratory in which these studies were made is a section of the Materials, Testing, and Control Division, supervised by R. F. Blanks and Arthur Ruettgers, both Members Am. Soc. C.E., senior engineers in the Denver office of the Bureau of Reclamation. Design studies and investigations are made under the direction of J. L. Savage, M. Am. Soc. C.E., chief designing engineer. S. O. Harper, M. Am. Soc. C.E., is chief engineer for the Bureau, and J. C. Page, M. Am. Soc. C.E., is Commissioner of Reclamation.

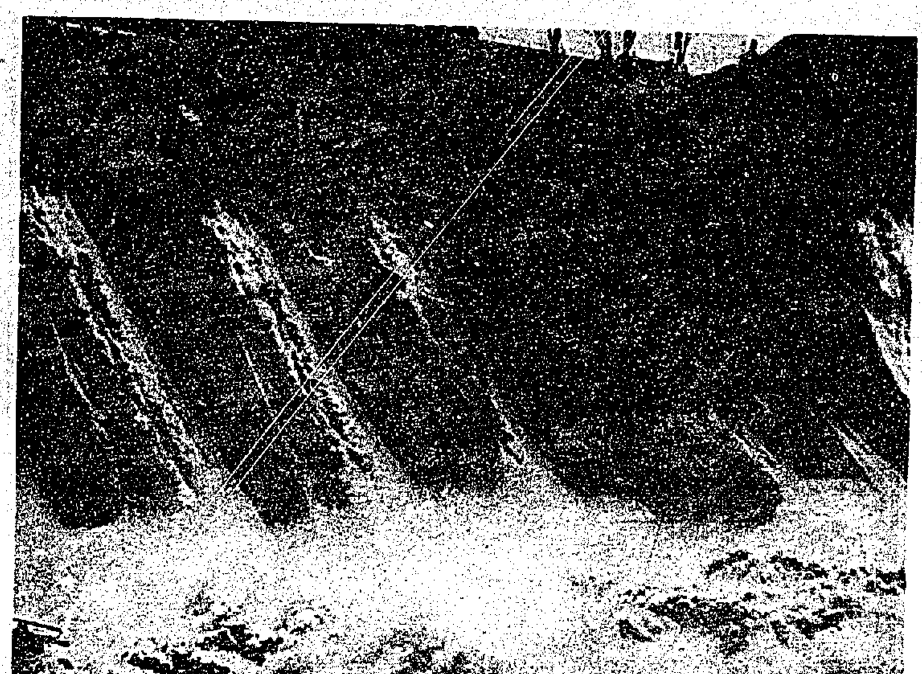

FIG. 9. PROTOTYPE ACTION CONFIRMS MODEL RESULTS
Boils and Spray in Foreground Suggest Tremendous Violence of Energy Dissipation