PAP 883

Model Tests
for
Battle Creek Bypass Tunnel
Energy Dissipation Structure

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Background

This report was prepared to document the results of a model study for planned facilities on the Battle Creek system near Sacramento California. The study was conducted at the United States Bureau of Reclamation, (USBR), Technical Service Center, (TSC), Water Resources Research Laboratory, (WRRL), in August 2001. Scale model tests were conducted to examine different configurations for a low Froude number, ($Fr < 3$), energy dissipation structure to be located on the Battle Creek Project near the outlet portal of the planned bypass tunnel that would deliver flow from the South Powerhouse to Inskip Canal.

Inskip Canal is oriented at nearly a right angle to the tunnel and lies a short distance from the outlet portal. Design objectives for the energy dissipation structure include control of upstream flow velocity in the unlined tunnel, dissipation of energy resulting from the elevation differential between the tunnel and canal, limiting the excavation required for the structure, and minimization of wave action which could overtop a wasteway in the canal located near the confluence. Crest elevation was set to achieve a desired range of tunnel velocities. Tailwater elevations were determined from backwater calculations for selected discharges in the canal. Tunnel construction criteria require that portals be located at a point where tunnel cover is at least twice the tunnel diameter, hence factors influencing the amount of required excavation would include structure length and the location of a diverging section. Designs for the configurations tested were developed by the USBR-TSC Water Conveyance Group.

Test Overview

Limited-scope two-dimensional sectional model tests of three types of energy dissipation structures were performed in a lab flume. Adjacent components of the planned system that might affect performance of the energy dissipation structure were not included. Each of the designs tested would require an upstream diverging transition from the eight-foot tunnel to the energy dissipator width which was not modeled. Additionally, the nearly right angle turn which flow would make exiting the energy dissipation structure could not be modeled in the straight flume. Subsequently, extensive use of judgment will be needed to assess the effects of the quantitative data obtained from these model tests to the prototype application.

Tests were performed in a 3 ft wide flume with transparent sides. Vertical constraints led to use of two different model scales. A key focus of these tests was the qualitative assessment of performance of the various energy dissipation designs over the expected range of operating conditions. A concern associated with low Froude number energy dissipation is the creation of a large wave of irregular period, caused by an oscillating jet that has been observed to form in some basin designs. Each of the design types was tested at three specific discharge rates, spanning the expected range of flows that might be encountered. At each tested discharge, performance was observed for a range of expected tailwater levels. Qualitative data includes visual observations, video recordings and photographs.

There were limited opportunities to collect meaningful quantitative data. Wave amplitude was measured using a hook-type point gage and velocity measurements were made using a propeller-type meter. Issues regarding utility of the quantitative data are discussed in the RESULTS section of this report.

Models Tested

Three types of energy dissipation structures were modeled in this study, a stepped weir system, a baffled apron drop and a single drop with a plunge pool. Model scale was determined by vertical limits of the laboratory flume. Table 1 summarizes the model type, scale and flow conditions tested for each model.

Table 1. Model Types, Scale and Flow Conditions

Model Type	Sectional/Full *(S/F)*	Froude Scale	Crest Elev. *(ft)*	Discharge *(ft³/s)*	Tailwater Flow *(ft³/s)*	Tailwater Elev. *(ft)*
Stepped Weir	S	1:6	1438.7	330	385	1437.87
(4 ft long)				330	165	1435.78
Stepped Weir	S	1:6	1438.7	330	385	1437.87
(6 ft long)				330	165	1435.78
Stepped Weir	S	1:6	1438.7	330	385	1437.87
(8 ft long)				330	165	1435.78
				220	220	1436.59
				220	0	n/a
				165	220	1436.59
				165	165	1435.78
				165	0	n/a
Baffled Apron	S	1:6	1438.7	330	385	1437.87
				330	165	1435.78
				220	220	1436.59
				220	0	n/a
				165	220	1436.59
				165	165	1435.78
				165	0	n/a
Single Drop	F	1:11	1438.7	330	385	1437.87
(33 ft wide)				330	165	1435.78
				165	165	1435.78
				165	0	n/a
Single Drop	F	1:11	1437.6	330	330	1437.87
(14 ft wide)				330	165	1435.78
				220	220	1436.59
				220	0	n/a
				165	220	1436.59
				165	165	1435.78
				165	0	n/a

The stepped weir system consisted of five steps with a drop of 1.5 ft per step. Each step had a vertical end sill of 0.75 ft. Three step lengths were tested, 4.0 ft, 6.0 ft and 8.0 ft. Figure 1 is a sketch of the stepped weir system.

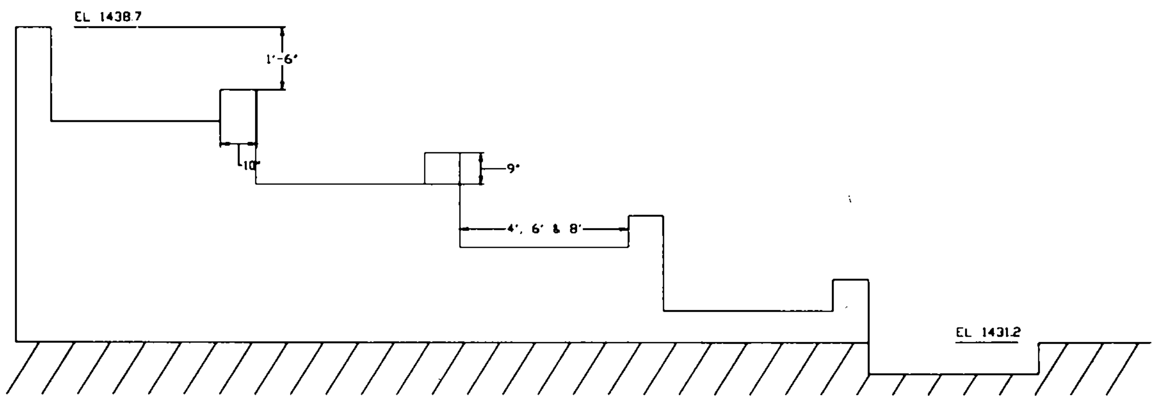

Figure 1. Profile of Stepped Weir System

The second energy dissipation device tested was a baffled apron. The apron face had a 2:1, (H:V) slope with baffle height of 1.33 ft normal to the apron plane. The structure had six rows of baffles with 2.67 ft row spacing. Baffles were 1.5 ft wide with in-row space of 1.5 ft between baffles. Successive rows were offset so that baffles were positioned directly behind the inter-baffle space of the row immediately upstream. Figure 2 is a profile sketch of the baffled chute. Elevation differential from the crest of the structure to the Inskip canal invert was 7.5 ft with a width of 33 ft for both energy dissipation structures.

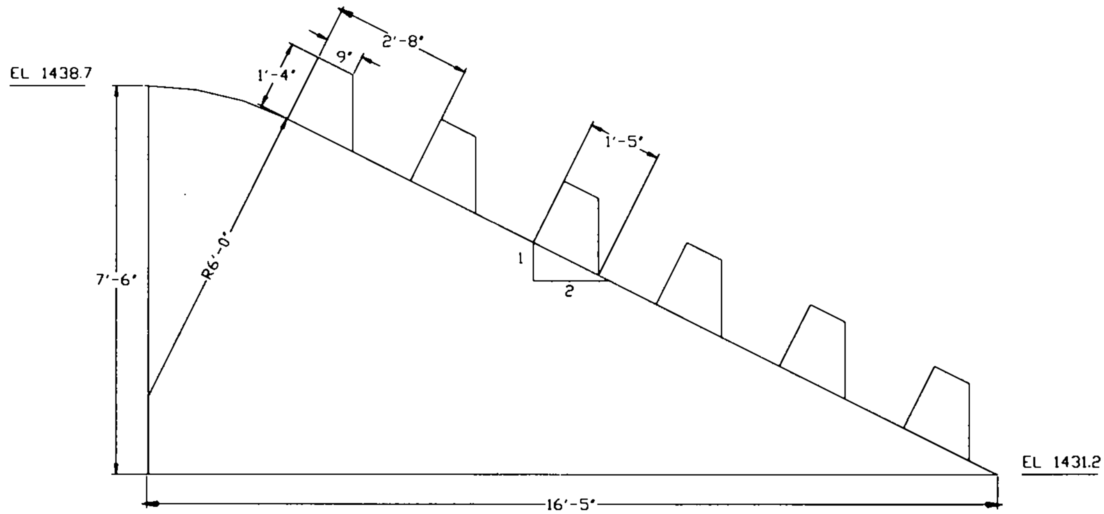

Figure 2. Profile of Baffled Apron System

The third type of energy dissipator tested was a single drop with a plunge pool. Two configurations were tested. A 33 ft wide and a 14 ft wide structure were modeled. Both were full width models. The narrower structure featured a diverging section downstream, (unlike other models tested), and would require significantly less excavation. Figure 3 is a sketch of the single drop structure, (the 33 ft model is shown).

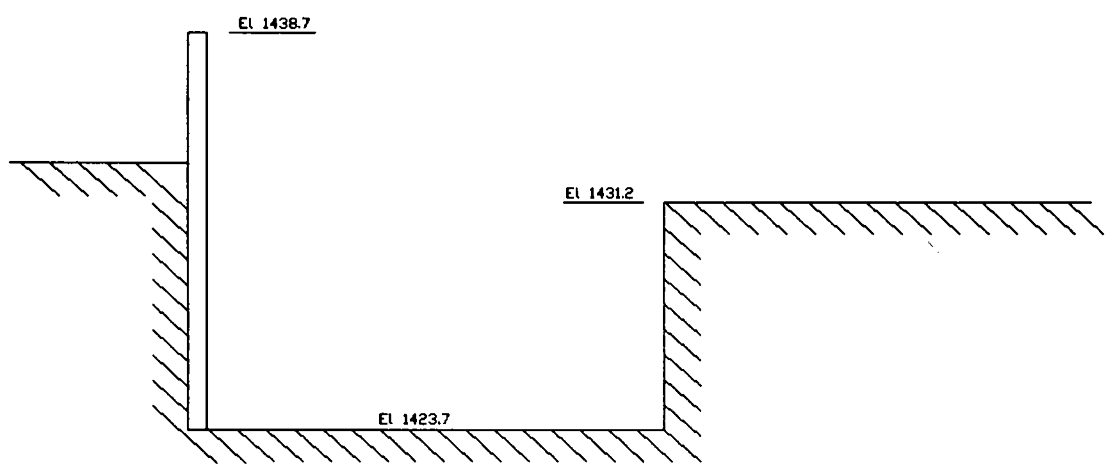

Figure 3. Profile of Single Drop with Plunge Pool

Results

Qualitative Observations: *Stepped weir, four foot step length* – Initial tests were conducted on the four-foot step length configuration. Flows were observed modeling 330 ft^3/s and 165 ft^3/s discharges. It was readily evident that at these two flow rates, the step length was too short to induce a hydraulic jump on each step. By regulating tailwater depth, a hydraulic jump could be formed downstream of the stepped weir structure, however the jump was extremely sensitive to tailwater depth. After briefly observing this configuration, it was decided to extend step length. No wave or velocity measurements were taken for four-foot length steps. Figure 4 shows a 330 ft^3/s discharge with a 165 ft^3/s tailwater depth with the four foot steps.

Figure 4: Four foot step length; Q = 330 ft^3/s, TW = 165 ft^3/s

NOTE: A hydraulic jump does not form on each step as desired.

Stepped weir, six foot step length – Extending the step length six feet caused a partially developed hydraulic jump to form on each step without tailwater influence. This length was an improvement, but still was too short to cause a well developed jump, as shown in Figure 5. No wave or velocity measurements were taken for the six-foot steps.

Figure 5: Six foot step length; Q = 330 ft^3/s, TW = 165 ft^3/s

NOTE: Partially developed hydraulic jumps form on unsubmerged steps.

Stepped weir, eight foot step length – At this step length, a well developed hydraulic jump formed at each unsubmerged step and a well defined stationary standing wave was observed above the highest submerged step for all discharge and flow conditions tested. Acceptable energy dissipation was achieved. Figure 6 shows a 330 ft^3/s discharge with a 165 ft^3/s tailwater. Wave amplitude and velocity profile measurements were taken for selected flow conditions. This information is included in Tables 2 and 3, respectively, at the end of this section.

Figure 6: Eight Foot Step Length; Q = 330 ft^3/s, TW = 165 ft^3/s

NOTE: A well developed hydraulic jump is formed on each unsubmerged step.

Baffled apron -- The baffled apron model appeared to provide a satisfactory level of energy dissipation performance under the range of tested conditions. Under a no tailwater condition, flow at the toe of the structure would be supercritical. However for each of the tested discharge rates with a tailwater level present, a stable submerged jump formed immediately downstream of the structure. In comparison with the eight foot stepped weir, flow exiting each unsubmerged step was sub-critical, however under a no tailwater condition flow quickly became supercritical after leaving the last step. Figure 7 shows a 330 ft^3/s discharge with a 165 ft^3/s tailwater for the baffled apron model. Wave amplitudes and velocity profiles were measured for selected flow conditions and are included in Tables 2 and 3, respectively.

Figure 7: Baffled Apron; Q = 330 ft^3/s, TW = 165 ft^3/s

Single drop with plunge pool -- Vertical limitations of the flume required use of a reduced model scale of 1:11 in order to model a plunge pool depth of 8 ft relative to the Inskip Canal invert. The smaller scale can be deceptive when visually evaluating the flow conditions and comparing to the other alternatives that were modeled with a 1:6 scale. For example, wave heights are 11 times higher than observed in the plunge pool model versus 6 times higher in the othermodels.

Thirty-three foot wide single drop model – The first configuration of this structure tested was a full width model with a 20 ft long plunge pool. As with the previously tested models, this model did not include the upstream diverging section. The performance of this model was similar under all flow conditions tested. A jet plunged to the bottom near the upstream end of the pool. Near the downstream end of the pool, the jet was turned nearly vertical, creating a boil at the water surface. A significant portion of flow from the jet recirculated in the upstream direction at the surface of the pool, with the balance of the jet proceeding on downstream. Under tested conditions, it appeared this model could provide a satisfactory level of performance if the downstream pool edge moved upstream a short distance from the confluence with Inskip Canal.

It was decided that the structure should be altered to model a 14 ft wide drop that included a diverging section between the plunge pool and the canal, so no measurements were taken with the 33 foot model. Figure 8 shows a 330 ft^3/s discharge with a 165 ft^3/s tailwater for the 33 ft single drop model.

Fourteen foot wide single drop – A key point of interest in the modification from the previously tested 33 ft wide model was that if the narrower structure proved effective, it could be constructed with a significantly reduced amount of excavation than any of the previously tested structures. This model configuration had a 14 ft crest width and a 14 ft wide by 30 ft long by 8 ft deep plunge pool. Downstream from the plunge pool was a transition section at canal invert elevation which diverged from 14 ft to 33 ft. Each wall diverged at an angle of 22.5° from the downstream direction. Figure 9 shows flow as it exits the diverging section for a 330 ft^3/s discharge with 165 ft^3/s tailwater.

Figure 8: 33 ft. Single Drop with Plunge Pool; Q = 330 ft^3/s, TW = 165 ft^3/s

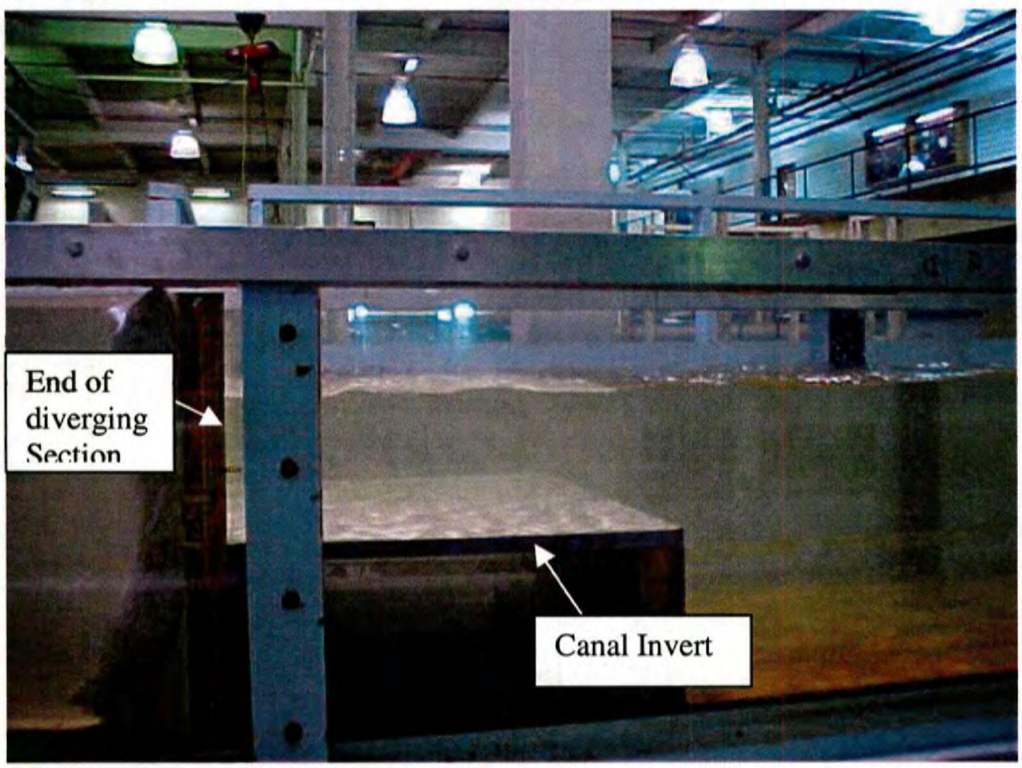

Figure 9: 14 ft. Single Drop with Plunge Pool; Q = 330 ft^3/s, TW = 165 ft^3/s

This structure appeared to provide satisfactory performance under the tested conditions. As had been observed with the 33 ft model, the upturned jet at the downstream end of the plunge pool created a boil at the surface with a significant portion of the flow being recirculated in the upstream direction at the surface of the pool. For all conditions with tailwater present, a submerged jump formed in the transition section with an associated stationary standing wave of modest amplitude.

The position of this wave within the diverging transition varied with discharge and tailwater conditions. For a 330 ft^3/s discharge with a 385 ft^3/s tailwater, the wave was located at approximately the exit of the diverging section. This is the furthest downstream location of the wave observed for the tested conditions. Wave amplitude measurements were made at the exit of the diverging section. Mid-profile velocity measurements were also taken at incremental distances transverse to the flow at this position. These are included in Tables 2 and 3, respectively.

Quantitative Data: As previously noted, there were limited opportunities to obtain meaningful quantitative data. The objective of these tests was to assess the effectiveness of each of the designs in dissipating energy and in limiting amplitude of waves at entering Inskip Canal. The tests were run at specific discharge rates and specific tailwater depths – hence specific cross section flow area. For an incompressible fluid, the average velocity is a function of discharge and cross section flow area, independent of what – if any – structure may be upstream. Thus downstream velocity, which would be an indication of energy remaining in the flow, is probably of little use in comparing energy dissipation between models. The velocity data acquired may be of greatest interest for the shape of the respective distributions.

Additionally, since the entrance to Inskip Canal was not modeled, it is unclear how accurately measured downstream wave amplitudes from the model may be used to predict wave amplitudes in the prototype application. Given the differences in the tested designs, and the limited testing scope, it was not feasible to establish testing standards to generate a reliable base of numeric data for comparing relative performance of the various designs. Instead, measurements were taken at the location of greatest interest for each respective model.

For the stepped weir model, the sill of the last step was actually a step up to the Inskip canal invert. The largest waves in this model appeared to occur 8 ft downstream of this "sill". Wave amplitude was measured at this location. For the baffled apron, the structure's comparatively short length provides flexibility for locating the structure in the reach between the tunnel outlet and Inskip Canal. Wave amplitude was measured at four points, representing possible distances from the structure to the canal. For the single drop – plunge pool structure, measurements were only taken for the 14 ft. wide model that included a diverging transition between the dissipation structure and the canal. For this model largest waves were formed at the exit of the downstream diverging transition so amplitude was measured at this point.

For the stepped weir and baffled apron models, (both 1:6 scale sectional models modeling 18 ft of a total 33 ft width), a vertical velocity profile was measured in the center of the flume. Being sectional models, it was presumed that edge effects might be distorting. For the 14 ft. single drop model, the smaller 1:11 scale with associated shallower flow depth made it impractical to obtain more than two velocity readings in the vertical profile with the propeller-type instrument used. Since this was a full width model, the velocity distribution across the exit of the diverging transition was of interest.

Velocity was measured at incremental distances across the width at mid flow depth.

Table 2. Wave Amplitudes

8' Stepped Weir

Q *(cfs)*	TW *(cfs)*	Amplitude *(ft)*
330	385	0.3
330	165	0.2
220	165	0.1
165	220	0.2
165	165	0.2

Single-Step 14' wide Drop

Q *(cfs)*	TW *(cfs)*	Amplitude *(ft)*
330	385	0.7 (standing wave)
330	165	0.3
220	165	0.3
165	220	0.2
165	165	0.1

Baffled Apron Drop

NOTE: Wave amplitudes for the Baffled Apron were measured at four distances below the structure, representing a range of possible locations for the structure relative to Inskip Canal.

		Distance below Structure Toe *(ft)*			
Q *(cfs)*	TW *(cfs)*	13	20	30	40
330	385	0.3	0.2	0.2	0.2
330	165	0.4	0.3	0.2	0.2
220	220	0.3	0.3	0.2	0.2
165	220	0.2	0.1	0.1	0.1
165	165	0.2	0.2	0.1	0.1

Table 3. Velocity Data

Vertical Velocity Profiles

8 ft Stepped Weir		Baffled Apron	
Q = 330	TW = 385	Q = 330	TW = 385
Elevation from Invert *(ft)*	Velocity *(ft/s)*	Elevation from Invert *(ft)*	Velocity *(ft/s)*
0.9	0.4	0.9	0.5
1.5	0.4	1.5	0.5
2.1	0.5	2.1	0.4
2.7	1.1	2.7	0.7
3.3	1.4	3.3	0.6
3.9	1.6	3.9	1.4
4.5	2.4	4.5	2.0
5.1	2.4	5.1	2.5
5.7	2.7	5.7	3.4
6.3	2.9	6.3	4.2
Q = 330	TW = 165	Q = 330	TW = 165
Elevation from Invert *(ft)*	Velocity *(ft/s)*	Elevation from Invert *(ft)*	Velocity *(ft/s)*
0.9	1.0	0.9	0.5
1.5	1.3	1.5	0.5
2.1	1.8	2.1	0.9
2.7	2.4	2.7	1.7
3.3	2.7	3.3	2.9
3.9	3.3	3.9	4.4

Table 3. (Contd.)

Vertical Velocity Profiles

8 ft Stepped Weir

Q = 165 TW = 220

Elevation from Invert *(ft)*	Velocity *(ft/s)*
0.9	0.2
1.5	0.4
2.1	0.6
2.7	0.1
3.3	1.1
3.9	1.3
4.5	1.7

Q = 165 TW = 165

Elevation from Invert *(ft)*	Velocity *(ft/s)*
0.9	0.4
1.5	0.5
2.1	0.7
2.7	0.6
3.3	1.3
3.9	1.8

Baffled Apron

Q = 165 TW = 220

Elevation from Invert *(ft)*	Velocity *(ft/s)*
0.9	0.3
1.5	0.3
2.1	0.5
2.7	0.6
3.3	1.0
3.9	1.8
4.5	2.1

Q = 165 TW = 165

Elevation from Invert *(ft)*	Velocity *(ft/s)*
0.9	0.4
1.5	0.6
2.1	1.3
2.7	1.8
3.3	2.2
3.9	2.8

Transverse Velocity Profiles: 14 ft wide Single Drop with Plunge Pool

		Distance from Right Side of Structure *(ft)*				
Q	TW	*5.5*	*11.0*	*16.5*	*22.0*	*27.5*
330	385	1.1	1.7	2.0	1.5	1.1
330	165	1.3	2.2	4.5	4.2	2.3
220	220	0.4	1.2	2.4	2.2	1.3
165	220	0.6	0.6	0.6	0.7	0.8
165	165	1.0	0.9	0.7	1.1	1.6

Summary

Three types of energy dissipation structures tested appear to provide effective energy dissipation for the targeted range of discharge and tailwater conditions. Given the limited scope of the modeling performed, it would be difficult make comparative assessments of the various systems, based on results of these tests alone. When factors such as available space, material requirements, excavation costs, debris handling capabiliby and ease of construction are weighed, perhaps a preferred alternative will become more evident.

These tests by no means represent an exhaustive examination of structure designs capable of providing desired performance. While multiple configurations of two of the structure types were tested, there is no reason to presume these tests suggest optimality for tested designs. Rather, the results of these tests only indicate that each of these designs has the potential to meet the energy dissipation needs for the targeted application.

Attachments

Accompanying this report are floppy diskettes containing digital still photographs and a VHS video cassette of various runs performed in this series of model tests.