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## Safety Analysis of Roller Compactors Exposed to Rollover

by Dennis B. Brickman\* and Ralph L. Barnett\*\*

### ABSTRACT

Roller compactors exhibit a high resistance to rollover which may be attributed to their low center of gravity, full width rollers, low speed, responsive braking system, high visibility, and operator profile. Tilt table testing of an Ingram pneumatic roller compactor demonstrates that its lateral stability normally exceeds or is comparable to other workplace vehicles. To eliminate or mitigate injuries resulting from roller compactor rollover excursions, a rollover protective structure (ROPS) and seat belt system has been widely debated as a proper countermeasure. Clearly, the roller compactor accident statistics demonstrate the potential of unbelted operators to suffer serious injuries inflicted by the ROPS safety device itself. In the face of reported low seat belt usage, the utilization of the ROPS and seat belt as standard equipment on a roller compactor is not straightforward and value systems are struggling with this dilemma.

### INTRODUCTION

The stability of roller compactors gives rise to two safety issues, a rollover accident and an overturning injury. The stability of roller compactors is rarely discussed in the safety literature and for this reason results are presented of a testing program which will illuminate the stability characteristics of these machines. Once a roller compactor has rolled over, technology provides the designer with a ROPS and a seat belt which may be used in combination to attempt to eliminate or mitigate operator injuries. What seems at first straightforward in the use of these devices turns out to be a thorny philosophical problem with important human factors implications.

If a vehicle moves at constant speed through a circular curve, centrifugal forces tend to roll it over while gravity forces counteract this effect. When the equilibrium equations are written to characterize this situation, they take the form of the equilibrium equations written for the same vehicle on a tilt table. For this reason, the tilt table has become a popular test device for characterizing vehicle stability. The authors were afforded an opportunity to test an Ingram model 9-2800-PA pneumatic roller compactor on a 4.57 m (15 ft) by 4.57 m (15 ft) tilt table which was acquired from the forklift division of the Allis-Chalmers Corp. Results of this testing are compared to tilting criteria for a number of other machines.

### ROLLER COMPACTOR STABILITY

The current study focuses on the Ingram model 9-2800-PA pneumatic roller compactor which is illustrated in Figure 1. As originally configured, the machine had five front steering and four rear driving wheel sets staggered to provide continuous compaction coverage. The owner of this equipment retrofitted the rear driving wheel axle by adding an additional outboard wheel on the right and left sides. The ROPS device characterized in Figure 1 was supplied as optional equipment by Ingram.

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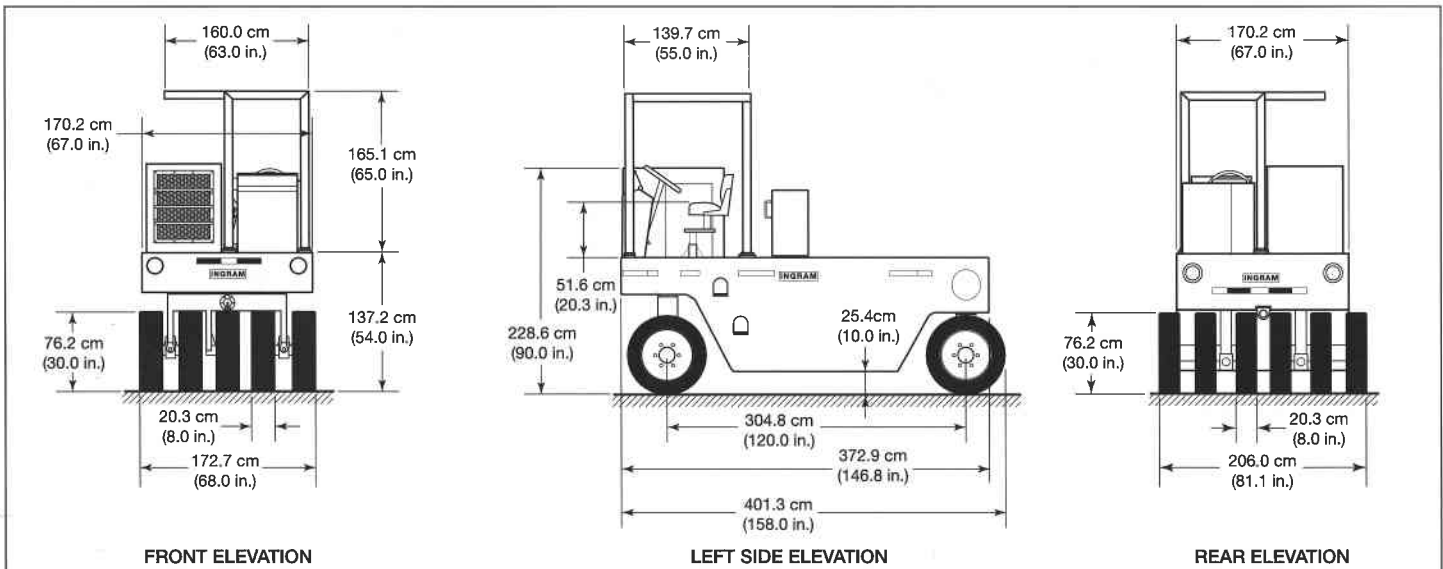


Figure 1 - Ingram Model 9-2800-PA Pneumatic Roller Compactor with ROPS

Using ballast to bring the total weight of the Ingram pneumatic roller compactor to 9,979 kg (22,000 lb), four combinations of side rollover tests were conducted as illustrated in Figure 2. The ROPS structure studied weighed 363 kg (800 lb) and clearly raised the center of gravity of the system; nevertheless, its influence on stability is found to be negligible ( $1.0^\circ$  for four rear wheels and  $0.4^\circ$  for six rear wheels). The addition of the outboard rear tires adds approximately  $6^\circ$  of lateral tilt resistance. These results have been accumulated in Table 1 which provides the lateral stability criteria for five different machines. We observe that the Ingram roller compactor equipped with six rear wheels exceeds the lateral stability criteria given for each of the other entries.

A second inquiry into the forgiving nature of the pneumatic roller compactor involves an illustration of the nature of stability using wide wheels that are either continuous or segmented. If an automobile approaches an embankment, eventually one of its wheels becomes unsupported which usually allows the entire vehicle to tilt over the embankment. Figure 3 shows the Ingram pneumatic roller compactor with three rear wheels suspended in the air while maintaining the equilibrium of the compactor. A companion illustration is given in Figure 4 which indicates that equilibrium is maintained by the roller compactor with one front wheel and two rear wheels suspended in the air.

The original work of this project grew out of an accident investigation case study that involved a caravan of road processing machinery that progressed single file forward up a curved slope. The trailing vehicle was the Ingram pneumatic roller compactor which departed from the construction protocol by suddenly driving rearward down the curved slope. The steering input did not track the curving road, allowing the compactor to be driven over the embankment where it rolled multiple times without a ROPS device. It was alleged by some accident investigators that the addition of the outboard wheels would adversely affect the stability of the Ingram pneumatic roller compactor. In response to this allegation, a 28.58 cm (11.25 in.) high ramp was constructed and the four rear wheel and six rear wheel configurations of the Ingram roller compactor were checked up accordingly as illustrated in Figures 5a and 5b respectively. The 28.58 cm (11.25 in.) ramp gave a tilt angle of  $11.3^\circ$  using four rear wheels and a tilt angle of  $8.7^\circ$  using six rear wheels. Clearly, wider is better relative to the stability of the subject Ingram pneumatic roller compactor.

As a last commentary on stability control, roller compactors are low speed vehicles especially during the compacting phase. The Ingram Model 9-2800-PA pneumatic roller compactor has a maximum speed of 6.7 m/sec (15 mph) and a recommended speed of 5.4 m/sec (12 mph) on level surfaces and 2.7 m/sec (6 mph) on inclines. Furthermore, roller compactors typically have hydrostatic transmissions which provide superior braking capability, leading to a higher avoidance capability. Along these lines, roller compactors generally possess heightened visibility in the neighborhood of the machine so that they can perform their compacting function. This characteristic also contributes to the roller compactor's avoidance capability, making it less likely to encounter anomalous protrusions. The operating environment for pneumatic roller compactors usually involves surfaces that have already been prepared by other construction equipment; off-road profiles are normally outside of their domain.

## ROLLOVER OPERATOR PROTECTION

Because of significant factors beyond the designer's control such as uneven, unstabilized, and sloped terrain, and operators' actions, rollover accidents have been experienced with roller compactors. The Safety Hierarchy (6) as shown in Table 2 indicates that when the danger cannot be eliminated by eliminating the hazard and/or the risk, safeguarding techniques should be explored as the next priority. A number of countermeasures have been developed and exploited for various vehicles to mitigate or eliminate injuries to operators resulting from rollover.

## Emergency Protocols

*Grab Onto Steering Wheel and Lean to High Side.* Forklift truck manufacturers have determined that a stuntman is capable of grabbing onto the steering wheel, forcing his back to the seat, and leaning to the high side of the tipping forklift, and that this procedure retains his body within the protective zone without allowing his head to strike the operating surface (7-8). A review of these stuntmen testing programs indicates that the heads of these stunt professionals "almost" touch the operating surface which suggests that ordinary forklift operators who are not expecting an excursion cannot succeed with this protocol. Tests involving forklift tipping with non-professional operators had to be terminated at tip angles which were less than  $90^\circ$  because the injury threshold of these operators was being violated (9). Part of the protocol involves on-

WITHOUT ROPS



A) 4 Rear Wheels: 23.0°

WITH ROPS



B) 4 Rear Wheels: 22.0°



C) 6 Rear Wheels: 28.8°



D) 6 Rear Wheels: 28.4°

Figure 2 - Side Rollover Tests

product warnings and instructions which are repeated in the forklift manual. Warnings of this type can impart information, but cannot be depended on to influence an emergency response during a tipover which involves training and not just information transfer.

**Jumping.** On machines such as forklifts that are not equipped with falling object protective structures (FOPS), operators may jump from or be thrown from the machines without having their upper bodies fall within the trajectories of the machine components. It should be noted that the mast of the forklift limits the rotation to approximately 90° when working on flat surfaces. Roller compactors that are not equipped with ROPS are capable of multiple rolls which usually contact operators who jump to the low side. Here, jumping to the high side is the most effective emergency protocol. It must be born in mind that jumping to the high side is not a natural reaction and is not easily achieved physically. An operator belted into a roller compactor without a ROPS will be in jeopardy as the roller compactor approaches 180° of roll.

### Rollover Protective Structure (ROPS)

ROPS structures on current roller compactors are usually designed with sufficient rigidity so that a protective zone is maintained during a rollover excursion (10). When the terrain is

relatively flat, these ROPS devices limit the roll to approximately 90°. On steep terrain, tumbling may occur while the protective zone is still preserved. Asperities such as rocks may enter the operator space and against this contingency the ROPS provides no protection. Gravitational and centrifugal forces tend to throw the operator from his seat and place his body into the trajectory of the horizontal portion of the ROPS. Typically, the unbelted operator is crushed between this massive ROPS structure and the ground.

There is nearly universal agreement among safety professionals that a ROPS cannot be used on roller compactors without a seat belt. For this reason, multiple on-product warning signs are commonly displayed admonishing operators that a seat belt must be worn on a roller compactor equipped with a ROPS. Typical locations for the on-product warnings and instructions include the operator's console, the underside of the front edge of the ROPS, the vertical ROPS uprights, and the seat belt buckle. Generally, these warnings and instructions are repeated in the roller compactor's manual and in the CIMA Roller Compactor Safety Manual (11) which often accompanies the machine. The ROPS device does compromise the stability of the Ingram pneumatic roller compactor, but the effect is negligible as shown by the tilt table results in the roller compactor stability

Table 1 - Lateral Stability Criteria

Machine	Measurement or Criteria	Reference
Ingram Roller Compactor with 6 rear wheels and no ROPS	28.8°	Fig. 2C
Ingram Roller Compactor with 6 rear wheels and ROPS	28.4°	Fig. 2D
Ingram Roller Compactor with 4 rear wheels and no ROPS	23.0°	Fig. 2A
Ingram Roller Compactor with 4 rear wheels and ROPS	22.0°	Fig. 2B
Counterbalanced Lift Truck (Travelling with no load)	$\tan^{-1}[15 + 2.25(\text{velocity in mph})]$ maximum 26.6°	ASME B56.1-1993 (1)
Rough Terrain Forklift Truck (Vertical Mast travelling with no load)	21.8°	ASME B56.6-1992 (2)
Ride-on Mower	20°	ANSI/OPEI B71.1-1996 (3)
Ride-on Turf Tractor	20°	ANSI/OPEI B71.4-1990 (4)
Ride-on Snow Thrower	20°	ANSI/OPEI B71.3-1995 (5)



Figure 3 - Three Rear Wheels Suspended in Air



Figure 4 - One Front Wheel and Two Rear Wheels Suspended in Air

section of this paper. Furthermore, the two or four vertical uprights which form the typical ROPS structure generally compromise the operator's visibility. Operators typically compensate for these obstructions by shifting their heads and torsos to look around the obstructions.

### Seat Belt

The seat belt on a roller compactor is an operator packaging concept which maintains the operator's body in the protective zone, with the potential exception of appendages. On narrow roller compactors, an operator's head may contact the operating surface during a rollover in much the same manner as a clapper striking a bell. On unimproved surfaces, the Head Injury Criterion (HIC) Index is non-critical; on improved surfaces such

as concrete, the HIC numbers for seat belted operators usually indicate severe injury (12-14). In forklift trucks, this whipping phenomenon or double pendulum effect is called "the flyswatter effect" and has been extensively studied (9,12,15). As a passing observation, most construction workers are required to wear helmets (16).

### Seat Belt Usage

The use of seat belts on construction equipment and in related industries is observed to be low in spite of massive educational programs, licensing, legal imperatives, warning signs, manuals, and technology transfer (17-18). A review of the literature indicates that construction equipment operators stated the following reasons, in random order, why they do not use seat belts (17,19):

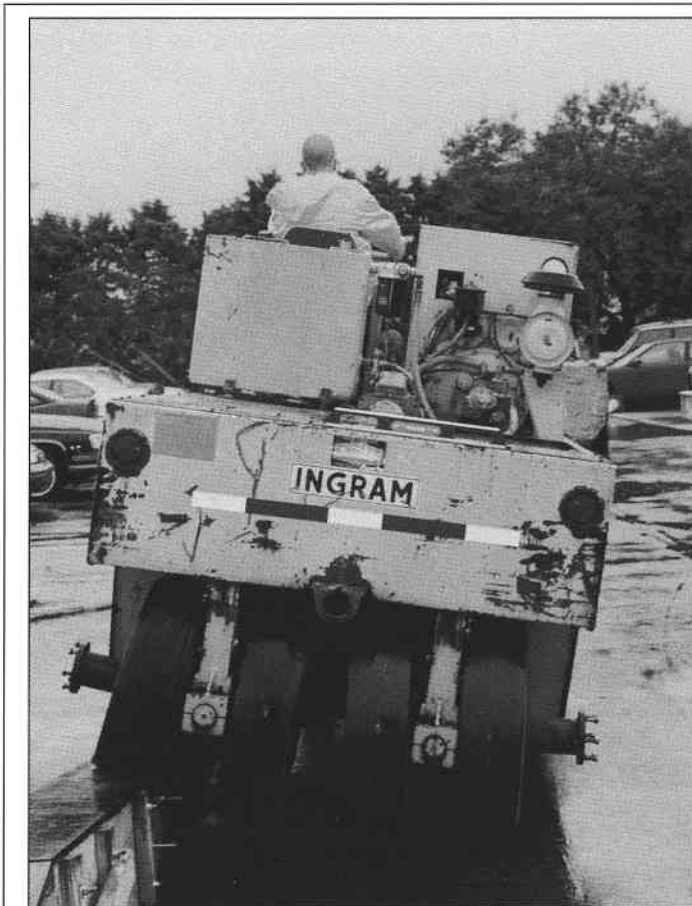


Figure 5a - Four Rear Wheels on 28.58 cm (11.25 in.) Ramp: 11.3°



Figure 5b - Six Rear Wheels on 28.58 cm (11.25 in.) Ramp: 8.7°

- Operators want the option of jumping in case of a rollover.
- Fear of being trapped in an overturn.
- Operator discomfort.
- Dirty belts.
- Operators don't want their personal belt buckles to be scratched or abraded by the seat belt buckling connection.
- Abrasion of the operator's pants in areas where the rough textured seat belt rubs.
- Inability to turn and look backward.

### Training and Supervision

Given the dangerous nature of the ROPS and the propensity for low seat belt usage, the roller compactor designer at present has to look at the fourth priority of the Safety Hierarchy. This requires training and supervision to assure continuous usage of the seat belt on those roller compactors equipped with a ROPS and a seat belt. The manuals traditionally supplied with roller compactors taken together with general industry-wide safety manuals such as the CIMA Roller Compactor Safety Manual (11), may form the basis of an effective program of training and supervision.

### Value Systems

The following value systems have considered or contain requirements for incorporating a ROPS and seat belt on roller compactors:

1. Cal/OSHA (20): ROPS and seat belts shall be installed and used on rollers and compactors specified in this section in accordance with the effective dates for each type or use of equipment listed.

Table 2 - Safety Hierarchy

First Priority	Eliminate the hazard and/or risk
Second Priority	Apply safeguarding technology
Third Priority	Use warning signs
Fourth Priority	Train and instruct
Fifth Priority	Prescribe personal protection

2. OSHA (21): The promulgation of specific standards for rollover protective structures for compactors is reserved pending consideration of standards currently being developed.
3. OSHA Draft Proposal (22): Rollers and compactors shall be equipped with falling object protective structures (FOPS).
4. CIMA Petition to OSHA (23): The Construction Industry Manufacturers Association (CIMA), through its Bituminous and Aggregates Bureau, petitions the Occupational Safety and Health Administration to commence rulemaking proceedings at the earliest possible date to address the issue of rollover protective structures (ROPS) on self-propelled rollers and compactors used in the construction industry.
5. Case Law (24): Roller was not rendered defectively dangerous due to lack of rollover protective structure as owner had known of availability of structure but made conscious decision not to purchase it.

In rollover situations which naturally limit themselves to a 90° roll, the inclusion of a ROPS device on a roller compactor extends the crushing zone and thereby introduces a new hazard. The dangerous safeguard consensus admonishes designers and manufacturers from introducing safety devices which in and of themselves create new dangers (25). Consequently, safety theory would preclude the introduction of a ROPS structure unless a value system gives permission for its introduction. One of the important functions of a value system is to weigh the upside and downside of safeguard systems and to suggest their usage when the upside is sufficiently compelling. In the case of a ROPS for a roller compactor, it may be argued that its downside is controlled by the introduction of a seat belt which when used eliminates the creation of a new hazard. Unfortunately, human factors considerations alter the situation. Specifically, low seat belt usage will expose the majority of operators to the expanded crush zone created by the ROPS. For this reason one should look to value systems for guidance in the adoption of a ROPS and seat belt system on a roller compactor. For example, because of the Cal/OSHA value system, certain specified roller compactors must be equipped with a ROPS and seat belt when used in California. In addition to rollover, one must also consider that a ROPS on a roller compactor introduces new hazards by compromising visibility, compromising stability, creating a shear hazard, and collapsing on the operator.

## ACCIDENT STATISTICS

Accident statistics have been accumulated for injuries associated with forklift FOPS and roller compactor ROPS. Selected accident statistics are reported in this section of the paper.

### Forklift Accident Statistics

Accidents involving FOPS on forklifts were studied in a survey conducted by the state of California (26). Here, it was noted that of the eight deaths caused by forklift rollovers in California in 1980, five of them were attributable to the FOPS device and descriptions of these accidents are presented.

1. A materials man, employed by a public utility, was operating a forklift in his employer's maintenance yard. He lost control of the vehicle and it overturned. The worker suffered fatal injuries when his head was struck by the vehicle's canopy. The employee's supervisor had instructed the worker not to operate the forklift because it was his first day at the job.
2. An 18-year old forklift operator, employed by a machine shop, was driving his forklift down a public road on his way to pick up some material. As he neared the material, he made a 170-degree left turn out into the street to gain distance from the curb so that he would have enough room to turn toward the material while picking it up. As he made the turn, the already cracked steering bolt broke, causing the forklift to go out of control and turn on its side. The operator was fatally crushed between the pavement and the overhead canopy guard.
3. A 19-year old maintenance worker, employed by an agricultural firm, had been servicing forklifts. He had just filled a lift with propane and was returning it to the warehouse. He was driving on a flat 12-foot wide driveway, with a warehouse on one side and an uphill 1:1 slope on the other. The forks were two feet high when the operator drove into the uphill slope. The forks struck the slope and raised the left side of the vehicle, causing it to turn on its right side. The driver was fatally crushed when he was thrown under the lift's canopy. The maintenance worker had no formal training in driving forklifts.
4. A farm laborer was driving a field forklift from a tomato field to the main shop. As he approached a left hand curve in the road, he crossed the center line and drove off the side of the road. The rear of the vehicle struck a power pole (the operator was driving in reverse) and turned on its side into the adjacent irrigation canal (20 feet wide by 15 feet deep with 5 feet of water in the bottom). The driver was pinned under the forklift's overhead guard and drowned. After the accident, the forklift was found to be in good mechanical condition.
5. A forklift operator, employed by a roofing paper manufacturer, was moving bales of paper from where they were stacked to a flatbed truck. The forklift carried two bales on each trip. A shift in the load caused the forklift to overturn. The driver jumped off the vehicle and was fatally crushed beneath the lift's overhead structure.

The California study includes four forklift rollover fatalities from January of 1965 to June of 1970 involving the FOPS canopy and descriptions of these fatalities are presented (27).

1. Three forklift trucks were being used to rotate a cylindrical steel cooker in a cannery. The cooker was 26 feet long, and 8 feet in diameter, and weighed about 5 tons. The forklifts were overloaded, and when one of the vehicles tipped on its front wheels and rolled backwards, most of the weight shifted to one of the other trucks. The second vehicle tipped over on its side, and its driver was crushed under the canopy.
2. A 21-year old operating engineer was unloading bundles of 10-inch by 13-foot transit pipe from a truck when the front wheels of the small forklift he was driving sank into soft ground. The vehicle overturned, and the worker jumped or was thrown out. The operator was pinned to the ground by the vehicle's canopy and died as a result of his injuries. The small lift truck was inadequate for the size of the load and the terrain.
3. A forklift driver in a paper mill was hauling bales of paper up a ramp from the yard and into the plant. Apparently, he lost control of the vehicle on the way down the ramp and swerved to the side of the ramp not protected by a rail. The vehicle hit several stacks of paper which kept it from going over the side until it got near the bottom. The left rear wheel then slipped off the edge, and the driver was fatally crushed under the edge of the canopy when the vehicle turned over on its side. A guard rail on the ramp probably would have prevented the death.
4. A laborer was operating a forklift carrying meal from outdoors into a warehouse. When the operator turned in too wide an arc and came within 3 feet of a drainage ditch, the vehicle skidded on oily cottonseed, slid into the ditch, and overturned. The operator was thrown from his seat and the framework of the truck's canopy fell across his neck, inflicting fatal injuries. The installation of bumper blocks along the drainage ditch would probably have prevented the accident.

### Roller Compactor Accident Statistics

The Occupational Safety and Health Administration (OSHA) has conducted investigations of accidents associated with roller compactors (28). Selected OSHA accident abstracts reported for roller compactors equipped with a ROPS and seat belt are presented in this section. With the exception of the deletion of the identity of the roller compactor manufacturers, these abstracts are quoted as they appear in the OSHA accident investigations for rollers or compactors. The text has not been edited; misspellings and incomplete sentences are unaltered.

### **No Date Summary #14493647**

Employee #1 was operating a steel roller for the purpose of levelling a dug-up area. He was backing the roller (a normal procedure), but went too near a 45% embankment. The machine started to turn over, so the employee, who was standing up while backing up, was either thrown off or attempted to jump off. The rollover bars came in contact with his upper body back and shoulders. He was crushed to death.

### **8-19-87 Summary #738872**

On August 19, 1987 at approximately 3:40 PM, was operating compactor at the roadway at the top of hf residue levee at the Pennwalt Corporation plant. Was rolling clay as part of the raising of the level of levee wall. The roadway was 15ft. wide, but drove the compactor beyond the edge of the roadway. As the compactor began to roll over on its side, the employee jumped off the compactor which fell on him. His skull was crushed by the rollover protective structure. Cause of death-massive head injuries.

### **9-18-89 Summary #851055**

Employee had been running a piece construction equipment road compactor stopped machine on slight incline put machine in neutral & apparently jumped off the machine toppled over & the top of roll bar struck employee pinned him to ground causing crushing injuries machine weighed in excess of 5 ton.

### **9-13-90 Summary #170196091**

On September 13, 1990 at approximately 12 noon, the contractor's crew was performing a chip seal operation on H/W 49 3 mes N of Plymouth. A front end loader was traveling backwards in the S/B lane (going north) carrying 1/2 rd of crushed gravel to overlay on a "holiday" in the N/B lane. The front end loader came too close to a rubber tired roller compactor operated by employee #1. The rear corner of the loader bucket struck the left front ROPS columns, tipping the roller on its side. Employee #1 was not seat-belted and received crushing fatal injuries to her pelvis, and other injuries.

### **7-13-91 Summary #767368**

Driver-operator of an earth compactor roller was not wearing the seat belt provided on a vehicle equipped with rollover protector and the machine overturned. Throwing the driver out just far enough for the ROPS member to strike his head, killing him. The vehicle was posted with danger notice of vehicle overturning, and the operator to wear seat belts.

### **7-22-91 Summary #170047294**

The compaction roller was being operated to close to the side of road bank and the machine operator was not wearing his seat belt and was thrown from compaction roller during the machine tipping onto its side at which time the operator was pinned and crushed beneath the rollover protection device.

### **9-09-93 Summary #954131**

9/9/93 at approx. 2:20 P.M. employee #1 was in the process of operating a vibrating compactor roller. This equipment was being used to compact a new road bed. During this process this equipment was operated too close to the soft dirt shoulder of the road bed, causing the roller to roll over. Employee #1 attempted to jump free. The equipment rope struck employee #1 causing lacerations and fracture of the left upper leg.

### **9-15-93 Summary #170727598**

Employee #1 was operating a pavement roller weighing approx 7000 lbs. with roll over protection attached. He was rolling the gravel shoulder of south bound hwy. 101 South of Pepper Road in Petaluma, CA. During this procedure the shoulder collapsed

in on spot as he ralled over it causing the equipment to slide sideways down an embankment and tip over on it's right side. The employee not wearing a seat belt was ejected face down and the equipment came to rest on top of him. The employee sustained severe head injuries and was pronounced dead at the scene.

### **11-10-93 Summary #14497408**

Victim #1 was operating a sheep foot vibratory soil compactor when he came too close to the edge of a six foot embankment. The machine rolled over on it's left side ad landed partly on the embankment and level ground. Victim apparently thrown from the drivers seat and was projected in the forward position hitting the right top portion of the ROPS from his right chest to the back area causing broken bones, massive internal injuries and death.

### **9-15-94 Summary #170060297**

Employee was working in his require assigned duty as a truck driver /low boy operator. His assigned task was to load a roller compactor onto a lowboy trailer and transport the equipment to place of storage. The roller was located in residential development where it had been used to com port asphalt employee #1 was working alone without supervisor after arriving at the loading point, employee #1 disconnected his truck tractor from the lowboy trailer and proceeded to load the equipment during the loading operation the roller overturned off the edge of the trailer, employee #1 was not wearing a seatbelt and was struck by the equipment roll over protection system (ROPS).

### **2-07-95 Summary #170561732**

Employee number 1 was operating a vibratory compactor. The employee number 1 used a blade attachment to push through and over a pile of dirt, when employee number 1 reversed the direction of the compactor to back up, he backed at an angle resulting in the compactor to traverse a 30-40 degree side to sided incline which resulted in the compactor turning over. The employee tried to jump or was thrown into the direction of the rollover ad was struck in the chest by the ROPS.

The following observations can be made regarding the roller compactor accidents presented:

1. The majority of the roller compactor rollovers presented resulted in serious injury or death.
2. Given the information available for the cases presented, most of the roller compactors were equipped with seat belts.
3. In every case presented, a seat belt was not used by the operator.
4. In the majority of the cases presented, the ROPS was the injury instrumentality.
5. The majority of the cases presented involved an embankment, incline or operator error.
6. The accident statistics presented corroborate the predictions made by the roller compactor industry regarding the injury potential to roller compactor operators who don't wear their seat belts.

### **CONCLUSIONS**

1. The roller compactor possesses a number of stability advantages that derive from its low center of gravity, hydrostatic braking system, low speed, high visibility, normal operation on pre-prepared surfaces, and wide wheel track.
2. An effective program of training and supervision is needed to prevent roller compactor rollover accidents due to operator error such as driving over an embankment or improper loading and unloading on a lowboy trailer.

3. The same level of proper training and supervision that minimizes rollover accidents also assures that the seat belt will be worn by roller compactor operators.
4. Without the use of the seat belt, the likelihood of serious injury or death is very high during a rollover of a roller compactor equipped with a ROPS.
5. Wider is better relative to the stability of the Ingram model 9-2800-PA pneumatic roller compactor.
6. The stability of the Ingram model 9-2800-PA pneumatic roller compactor is not considerably compromised by the use of a ROPS and seat belt.

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