MCO IMPACT ABSORBERS USING CRUSHABLE TUBES[1]

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ABSTRACT

Spent nuclear fuel from the Hanford N-Reactor is currently stored in pools, the K-East and K-West basins. As part of Hanford's Decontamination and Decommissioning effort, this fuel is to be placed in dry interim storage in the Canister Storage Building (CSB). The storage arrangement consists of an array of sealed vertical storage tubes, each capable of holding two Multi-Canister Overpacks (MCO), one on top of the other. To protect the MCOs from damage during loading, two impact absorbers are used, one placed below the lower MCO and one between the lower and upper MCOs. Since the MCOs can only move axially in the tube, the impact absorbers need only function in one axis. The impact absorber consists of an array of mild steel tubes arranged symmetrically between relatively rigid end plates. Under impact load, the tubes collapse by a process of regular crippling which safely absorbs the energy of the dropped MCO without exceeding load or deflection limits.

In designing tubes which would crush reliably, consistently, and smoothly, three primary design challenges were met:

1. Development of a physical configuration to ensure a stable buckling mode to avoid gross collapse.
2. Mitigation of the force spike which occurrs at the initiation of tube crush.
3. Choice of a design configuration which accommodated material property, dimensional, and temperature variations while keeping the average crush force within a narrow design envelope.

The successful approach to these challenges is discussed in this paper, including results of full scale prototype testing.

INTRODUCTION

Spent nuclear fuel from the Hanford N-Reactor is currently stored in pools, the K-East and K-West basins. As part of Hanford's Decontamination and Decommissioning effort, this fuel is to be placed in dry interim storage in the Canister Storage Building (CSB). The storage arrangement consists of an array of sealed vertical storage tubes, each capable of holding two Multi-Canister Overpacks (MCO), one on top of the other, as shown in Figure 1. The MCOs may be removed and replaced in the storage tubes during the life of the facility. To protect the MCOs and the storage tube from damage in the case of a crane failure or other handling accident, two impact absorbers are used, one below the lower MCO (the lower absorber) and one between the lower and upper MCOs (the intermediate absorber). Should one of the MCOs be accidentally dropped, the drop energy would be safely absorbed while keeping the impact force below a specified limit. Since the MCO is contained within a cylinder, there is a single impact orientation to be considered, and consequently, the impact absorbers need only function along a single axis.

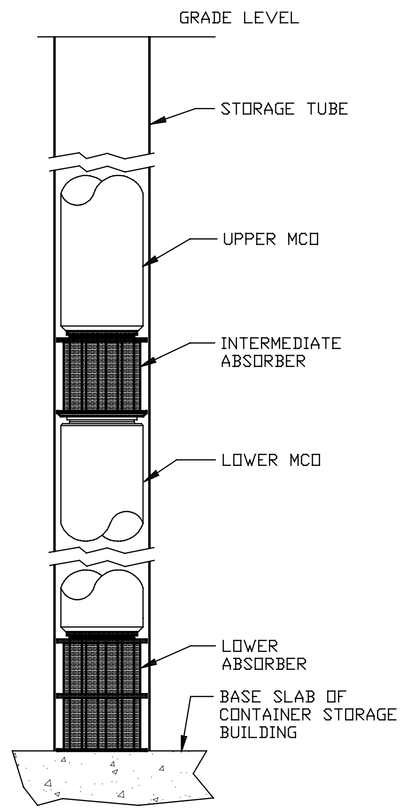

Figure 1 Schematic of CSB Storage Tubes and MCOs

The development of the impact absorber design was complicated by the application of the following design requirements:

- The operating temperature range is between -7 ºC and 166 ºC
- The energy absorbing material, if organic, must not produce combustible offgas products
- The energy absorbing material must not creep under the weight of two MCOs at maximum storage temperature, and must retain its original physical properties for a 75 year design life
- The maximum impact acceleration of the MCO during impact must not exceed 34g
- The space available for the absorber is limited
- Cost must be low since a large quantity of absorbers (approximately 440) is needed.

Several of these constraints served to rule out the use of most common, inexpensive energy absorbing materials. For example, the requirement for a 75 year design life at temperatures up to 166 ºC made use of organic materials of any kind questionable. Therefore, only metallic materials were considered. Furthermore, the restriction of the impact to a value of 34g, when combined with the large weight of an MCO and the small available space, required an absorber solution was required which combines the long lifetime of a metallic material, with a constant force behavior and low cost. This was achieved through the use of crushable tubes.

ABSORBING ENERGY WITH AXIALLY CRUSHABLE TUBES

The axial crush of both round and square tubes has been well studied in the automotive industry, for the purpose of absorbing crash energy. As long as it is not too slender, a tube responds to axial impact loading by a progressive crippling. The crush load varies cyclically about a mean value which is surprisingly consistent for tubes manufactured from the same lot. An energy absorber can be made from an array of such tubes, and the crush force can be conveniently varied by the addition or subtraction of individual tubes, as well as by the alteration of tube parameters. In this way, an array of crushable tubes is analogous to a coarse metallic honeycomb material. Since the tubes in the array must be spaced so as not to mutually interfere during crushing, they receive no mutual lateral support, and gross buckling, by the formation of a single plastic hinge, is a possibility. This can however be safely avoided by limiting the length-to-diameter ratio of the tubes in the absorber to a value which ensures regular crippling, rather than a gross hinge buckling response.

Axially loaded tubes crush in essentially two different modes: *Concertina*, in which the material cripples with consistent, axisymmetric, rounded folds, and *Lobed*, in which the walls cripple nonaxisymmetrically, as if pinched locally from the outside. Further, the lobed mode can differ in form, depending on how many individual lobes form around the circumference. The concertina, 2-lobed, and 3-lobed modes are shown in Figure 2. As seen in the figures, the deformation of the material is fairly severe and relatively well distributed, indicating good repeatability and energy absorption efficiency. Although the concertina crush mode tends to be favored by thicker and stronger tubes, it is not easy to predict which crush mode will prevail for any given configuration. The preferred mode can, however, be encouraged as discussed below.

In testing performed by Packaging Technology, Inc., it was learned that the crush force for the concertina mode is somewhat higher than for the lobed mode, and further, it was observed that some specimens which began to crush in the concertina mode, transitioned to the lobed mode. In doing so, the crush force did not remain constant. Since that is undesirable from the standpoint of maximum crush efficiency (where crush uniformly at the maximum acceptable crush load is desired), and because the potential switch in modes cannot be easily controlled, it was decided to induce the lobed mode from the start. Since a switch in modes from the lobed to the concertina modes does not occur, a change of mode can thus be precluded. The number of lobes in the crush pattern is also important. In a 2-lobed crush pattern, both sides of the tube come together until they touch, and at that point, the effective bending stability of the tube is very small, and a plastic hinge can form. This can lead to instability as shown in Figure 2b, particularly the last specimen on the right. For this reason, the 3-lobed pattern, shown in Figure 2c, is preferred. The 3-lobed pattern can be consistently achieved by crimping one end of the tube in a triangular pattern.

Figure 2a Concertina Deformation Mode

Figure 2b Two-Lobed Deformation Mode

Figure 2c Three-Lobed Deformation Mode

The material chosen for the tubes is not in itself particularly important, except as the type of material affects the variation in crush strength, as discussed in the next section. A certain minimum ductility is required, but this can be achieved by most mild steels. A small amount of material tearing in the most highly strained regions was found to have no effect on the effectiveness of the impact absorber. The important parameters of the material with regard to the MCO impact absorbers were its consistency, low degree of temperature variability, low cost, and commercial availability in forms where wall thickness was well controlled.

DESIGN OF AN IMPACT ABSORBER

The CSB impact absorber design consists of an array of thin walled tubes placed between relatively rigid upper and lower end plates. In a drop accident, the dropped MCO would strike the upper plate, causing the tubes to cripple and absorb energy. The design process consisted of choosing the size and strength parameters of the tubes, including features to control the mode of crippling and the variation of crush force.

The Design Formula

For the average crush force in a thin wall circular tube, Equation 9.81 of Reference [1], gives:

$$P_m = 21.1(R)(H)\frac{\left(1+0.41\sqrt{\frac{H}{R}}\right)}{\left(2.14\sqrt{\frac{R}{H}}-1\right)}(\sigma_e)f(\dot{\varepsilon},T) \qquad [1]$$

where: P_m = the average crush force over the entire crush length of the tube, lb.
R = the mean tube radius, inch
H = the wall thickness, inch
σ_e = the effective strength of tube material, psi
$f(\dot{\varepsilon},T)$ = a factor that is a function of the strain rate and material temperature.

The empirical constants are intended for use with English units. As shown, average crush force P_m is a function of two geometry parameters (the mean radius and the wall thickness) and two material parameters (the strength and a term modifying the strength for strain rate and temperature). The strength parameter represents a measure of the average flow strength of the material during the crushing event. At various locations in the tube, material is undergoing various degrees of deformation, from beginning yield up to nearly ultimate strain in the most highly strained regions. Therefore, the effective strength parameter should include a measure of both yield and ultimate strength, and for this purpose, the common flow stress, or average of yield and ultimate, was used. Since the use of an average value is somewhat arbitrary, a calibration factor was used to refine the result to actual test behavior. The calibration factor was based on a series of scale bench tests.

The strain rate and temperature adjustment factor, $f(\dot{\varepsilon}, T)$, represents a measure of the variation in material behavior as the strain rate and the material temperature vary. Considered independently, it is well established that steels experience an increase in strength with an increase in the rate of strain, and a decrease in strength with an increase in temperature. However, since the two effects may not be merely concurrent, but interdependent (as implied by Figure 15.23 of Reference [2]), the two effects are considered together. The value of this parameter was also determined using scale bench testing.

Calibration of the Design Formula

As an aid in calibration, the design formula given above is recast into a form that separates the parameters by type and introduces calibration factors, as follows:

$$P_m = (K)(\sigma_o)(f_\sigma)(f_{\dot{\varepsilon},T})f_{\Delta\dot{\varepsilon}} \qquad [2]$$

where each of the terms is described below.

- *K* is the portion of the design formula which is dependent solely on the geometry parameters R and H, that is:
-

$$K = 21.1(R)(H)\frac{\left(1+0.41\sqrt{\frac{H}{R}}\right)}{\left(2.14\sqrt{\frac{R}{H}}-1\right)} \qquad [3]$$

  In other words, K is equal to the basic design formula given above, without any material strength-related terms. The K term can be readily evaluated by substitution of the mean radius, R, and the wall thickness, H.
- σ_o is the flow stress, or the average of yield and ultimate strengths as provided by the material supplier from static tensile testing of the tube material.
- f_σ is a factor which corrects the simple average flow stress to the actual effective stress found from test. The actual flow stress can be back-calculated from a static, room temperature crush test, in which there are no strain rate or temperature effects.
- $f(\dot{\varepsilon}, T)$, as discussed previously, is a factor which corrects the design formula for the effects of dynamic strain rate and material temperature. It is equal to the ratio of the effective dynamic stress to the effective static stress, and can be back-calculated from dynamic drop tests at pertinent temperatures.
- $f_{\Delta\dot{\varepsilon}}$ is a factor which is made necessary by the fact that material strain rate does not follow scaling laws. These laws state that the material unit stress is invariant with scale. However, in cases where material strain rate has a significant effect on the effective unit stress, the resulting dynamic stress is not invariant with scale. As long as the bench testing parameters maintain a relatively consistent scale factor to the prototype, the factor is near to unity. The correction factor is equal to the ratio of the strain rate effects.

Energy Absorption and Crush Force Limits

The impact absorber must decelerate the dropped MCO by exerting a limited force, and it must do so over a limited distance. The potential energy associated with the drop is found from the familiar equation

$$E_{pot} = W(h) \qquad [4]$$

where W is the value of the falling weight and h is the distance through which it falls. This energy is most efficiently absorbed by exerting a constant force, F, on the weight through some distance, d, or

$$F(d) = W(h) \qquad [5]$$

The weight and the drop height are set by the design specification.

The impact absorber crush force must not exceed the maximum allowable value (under maximum strength, cold conditions), nor must it exceed the crush length capacity of the tubes (under minimum strength, warm conditions). The maximum allowable force is the product of the maximum allowable impact g-level and the weight, or

$$F_{max} = W(g) \qquad [6]$$

For a bounding MCO weight of W = 9,072 kg, and a maximum allowable impact of 34g, the maximum force is 3.02 (10^6) N. The minimum allowable crush force is established by the maximum allowable crush distance available in the absorber. The maximum space allotted to the lower impact absorber, for example (located beneath both MCOs), is 880 mm. From this distance, 89 mm is used by the upper and lower end plates, leaving 791 mm for the crushable tubes. Testing has demonstrated that each crush tube has a useful crush length of at least 70% of the initial active length. In other words, a tube can exert a uniform force until it has crushed to 30% of its initial length, at which point it becomes "solid", with a rapid increase in crush force. Therefore, the maximum allowable crush distance of the lower absorber is

$$L = 0.7(791) = 553.7 \text{ mm} \qquad [7]$$

The minimum force which can absorb all of the MCO potential energy is therefore (from Eq. 5)

$$F_{min} = \frac{W(h)}{L} = 2.169(10^6)\text{ N} \qquad [8]$$

where h = 13.51 m. Therefore, to function properly, the absorber crush force must be between 3.02 (10^6) N and 2.169 (10^6) N. The design formula and calibration factors are used to assure this is achieved with consideration of the possible variations in tube cripple strength which may occur due to material strength, wall thickness, and temperature variations.

Absorber Design

In the design of the MCO impact absorbers, it was found that the normal variations in fabricated tube crush strength, further modified by specified potential temperature extremes, caused the variation in absorber crush force to fall outside of the allowable design window. This difficulty was overcome by employing a variable number of tubes in the absorber, the quantity being a function of actual tube strength. For example, if the tubes as fabricated exhibited a crush strength which placed them near the upper bound of their tolerance limit, a smaller quantity of tubes was used. Alternately, if the crush strength was nearer the lower bound, a larger quantity of tubes was used. In this way, the potential variation in absorber crush force could be made to have a smaller range than the potential variation in tube crush force. The design of the end plates accommodated a variable quantity of tubes. The actual crush force of the tubes is determined by static crush testing of samples before final assembly of the absorbers. The MCO impact absorber design therefore consists of an array of 88.9 mm diameter, 2.41 mm thick tubes having a quantity which can vary between 13 and 17, depending on actual tube strength.

Due to the energy which must be absorbed by the lower absorber (since, due to its position, the drop height is relatively large), the required crush length of the tubes exceeded the permissible free length to avoid gross buckling. This absorber was therefore designed with two tiers, each having an acceptable length.

Finally, to mitigate the initial force spike which can occur upon impact, the tubes were precrushed. This process caused the first folds in the tubing to form, greatly reducing the initial crush resistance of the tubes.

PROTOTYPE TESTS

As a proof of the design, full scale prototype testing was performed. The test was performed on a large reinforced concrete pad, on which a simulated storage tube was erected. A total of six inches of steel was placed on top of the pad to protect the pad and increase its resistance to shock loading. The prototype absorbers were placed within the simulated storage tube, and simulated MCOs were dropped from the specified height. The test setup is shown in Figure 3. Three tests of each type were performed. To test the lower absorber, a prototypic specimen was placed directly on the steel plates, and a simulated MCO was dropped into the storage tube from a height of approximately 13.5 m. During the test of the intermediate absorber, support was given by a prototypic lower absorber resting on the steel plates, and a simulated lower MCO. A simulated upper MCO was dropped on the intermediate absorber from a height of approximately 9 m. In this test, energy was absorbed by both test specimens, since both were in the path of the impact load, although the upper absorber crushed by far the most.

The behavior of the absorbers during the impact event was recorded using a high speed, 1000 frame per second video camera. The camera was set on a tripod about 4 m away from the storage tube, and filming was done through a lexan window in the tube. By measuring the position of the dropped MCO against a stationary scale in each frame, post-test examination of the video record produced a displacement-vs.-time curve at 1/1000 second intervals.

Figure 3 Impact Absorber Prototype Test Setup

As described in the design section above, the primary criteria (that impact not exceed 34g) was first converted into max/min force limits at specified operating temperature extremes(F_{max}/F_{min}). For the test, these force limits were converted into min/max crush distance limits at the test temperature of approximately 20 °C. The maximum crush distance was measured two ways: from the video record, and from post test direct measurements of the specimens. It was found that the video record of maximum crush distance was always greater than the direct measurement. This is due to the fact that the direct measurement of the specimen omits any deflection which may have occurred due to ground motion upon impact. In contrast, the video record shows the actual motion of the simulated MCO itself, from which the actual impact deceleration can be easily derived. In each case, the video record of maximum crush fell within the specified min/max crush limits, and the design was accepted for use in the Container Storage Building. A tested impact absorber is shown in Figure 4.

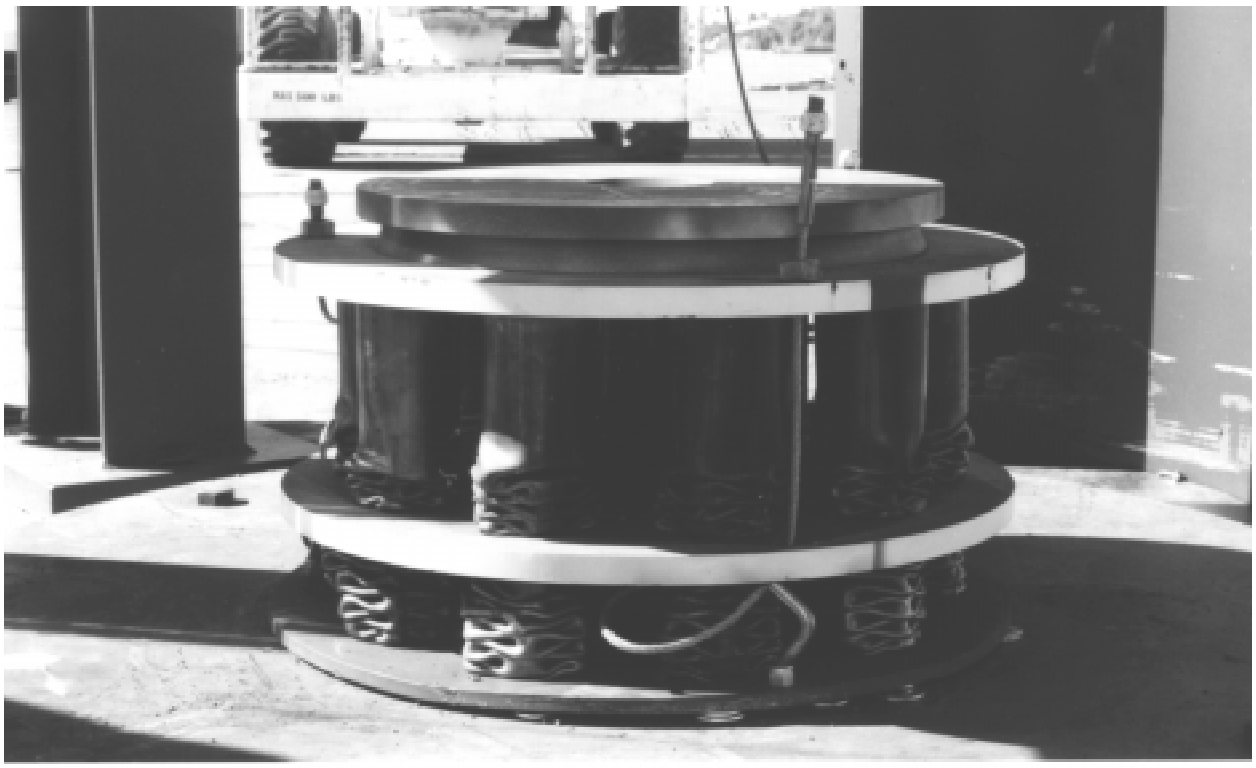

Figure 4 Lower Impact Absorber After Prototype Drop Test.

SUMMARY

An impact absorber has been designed for the Hanford Container Storage Building to cushion the impact of a potentially dropped MCO. Designs were created for the lower and intermediate positions inside the storage tube. The absorber design consists of straight, circular steel tubes which, upon impact, absorb drop energy by local progressive crippling. The key design parameters are the diameter and wall thickness of the tubes, the strength of the material, and the quantity of tubes used. The initial impact force spike is mitigated by the use of slight precrushing of the absorber assemblies. Full scale prototype testing demonstrated the ability to protect the MCOs during handling operations.

FOOTNOTES

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