Emergency stop devices and the human factors of response

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EMERGENCY STOP DEVICES
AND THE
HUMAN FACTORS OF RESPONSE

by

Robert P. Guinter

Thesis submitted to the Faculty of the Graduate School of the New Jersey Institute of Technology in partial fulfillment of the requirements for the degree of Master of Science in Management Engineering 1986
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ABSTRACT

Title of Thesis: Emergency Stop Devices and the Human Factors of Response

Robert P. Guinter, Master of Science in Management Engineering, 1986

Thesis directed by: John Mihalasky, D.Ed.
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The manual emergency stop was recognized as an important aspect of machine control very early during the history of powered mechanical systems. The purpose, of course, was to allow machinery to be quickly stopped during emergencies to minimize equipment damage and/or personal injury. Today, however, the emphasis of control is being shifted more and more toward totally automatic systems. Often, the importance of manual emergency stopping and override of these systems is lost in the zeal to perfect automatic controls. The problem that evolves is how and when to provide an efficient human-machine interface to allow a manual emergency stop.

Here, some common emergency stop devices are studied in light of ergonomic principles that apply during manual emergency response. Information on legal and consensus standards applicable to emergency stopping devices are included with a summary of useful recommendations regarding design and placement of devices for efficient human use.
The focus of this study is an ergonomic experiment concerning different arrangements of emergency stop pushbuttons commonly found on machinery. The results indicate that an unguarded pushbutton is superior to a guarded button in terms of the average human response time to activate and a reduction in the frequency of miss response (unsuccessful attempts at activation). Further results indicate that a large, 3 inch mushroom style pushbutton is superior to a 7/8 inch unguarded pushbutton and a significant reduction in frequency of miss response under adverse conditions is possible by redesigning the surface of the standard mushroom head.
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CHAPTER I

EMERGENCY STOPPING OF INDUSTRIAL MACHINES

The Problem

Perhaps one of the most important aspects of industrial history has been the design and development of machines. No one would deny that machinery has been the driving force behind a 200 year revolution, a revolution that is still in progress, and a proliferation of technology that brought unforeseen changes to labor and production. In short, the industrial development seen in the last two centuries has produced a standard of living that was heretofore impossible without use of machines. Before this time most American families led rural lives: living, working, and dying on the farm. Mass production did not exist and most needed items were either made at home or constructed by tradesmen one piece at a time.

Accidents of course have always been a familiar part of life and work. These sudden adverse events may have often been caused by environmental conditions or by some form of negligence, but the results over the years have been much the same. To a tradesman or farmer before the industrial revolution, an accident causing loss of a limb was likely a very rare but disastrous event. Nonetheless, the hardship, the pain and suffering this type of accident
causes has not changed with the advent of machines; although some might say that the frequency of occurrence has greatly increased.

Safety theory that developed with industrial work has seemed to emphasize accident prevention. There can be no argument that it is better to prevent accidents than to develop responses contingent on their occurrence. For example: although it is wise to learn efficient fire fighting methods, it would be wiser indeed to strive for fire prevention; for without the fire there is truly no need for response. However, it is doubtful that human control over events could become so complete that no fire would ever occur; and one could not assume that a time will ever come when fire response will no longer be needed. Therefore, wise humans will continue to develop contingency plans. It is within this line of reasoning that situations requiring manual emergency stops of industrial machines are considered.

The Emergency Stop

It is assumed that, no matter what care is taken in design, installation, maintenance, and control of machines, situations will arise when those machines will require manual activations of an emergency stopping device. This could be due in part to one or any combination of mechanical, electrical, environmental, or human failures.
Furthermore, no machine can ever be expected to fail safely at all times. Even the most reliable electrical components will ultimately fail (if left in service indefinitely); and there is no guaranty that the failure will not cause some related dangerous condition. A machine could run wild due to a frozen relay contact, a short-circuit could place dangerous voltage on normally safe parts, or a broken ejection solenoid could cause machine parts to jam with resultant shattering of metal. These are only some of the common malfunctions that industrial operators may eventually face during their lifetimes of work. The following are some emergency conditions that could be expected to require a manual emergency stop.

(1) An electrical explosion.
(2) Jammed work parts.
(3) An entangled operator stuck in the machine.
(4) Broken machine tools.
(5) A runaway power source.
(6) A defect or mis-alignment of stock.
(7) Blockage of feed.
(8) Loosening of parts.
(9) A sudden unbalance.
(10) An extraneous part in the feed.
(11) Spillage of dangerous chemicals.
(12) An outbreak of fire.
Although this list could not by any stretch of the imagination be considered complete, the point is perfectly clear. Irrespective of automatic controls in use, emergency stopping of industrial machines has been, and will continue to be, an important part of the operator's function. Contingency plans for the execution of an emergency stop motion must be considered in operator training and machine design to ensure efficiency when an accident eventually occurs.

**Types of Devices**

In the early days of industrial machine design, power was often obtained from an intricate maze of overhead shafts, which transmitted rotational mechanical energy from the source or "prime mover" throughout the plant.¹ Individual machines were connected and disconnected as needed to the main shafting and obtained their power through rotating belts and pulleys. Frequently, the prime mover was a steam driven engine located in a separate room at the factory called the "powerhouse."² Methods of disconnecting power from individual machines consisted of crude belt shifting devices which, while push-

²Ibid., pp. 142-143.
ing a lever, threw the rotating belt off the main drive pulley onto a smaller loose pulley. Alternatively, some type of clutch device was often used.³

Attempts at electrical control during this period were primitive indeed. An electric button or bell-push alarm was often installed in various locations around the plant.⁴ Assuming the batteries were charged, an alarm would ring inside the powerhouse and the attendant would shut down the prime mover when the accident alarm sounded. Obviously, the effectiveness of the system depended jointly on the response time of the attendant and the braking speed of the machine. It was likely that the flywheeling effect could keep mechanical energy applied to the system for many seconds after tripping the prime mover. Other efforts at direct control usually consisted of an electrical or mechanical device that would disconnect the head of steam from the prime mover or interrupt vacuum in condensing compound engines. These devices were activated by pushing or pulling a control device inside the plant.⁵ Again, inertia of thousands of pounds of rotating shafting likely prevented instant stopping of machines.

As technology improved and individual machines became fitted with electric motors as power sources it became much easier to include an emergency stopping device.

³Calder, pp. 136-140. ⁴Ibid., pp. 142-143. ⁵Ibid., p. 143.
One common arrangement was the typical dual pushbutton station still seen on many industrial machines today. An example is shown in figure 1-1. The problem with many of these devices is the close proximity of start and stop buttons. In an emergency an operator could inadvertently press the wrong button causing delay in stopping a machine. Also, the stop function is not secure in the event an operator accidentally presses the start button after the emergency stop.

Other station panels have become more complex, containing multiple switches, pushbuttons, and signal lights; typically these panels are custom designed by an engineer using standard parts to assemble a control station to personal specifications. A typical six unit custom built pushbutton station is shown in figure 1-2. Operator confusion in an emergency is possible if the designer does not select and assemble controls in accord with established ergonomic principles.

Other types of devices have become popular for stopping industrial machines. Mushroom head pushbuttons have been in use for over fifty years with excellent results. Many variations have been devised to make the

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7Ibid., p. 223.  

8Ibid.

9Eugene J. Verret, Manager-Corporate Product Safety Allen-Bradley Company, Personal Correspondence (Milwaukee, Wisconsin, February 5, 1985)
Dual Pushbutton

Figure 1-1
Custom Control Station

Source: Allen Bradley Industrial Control Catalog no. 107, p. 223.

Figure 1-2
emergency stop secure. Two examples are shown in figure 1-3.\textsuperscript{10} The first device requires a simultaneous pull and twist motion to release the mushroom head after an emergency stop and the second device requires only a pull to release. Both devices would provide a substantial margin of safety after an emergency stop if they were combined with separate start buttons; restarting the machine would require a different and distinct set of motions.

Some machines produce their own special problems when selecting a suitable emergency stopping device. Calenders, rolls, and conveyors are examples. Since the point of operation can frequently be many feet wide for rolls or many yards for conveyors, the problem of locating a stopping device becomes very difficult indeed. In some cases the solution might be to install separate push-buttons every few feet down the length of the machine; for others, a trip-wire connected to a microswitch might be better.\textsuperscript{11,12} This technique has also been suggested for stopping towed agricultural implements.\textsuperscript{13} However, these

\begin{itemize}
\item \textsuperscript{10}Allen Bradley Industrial Control Catalog no.107, p. 232.
\item \textsuperscript{11}\textsuperscript{1320.1-1947, Safety Code for Conveyors, Cableways, and Related Equipment, American Standards Association (New York, 1947), p. 31.}
\item \textsuperscript{13}J. B. Sevart and Bradley Klausmeyer, "Emergency Stop Devices for Agricultural Machinery," \textit{Agricultural Engineering}, Volume 63, Number 9 (September, 1982), 13.
\end{itemize}
Mushroom Pushbuttons

Figure 1-3
authors prefer a mechanical stop at the main driveshaft for positive control. The point of importance, when dealing with rolls, conveyors, or farm implements is clear; on this type of equipment an emergency stopping device is needed wherever a human entanglement can occur.\textsuperscript{14} Ironically, an emergency stopping device can be useless if it cannot be reached by someone entrapped. An example of an emergency trip-wire is shown in figure 1-4.\textsuperscript{15}

**Accidents Involving Machinery**

Stories of accidents involving machinery can become very gruesome accounts. In the early factory days open gears, pulleys, in-running belts, and protruding set-screws on overhead shafts often caused entanglements.\textsuperscript{16} Many persons died or were seriously maimed when clothing got caught and bodies were whipped violently around. A person caught in a gear could have an arm almost instantly chewed to bits.\textsuperscript{17} Very likely the equipment did not stop as inertia kept shafts turning with human bodies attached. Nevertheless, in spite of present safe-guarding techniques,

\begin{footnotesize}
\begin{enumerate}
\item \textsuperscript{14}Sidney J. Williams, *The Manual of Industrial Safety* (Chicago and New York, 1927), p. 98.
\item \textsuperscript{15}Safety Code for Rubber Mills and Calenders, pp. 3-5.
\item \textsuperscript{17}Ibid.
\end{enumerate}
\end{footnotesize}
Emergency Trip-wire

Trip-wire

Microswitch

Figure 1-4
entanglements can still occur. Many machine operators know of or have heard of someone injured from this type of accident.

Factory owners seemed rarely to be interested in safety development. Installing guards around dangerous machine parts cost money or could slow production and these were often seen as unnecessary expenses. Accident prevention measures very often waited for public support and legislative action, mostly being driven by newspapers printing the gory details of serious cases. Sometimes these stories hit very close to home as whole communities might have been employed in one local factory. Co-workers during the shift became friends and neighbors after work and serious accidents could affect whole towns.

Today we are still affected by these sensational stories although they can now be seen directly on the local news. One recent newscast told the tale of an elderly man killed by a train in New York City. While waiting at the subway station he slipped and fell to the track. Anxious bystanders tried to help him up but he had been stunned by the electricity; although he wasn't yet seriously hurt, he could not help his would be rescuers. One woman even risked personal injury and jumped down to try and push the man up; but she couldn't lift

him and other bystanders would not help, being afraid of
electricity and the on-coming train. Several minutes
later the train came into the station and crushed the man
to death, even while transit personnel were handling the
information that someone was on the track. Ironically, it
was later found that the means to save this man's life
were available at the site because, hidden at the station
was a master emergency stop switch.

Although this accident points out the need for an
emergency stopping device, especially where innocent by-
standers can be involved in an accident, the point could
be made that one was actually available and the cause of
this death was ignorance of the device location. Obvi-
ously, in New York City such a device would have to be
hidden to prevent vandalism, however, someone at the site
should have known where it was.

Other accidents can occur where no emergency stop
device exists, and very often, operating characteristics
of particular machines may encourage machine operators to
approach a live hazard point. Maintenance or operating
procedures can even require the machine to be powered
and this may be so stated in the operating manual. 21
Consider the following account of an operator's injury
when required to work next to a live hazard:

21 J. B. Sevart and Bradley Klausmeyer, Emergency Stop
Devices for Agricultural Machinery, American Society of
Agricultural Engineers Paper No. MCR-81-401 (St. Joseph,
Gene Brandies, an 18 year old farmboy worked daily with a Farmhand Feedmaster model F81-C drop feeder at Carter's dairy. He knew well how it operates. Taking power from a tractor, it receives, mixes and discharges feed by means of augers which rotate at high speed in cylindrical housings. Feed is thus received, propelled into a mixing tank, mixed and forced up to a drop point where it falls through a shute into a hopper welded to a discharge sleeve several feet long. A discharge auger rotates within that hopper and sleeve.

The hopper is box-shaped, 10 inches or so wide, about 20 inches long, and open at the top to receive falling feed. Just inches below the top of the hopper, the discharge auger whirls at 380 rpm to force feed through a hole in the hopper, cut round in the circumference of the auger, and thence through the discharge sleeve to its destination at a sack or trough several feet away. The hopper is waist high to an operator standing near the clutch handle which engages the discharge auger. To one standing in that position, the auger is exposed in the hopper; it is readily visible and, in operation, openly and obviously dangerous. Gene Brandies, who grew up on a farm, had "seen enough of it," in his words, to know that it was dangerous. He knew "not to put my hand in there."

One day, however, that is what he did. He and Carl Smith were sacking cornmeal for sows in the farrow barn. Smith was in the barn filling sacks with meal which flowed from the discharge sleeve. Brandies stood outside, his back to the Feedmaster. With his right hand on the clutch handle he regulated the flow of cornmeal as the sacks were filled by Smith; with his left he steadied the shaking discharge assembly. His left hand dropped into the hopper. In a split second, the whirling blade of the auger pulled his fingers, then his hand and forearm through the pinch point at the end of the hopper and tightly into the discharge sleeve. The auger mangled Brandies' hand before Smith could run out of the barn and throw the clutch handle.22

Clearly, an emergency stopping device could not have stopped Brandies' injury. Only the proper combination of operator care and machine guarding could have prevented the accident. However, it is not the intent of an emergency stopping device to prevent all injury, but to minimize the severity of injury when an accident occurs. "If one considers a reaction time of even two or three seconds, which is several times the normal instinctive reaction time of adults, and a stop time of three seconds, the power of the machine is available to do injury to the victim for only five to six seconds."\(^2\) One can only wonder how much more than six seconds elapsed between Brandies' entanglement and Smith's emergency stop of the Feedmaster.

Safety engineers and accident investigators have long acknowledged the value of the emergency stop, especially during those accidents where injury becomes time dependent.\(^3\) The following excerpt illustrates the situation:

\(^3\) Ibid., pp. 2-3.
...I have investigated many accidents where farmers or industrial workers were caught in in-running nip points and experienced severe damage to the nerve and circulatory systems of the arm(s) without having broken a bone. The medical profession can repair broken bones but the gross burning and erosion of the nerve and circulatory systems are non-repairable and result in amputation. I have also encountered accidents where farmers got one or more additional limbs entangled in the machinery while trying to get the first trapped limb out. The emergency stop device is most useful to reduce the injury severity in such accidents. Shock is also minimized if the machine can be quickly shut down.25

Trappers have noted that animals caught in traps will do almost anything to free themselves; even if this means knawing or wrenching a trapped limb completely off. Humans have shown a similar instinct when caught in a machine by attempting to wrench a trapped limb free using another hand or foot. Frequently, as the above author points out, the result of this action is further entanglement and more serious injury. Again, an emergency stopping device cannot prevent this type of accident from first occurring. However, it can provide a reliable means for an entrapped operator to quickly stop the machine before instinctive wrenching can cause further entanglement. The following account of an accident with a printing press illustrates the problem:

25J. B. Sevart, P.E., Personal Correspondence (Wichita, Kansas, 1984).
After each run, the press was stopped, pans were placed under the rollers, and the press was turned on so that all six units were idling. Each crew member, armed with a bottle filled with naptha, a cleaning solvent, then stood on a catwalk running around each unit, and into the machine and squirted naptha on the unguarded, revolving rollers. Some of the naptha, mixed with ink, would be thrown back onto the catwalk as the rollers turned. Most of the ink and solvent would drip onto the lowest rollers and into the pans. The lower roller was cleaned by a blade that scraped off the accumulating residue. This blade was adjusted before and during the process to ensure that all the residue was removed. Wansor's injuries occurred while he was making this adjustment...

To adjust the scraper blade, Wansor had to crouch on the catwalk to avoid being hit by the rollers above him, turn two screws located about fifty inches apart, then back out in the same Russian-folk-dance crouched walk. On the date involved here, Wansor had finished adjusting the screws and was beginning to back out of the machine when...his right hand became caught in the unguarded rollers. He attempted to pull his hand out but succeeded only in entangling his left hand as well and in the struggle caught his hair on the upper rollers. Although the machine was quickly turned off, Wansor's hands were severely mangled. Despite extensive medical treatment, he lost most of the fingers and part of the thumb from his right hand and two fingers from his left hand.26

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Although it is apparent that an emergency stopping device located near these rolls would not have prevented the initial injury to Wansor's right hand, it is possible that further injuries, including those to the left hand could have been avoided. Clearly, within a split second of entanglement, fear and an instant recognition of hopelessness caused Wansor to react in panic; and, in the attempt to wrench the trapped hand free further unnecessary damage occurred. The questions might be asked: why did the machine designer require operators to enter such a dangerous area, especially in such an unnatural human posture (crouching)? Why were better procedures for cleaning not considered in the design? The answers to these, and other related questions can only be explained in terms of foresight. Obviously, the designer of this machine did not envision the mangling of hands; therefore, cleaning procedures may have been overlooked in the zeal to perfect an efficient mechanical design.

Another area that can be overlooked by machine designers is the frequent need to manually clear a stalled machine. Industrial operators can be faced with the following situation:

Perhaps the most dangerous of all operating modes is that where the hazardous rolls, or other moving parts, are stalled due to a plug. It is simply contrary to normal human behavior to turn a stopped machine off. (Who hasn't replaced a light bulb to find with surprise that the light was still on.) Under this condition, the opera-
tor begins to remove the plug and does not recognize any danger because the machine is "stopped". As the plug is diminished, suddenly the torque of the drive is sufficient to drive the machine and a slip clutch re-engages. The condition just described is a trap and represents a very dangerous condition that the ordinary operator does not comprehend under the mental pressures of having a specific, but unrelated task to perform.\textsuperscript{27}

The preceding accounts have all focused on the human aspects of accidental contact with machines and the need for an emergency stopping device located close to the point of hazard, to minimize severity of injury. Largely, the damage caused to machines in accidents where they cannot be quickly stopped has been ignored. Perhaps these stories are not nearly as spectacular as those causing serious human injury and are, therefore, quickly forgotten. In any case, the emergency stopping device, when properly placed can minimize the severity of damage and monetary loss in an accident. The following two cases are examples (author's personal observations):

Case 1

In the pharmaceutical industry, tablets are formed on a rotary mechanical press which takes powder and presses it between two punches (rams) in a die. Upper and lower punches operate vertically and, as a die table revolves,

\textsuperscript{27}Sevart and Klausmeyer, 1981, p. 4.
motion of many sets of punches are controlled by stationary cams. The sequence of tablet formation is as follows; powder enters a force feeder mechanism positioned 0.003 inch above the revolving die table; upper punches ride the cam track and clear this feeder assembly while lower punches are drawn down in the dies to pull powder into the chambers; upper punches are then lowered into the die holes and pressure up to five tons is provided to press the tablets; upper punches are then withdrawn and, as the die table completes its revolution, lower punches are raised in their dies to eject the completed tablets. This sequence continues indefinitely.

One day during a press run an operator inadvertently forgot to tighten a die retaining screw and ultimately this die was forced out of its mount. The die table was revolving at about thirty rpm when die contact was made with the feeder. On the first revolution (2 seconds) the feeder was torn from its mount. On succeeding revolutions, pieces of broken feeder were mangled further and ultimately bits of metal became jammed in other dies, thereby stalling the machine. It was estimated that the accident duration was on the order of ten seconds.

During the accident the operator did not stop the machine because the stop button was located under the feeder assembly. No emergency stopping device was included any place else on the machine. Cost of the accident was over $20,000 due to broken machine parts and
complete destruction of one set of punches and dies.

Case 2

Pharmaceutical capsules are often made on similar types of rotating machines. However, revolving die tables usually index and remain at one stationary position for a certain length of time. Operations performed during dwell time include: empty capsule placement, opening, filling, closing, and cleaning, all of which are done at different station locations.

One day during a capsule run vibrations loosened a retaining screw holding the powder hopper in place. Suddenly the dosing mechanism contacted the powder hopper and breaking of metal ensued.

On the side of the machine, away from all moving parts, was a large, red, mushroom style, emergency stop pushbutton which the operator quickly activated. At the time of the accident it was estimated that the dosing mechanism was rotating at thirty-five rpm. On the first revolution (1.7 seconds) the dosing mechanism and powder hopper were severely damaged but the emergency stop was completed before any further revolutions were made. Cost of the accident was estimated at about $2,500 to replace the broken parts.

These two accidents are typical of what can happen with high speed rotary machines when machine parts loosen, work parts jam, or extraneous debris finds its way into
areas of tight clearance. Although these two particular accidents cannot be directly compared due to differences in machine operation, the fact that the indexing style capsule machine was stopped before it jammed completely is a significant observation. Clearly, the operator in case 1 did not attempt an emergency stop because the machine controls were too close to the danger zone. In fact, this particular operator backed away from the machine in order to avoid flying bits of metal. Furthermore, there was no master emergency stopping device in the room. Machines that jam under these conditions are sure to be severely damaged, therefore, provisions must be made for the emergency stop. In case 2 the means for stopping the machine quickly were included in the original design. Obviously, the designer considered operator and machine safety as an important criterion.
CHAPTER II

STANDARDS AND REGULATIONS: EMERGENCY STOPPING OF MACHINES

Background of Development

"Industrial accidents cost this country 35,000 human lives and more than $500,000,000 annually. In addition, dismemberments and other serious injuries total about 350,000 yearly while the number of minor accidents, causing loss of time, exceeds 2,000,000."28 These statements seem impressive today but even more so when one considers that they were written in the early 1900's.

The situation that this author was referring to (industrial accidents) probably included many different types of accidents such as fires, explosions, and collisions as well as machinery related accidents which are of interest here. But it cannot be denied that machinery mishaps have been a significant factor in industrial safety standards development and legislative action throughout the history of industrialization. For example: the first law requiring guarding of dangerous machine parts was enacted in Massachusetts in 1877.29 During this time period

29Blake, p. 13.
many young girls (children) were employed in textile mills to operate spinning machines. They were required to work with their hands very close to unguarded gears and a very common accident was mangling of fingers. Strong public opinion finally resulted in passage of legislation only after many years had passed and an untold number of mangled young hands had accrued.  

This sequence seems to have been repeated time after time throughout history. In fact, it was once stated by a railroad executive when the Railway Safety Act was being considered (1893) that the cost of burying a man killed in an accident was less than the cost of putting air brakes on a car. This man, as pointed out by Hammer, was probably not inherently evil; rather, the statement indicated that the major industrial concern was often economics rather than safety. Therefore, it often remained for public indignation and concern to force law makers to take required action while industry dragged its feet. 

In the 1900's, realizing that something would ultimately be done and fearing a growing intrusion of governmental regulations, industries began to take action by forming committees and organizations to propose voluntary

30Blake, p. 13.
32Blake, pp. 13-14.
In 1911, at the request of the Association of Iron and Steel Electrical Engineers a national industrial safety conference was called. This resulted in the formation of the National Council for Industrial Safety (1913) which later became known as the National Safety Council. Their basic premise was: that the same principles that were being used to expand production could also be used to prevent accidents through a proper application of Engineering, Education, and Enforcement - the "Three E's of Safety."

One of the early results of the National Safety Council's efforts was the sponsoring of the American Engineering Standards Committee which developed voluntary consensus standards. This committee, which became the American Standards Association, then the United States of America Standards Institute, and finally (1969) the American National Standards Institute (ANSI) developed safety codes applicable to various industrial operations.


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33 Hammer, p. 67.
Code for Mechanical Power Transmission Apparatus (1927).

ANSI standards developed over the years have never been mandatory. Each current standard contains the phrase:

An American National Standard implies a consensus of those substantially concerned with its scope and provisions. An American National Standard is intended as a guide to aid the manufacturer, the consumer, and the general public. The existence of an American National Standard does not in any respect preclude anyone, whether he has approved the standard or not, from manufacturing, marketing, purchasing, or using products, processes, or procedures not conforming to the standard.\textsuperscript{37}

This means that neither manufacturers nor consumers are required by law to manufacture or use products in accordance with any consensus standard. However, it often behooves them to do so because, if a victim can show that use of a non-conforming product resulted in an accident, the probability of him/her presenting a successful lawsuit greatly increases.\textsuperscript{38} Furthermore, use of a product conforming to an ANSI standard does not necessarily mean that product is completely safe and an accident cannot occur. Although some may believe that products conforming to consensus standards, such as ANSI standards, are safe to use, this may not always be true. It must be remembered


\textsuperscript{38}Hammer, p. 73.
that a consensus standard implies an agreement among "...those substantially concerned with its scope and provisions."\textsuperscript{39} and may include significant input from committee members representing manufacturers. As such, a consensus standard could be interpreted as the minimum safety requirements the industry was willing to accept.\textsuperscript{40} Therefore, the motto, "let the buyer/user beware" should still be applied.

\textbf{ANSI Standards Applicable to Emergency Stopping Devices}

Many consensus standards developed over the years and applicable to industrial machines have called for or referred to an emergency stopping device. Unfortunately, most of these standards do not provide specific information on how the emergency stop is to be accomplished, where the device should be located, or what type of device should be used. The following excerpt from a personal correspondence with Mr. Carvin DiGiovanni - Assistant Secretary, B11 American National Standards Committee illustrates the situation:

\textldots regarding your research on emergency stop devices, I can advise you that existing standards language relevant to this subject that are listed throughout the 19 B11 standards are done so in performance styled language. This means that each standard calls for the need of an emergency stop

\textsuperscript{39} ANSI B11.1-1982, p. 2. \textsuperscript{40} Hammer, p. 67.
device, then describes what it is supposed to do, and then may briefly describe its location in terms of accessibility to the operator. The standard's reference however, does not provide specific standards language on how this is to be accomplished. Thus, leaving the requirements to remain flexible for each manufacturer to design a system innovated for each piece of equipment.

The 19 B11 standards referred to above are:

B11.1 - Mechanical Power Presses
B11.2 - Hydraulic Power Presses
B11.3 - Power Press Brakes
B11.4 - Shears
B11.5 - Iron Workers
B11.6 - Lathes
B11.7 - Cold Headers and Cold Formers
B11.8 - Drilling, Milling, and Boring Machines
B11.9 - Grinding Machines
B11.10 - Metal Sawing Machines
B11.11 - Gear Cutting Machines
B11.12 - Roll Forming and Roll Bending Machines
B11.13 - Single and Multiple Spindle Automatic Screw/Bar and Chucking Machines
B11.14 - Coil Slitting Machines/Systems
B11.15 - Pipe, Tube, and/or Shape Bending Machines
B11.16 - (To be assigned)

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41Mr. Carvin DiGiovanni, Personal Correspondence (McLean, Virginia, October 29, 1984)
Although, as Mr DiGiovanni points out, performance styled language can allow flexibility for manufacturers to design emergency stopping devices according to their own particular needs, consistency among functionally similar pieces of equipment has been ignored. Consider the operator who changes jobs or, perhaps, operates several different brands of machine within the same shop. On one machine the emergency stopping device could be located on the right side of a point of operation hazard while on another machine made by a different manufacturer, it could be on the left. Furthermore, different devices could be used. This question of consistency is currently being considered, among other problems, by the American Foundrymen's Society Safety Committee. Consider the following excerpt from a personal correspondence with Mr. William B. Huelsen - Vice President, Environmental Affairs, American Foundrymen's Society:

The American Foundrymen's Society Safety Committee is working on a series of graphic machine symbols which are intended to replace printed legend plates on push buttons and selector switch controls. This committee has not only been working on the graphic symbols, but also the ergonomics...

One of the problems our committee has wrestled with on many occasions is the location of
the master emergency stop on each control panel...

At one time our committee thought perhaps the emergency stop button should be located in the center of each control panel, but one of our members had experience with this on one of his machines and found that the operator occasionally brushed by the emergency stop button and shut the equipment down. The machine then had to be manually returned to its initial mode of operation and restarted. We have concluded though that the master stop button should be located at the same place on each control panel, even though it may be cut of reach of the operator in an emergency. Additional stop switches would be connected in series with the master stop and might be actuated by presence sensing devices such as photo electric cells, light shields, pressure pads, cables, etc. specifically designed and located so they could be easily actuated in an emergency by the operator(s).42

Obviously, the question of where the master emergency stopping device should be located has not yet been completely resolved. Security against inadvertent stopping of machines (Bumping) often poses a significant concern.

ANSI B11.1-1982, the American National Standard for Machine Tools-Mechanical Power Presses-Safety Requirements for Construction, Care, and Use contains the following requirements pertaining to emergency stopping devices:

2. Definitions

2.49 Stop Control. An operator control designed to immediately deactivate the clutch control and activate the brake to stop slide motion.

42William B. Huelsen, Personal Correspondence (Des Plaines, Illinois, December 5, 1984)
3. Construction, Reconstruction, and Modification

3.3 Brakes. Friction brakes provided for stopping or holding the slide movement shall be set with compression springs. Brake capacity shall be sufficient to stop the motion of the slide quickly and shall be capable of holding the slide and its attachments at any point in its travel.

3.5.2 Controls

3.5.2.1 Stop Control. A red color stop control shall be provided with the clutch/brake control systems. Momentary operation of the stop control shall immediately deactivate the clutch and apply the brake. The stop control shall override any other control, and reactivation of the clutch shall require use of the operating (tripping) means which has been selected.

E3.5.2* Controls

E3.5.2.1 Stop Control. A stop control should be available to each operator....

3.6 Electrical

3.6.2 Motor-Start Button. The motor start button shall be protected against accidental operation.\(^4^3\)

Currently the ANSI B11.19 subcommittee is working on a standard that will establish the requirements for guards, devices, and methods to be used when they are called for in the other ANSI B11 series of standards. The following excerpts from ANSI B11.19 Draft - 2/15/85, the American National Standard Performance Criteria for the Construction, Care, and Operation of Safeguards as Specified in the Other B11 Standards, apply to emergency

\(^*\)In current ANSI standards an (E) designation refers to explanatory material which is not part of the standard.

2. Definitions

2.40 Operator Controls.
An operator control is a pushbutton, switch, lever, hand wheel or other device activated by the operator which initiates, cycles, controls or stops the motion of a machine tool.

5. Auxiliary Devices

5.2 Stop Control

The requirements of this section shall apply to all stop controls recommended for safeguarding the hazards associated with the point of operation of machine tools by the other B11 safety standards or by section 4 of this standard.

5.2.1 The stop control shall be designed and constructed as a means of stopping hazardous motion by:

A. Immediately deactivating and overriding all other controls or;

B. Disconnecting the machine tool from the power or drive source or;

C. Deactivating or overriding the controls or disconnecting the power source and simultaneously applying a brake to stop motion or;

D. Deactivating or overriding the controls or disconnecting the power source and simultaneously reversing the hazardous motion.

5.2.2 An emergency stop control shall be provided for each operator control station or position and shall be readily distinguishable and shall be clearly labeled.

E5.2 An emergency stop control is sometimes referred to as a master control or stop control.

E5.2.1 The stopping of hazardous motion is necessary for a stop control to provide safeguarding of the operator.

If the driven portion of the machine tool coasts after the stop control is activated, it may be
necessary to use a brake in conjunction with the stop control to achieve the desired stopping performance.

E5.2.2 A typical stop control may be a button, cable, foot control, trip bar or other sensing means.

5.5 Control Reliability

E5.5.1 Where possible, all controls and pilot lights utilized on a machine tool should be standardized in configuration, location, function and color code. The controls and indicators should be accessible and readily visible from the operator's station or normal location....

5.7 Die and Machine Malfunction Detection and Monitoring Devices

5.7.1 Restarting of the machine tool after a malfunction is detected shall require start up of the machine tool system at the operator's station. 44

As can be seen from the representative excerpts presented from ANSI B11.1 and the B11.19 draft, emergency stop control requirements are written in performance styled language. The need for the device in order to safeguard the operator and the machine from accident injury and damage has been established and this is reflected in these ANSI consensus standards. But, within very general limits, the location and the design of the device is left to the discretion of individual manufacturers who may choose to utilize available technology in order to design the most efficient system practical, or

may ignore established ergonomic principles and opt for a less efficient system.

Consensus standards over the years have shown many changes that accrued due to industrial development. Obviously, recommendations applied to early industrial practices would have to change with advancing technology as the inherent hazards of these processes changed. For example: consensus standards applicable to early shops using overhead shafting for mechanical power transmission would likely not be applied today in modern manufacturing plants. The hazards of this type of apparatus have largely been superceded by newer hazards inherent with modern machines.

As consensus standards were developing, occasionally some particular recommendation would conflict with established ergonomic principles; principles that were known long before the standard was written. Sometimes these standards went against recommendations made by other authorities or even against other standards promulgated by the same organization at the same time period. When these standards are read today the reader might wonder what circumstances at the time caused the error to be made, especially when the error is blatantly obvious.

The following excerpts follow the historical development of ANSI B15.1-1984, the Safety Standard for Mechanical Power Transmission Apparatus as it is known today. They provide examples of changing recommendations and standards in conflict with established ergonomic principles.
Part III Starting and Stopping Devices

Section 31 Belt Shifters, Clutches, Shippers, Poles, Perches, and Fasteners

Rule 310 - Belt Shifters

(c) All belt and clutch shifters of the same type in each shop should move in the same direction to stop machines, i.e., either all right or all left.\textsuperscript{45}

Part VI Discussion

3. Power Control - Among the methods used for power control may be mentioned motor switches, friction clutches, belt shifters and engine stops. The means for controlling power should be positive and should be so arranged as to permit of operation from a point not more than 100 feet from any machine driven from the source of power in question. If the stations can be arranged to be within 50 feet of any machine, it is highly advisable. There will be cases, as for example in the steel industry, where a greater distance from the machine becomes necessary.

It is advisable to mark the stop station with a mark easily distinguishable - green bands on posts and green circles on walls are recommended, together with a sign "Stop Station" or "Emergency Stop." A light of characteristic color should be added in shops where night work is carried on.

All electrical safety devices should operate by the opening of a normally closed circuit. Any failure of the current or device will thus be indicated by the stopping of the prime mover. It is advisable to test such devices daily by shutting off the power at noon or night by such means.\textsuperscript{46}


\textsuperscript{46}\textit{Ibid.,} p. 25.
B15.1-1953

Entries applicable to starting and stopping devices are the same as in B15-1927.

B15.1-1972

This edition of the B15.1 standard does not contain any reference applicable to emergency stopping devices. The appendix, which was not part of the standard, contains the following reference:

A6.6.3 All belt and clutch shifters of the same type in each shop should move in the same direction to stop machines, i.e., either all right or all left. 47

B15.1-1984

3 SAFEGUARDING OF HAZARDS

3.2 Types of Safeguards

3.2.2 Devices
(a) A motion hazard safeguarding device shall provide protection to personnel by:

(1) preventing and/or stopping normal motion of the mechanical power transmission source of hazard if personnel inadvertently enter the hazardous area;

(2) providing the means to stop the system in the event of inadvertent involvement with the hazard.

E3.2.2 Devices

(2) Emergency pull cords, body bars, and/or other means to stop the system are examples of this type of device.48

Clearly, the early editions of B15.1 were heavily influenced by the state-of-the-art in power transmission at the time with references to belt shifters and clutches as examples. These indicate the extensive use of shafting, pulleys, and belts for power transmission throughout industry. However, it should be noted that early editions (1927 and 1953) included material relevant to emergency stopping of the equipment while in 1972 these references were dropped. They were not revived again until 1984. One could not assume that between 1972 and 1984 emergency stopping of power transmission apparatus was no longer needed; rather, it might be surmised that committee members at that time did not see or could not agree on the need for emergency stopping devices. It must be remembered that consensus standards cannot be regarded as indications of maximum concern for safety, but often they reflect minimum acceptable standards.49

49Hammer, p. 67.
Furthermore, these standards can contain serious errors of judgement that are very difficult to explain. Until 1972 the B15.1 standard advocated use of green bands on posts and green circles on walls to designate emergency stop control locations, even though this is clearly in violation of long established precedence denoting red as the emergency color. "Red has been the universal danger color for many years."\(^5^0\) This statement was made in 1916. Also, the American Standard Safety Color Code for Marking Physical Hazards and the Identification of Certain Equipment, 253.1-1945 stated:

2. Color Identification

2.1 Red. Red shall be the basic color for the identification of:

(a) Fire Protection Equipment and Apparatus
(b) Danger
(c) Stop\(^5^1\)

Clearly, any standard retained in the 1953 edition and recommending the color green be used to designate emergency stop control locations is in violation of 253.1. One can only wonder if any serious accidents occurred due to use of this recommendation.

\(^{50}\) Cowee, p. 30.

Certain industries such as paper and pulp mills and rubber mills utilized equipment that quickly developed a reputation for potentially severe, possibly fatal human entanglements. The machines that were used in paper and rubber processing often contained sets of revolving rollers (rolls) or calenders which produced in-running nip points. Depending on the spacing between rolls, hair, fingers, hands, arms, and even legs could become entangled with disastrous consequences. During rubber processing these rolls were often heated internally and human entanglements could produce additional heat through friction with resultant tearing and burning of flesh. Catching significant amounts of hair between rolls could easily result in scalping. The possibility of bleeding to death from any of these accidents existed if the means were not available to stop the machine quickly and someone was not available to perform first aid.

Early ANSI standards covering this equipment reflected the need for emergency stopping devices. Also, the severity of potential accidents resulted in these standards specifying design and location of devices to be used. Consider the following excerpts regarding emergency stop devices taken from the American Standard Safety Code

52Williams, p. 98.

for Paper and Pulp Mills (P1-1925) and the Safety Code for Rubber Mills and Calenders (B28-1927):

P1-1925

PART VII - MACHINE ROOM

Rule 701. Emergency stops.

Both the operating and the back sides of the paper machines shall be equipped with devices that will stop the machine quickly in an emergency. The device shall consist of push buttons for electric motive power or electrically operated engine stops, pull cords connected direct to the prime mover, control clutches, etc. The devices shall be tested frequently by making use of them when stopping the machine.

PART VIII - FINISHING ROOM

Section 80. SUPER CALENDERS

Rule 803. Emergency stops.

Push buttons (for electric power) or manually operated quick power-disconnecting devices shall be provided on all sides of the machine within easy reach of all employees.54

B28-1927

SAFETY-TRIP CONTROLS AND QUICK-STOP FACILITIES

Rule 110. Safety-trip controls -- Mills.

(a) A safety trip rod or tight-wire cable for each individual mill shall be provided front and back of

all mills, extending the length of the face of the rolls. It shall operate sensitively if it is pushed or if it is pulled.

(b) The normal location of the safety-trip rod over the front roll shall be two (2) inches to four (4) inches in from the edge of the front roll and not more than sixty-nine (69) inches above the working floor level on which the operator stands, with provision made for adjustment of three (3) inches either up or down.

(c) The normal location of the safety-trip rod at the back of the mill shall be two (2) inches to four (4) inches in from the edge of the back roll and shall be in the same horizontal plane as the safety-trip bar over the front roll, and the length of the lever from fulcrum shall be the same.

Rule 112

The locations of safety-trips apply to all sizes of mills.

Rule 120. Safety-trip control -- Calenders.

(a) A safety-trip rod or a tight-wire cable shall be provided across the front and the back of all calenders, extending the length of face of rolls, to operate sensitively if it is pushed or if it is pulled. This rod shall be at a height not more than sixty-nine (69) inches above the working floor level or platform on which the operator stands and shall be within easy reach, with provision made for adjustment either up or down of three (3) inches in each direction.

(b) On each side of all calenders and near both ends of the face of the roll there shall be a vertical tight-wire cable connecting with the bar tipping mechanism at the top and fastened to the frame within twelve (12) inches of the floor. These cables should be positioned at a distance of not more than twelve (12) inches from the face of the roll and at a distance of not less than one (1) inch from calender frame.
daily, and accurate measurements of distance of travel shall be taken at least once every thirty (30) days.\textsuperscript{55}

Obviously, the severity of accidents which routinely occurred with rolls and calenders prompted committee members to include significant emphasis on emergency stopping within these early standards. Consider the following statement: "It is realized that the quick stopping of mills and calenders is a very important factor in accident prevention in that it limits the injury to a worker if caught between the rolls."\textsuperscript{56} As a result, current ANSI standards B28.1-1967 and P1.1-1969 continue to include specific standards language describing devices to use, locations, and limits of travel for rolls (after emergency stop device activation). This is an important exception with current consensus standards regarding emergency stopping devices.

Similar references to emergency stopping devices can be found in many other ANSI standards. Currently, there are over 10,000 standards approved by ANSI.\textsuperscript{57} Some important ones have been selected and the following excerpts are included for relevant information:

\begin{itemize}
\item \textsuperscript{55}Safety Code for Rubber Mills and Calenders, B28-1927 (New York, 1927), pp. 3-4, 10.
\item \textsuperscript{56}Ibid., p. 10.
\item \textsuperscript{57}American National Standards for Safety and Health 1983-84 Catalog (New York, 1983), p. 2.
\end{itemize}
3. Purpose

The intent of this standard is to establish a safety color code that will alert and inform persons to take precautionary action or other appropriate action in the presence of hazards.

4. Applications

4.1 The criteria of this standard shall apply to the use of safety color coding for the identification of physical hazards, the location of safety equipment, protective equipment, stationary machinery, portable powered hand tools, signs, and markers.

6. Color Meaning

6.1 Safety Red. Safety red shall be the color for the identification of (1) Danger; (2) Stop.

The following are examples of applications of the color Safety Red:

(1) Emergency stop bars on hazardous machines
(2) Stop buttons or electrical switches used for emergency stopping of machinery

7. Color Specification and Test Methods

7.1 Visual

7.1.1 The primary color specification is in terms of the Munsell Notation System, a color identification and specification system based on equal visual spacing as described in American National Standard Method of Specifying Color by the Munsell System, ANSI/ASTM D 1535-68 (Z138.5)....

7.5 Color Blindness. The colors in the Combined Standard Safety Color Code have been chosen to give maximum feasible recognition to both normal and color-deficient (specifically red-green confusing) observers.58

5.11.2 Control Station

(a) Control stations should be so arranged and located that the operation of the equipment is visible from them, and shall be clearly marked or labeled to indicate the function controlled.

(c) Remotely and automatically controlled conveyors, and conveyors where operator stations are not manned or are beyond voice and visual contact from drive areas, loading areas, transfer points, and other potentially hazardous locations on the conveyor path not guarded by location, position, or guards, shall be furnished with emergency stop buttons, pull cords, limit switches, or similar emergency stop devices.

(1) All such emergency stop devices shall be easily identifiable in the immediate vicinity of such locations unless guarded by location, position, or guards. Where the design, function, and operation of such conveyor clearly is not hazardous to personnel, an emergency stop device is not required.

(2) The emergency stop device shall act directly on the control of the conveyor concerned and shall not depend on the stopping of any other equipment. The emergency stop devices shall be installed so that they cannot be overridden from other locations.\(^5^9\)

01.1-1975 - Woodworking Machinery

5.1.3 Machine Control

5.1.3.1 Each machine, whether mechanically or electrically driven, shall be provided with a device that will make it possible for the operator to cut off the power supply to the machine without leaving his normal operating position.

5.1.3.5 Power controls and operating controls shall be located within easy reach of the operator while he is at his regular work station. They shall be positioned so as to make it unnecessary for him to reach over a hazardous area to actuate the control.  

Z245.5-1982 - Baling Equipment

4 Construction and Modification Requirements

4.1.1.3 Controls. Each operator control shall be conspicuously labeled as to its function. Operating controls shall be designed and located to prevent unintentional activation.

4.1.1.3.2 Stop buttons and emergency stop buttons shall be red, distinguishable from all other controls by size and color, and shall not be recessed.

4.1.1.5 Emergency Stop. A means of stopping and controlling the movement of the ram at any point shall be provided. For multiple-stage balers, an emergency stop mechanism shall be provided to stop all rams. Located next to this mechanism shall be reverse mechanisms, one for each ram.

A90.1-1976 - Manlifts

5.8 Rope Control Stop

5.8.1 Requirements. A rope control stop means shall be provided.

5.8.2 Location. This control shall be within easy reach of the up and down runs of the belt, incorporating rope guides and pulley arrangements to restrict lateral movement.


5.8.3 Operation. This control shall be so connected to a control lever or operating mechanism that it will cut off the power and apply the brake when pulled in the direction of travel.

5.8.4 The control shall consist of rope with a diameter not less than 3/8 in. (9.525 mm). Wire rope shall not be used.62

Z245.1-1975 - Refuse Collection and Compaction Equipment

7. Specific Mobile Equipment Safeguards and Features

7.1 Front-Loading Compaction Equipment

7.1.4 Controls

7.1.4.1 Each control shall be conspicuously labeled as to its function.

7.1.4.2 Controls for operating the container-lifting mechanism, packer panel, and tailgate shall be designed and located to prevent unintentional activation.

7.1.4.3 All controls for operating any part of the container-lifting mechanism shall be dead-man controls.

7.3 Rear-Loading Compaction Equipment

7.3.3 Controls

7.3.3.1 Each control shall be conspicuously labeled as to its function.

7.3.3.2 Controls (for example, for operating the packer panel, tailgate, point of operation guards, ejector panel, container hoists) shall be designed and located to prevent unintentional activation.

7.3.3.2.1 Start buttons shall be recessed or located to prevent unintentional activation.

7.3.3.2 STOP button controls shall be red, distinguishable from all other controls by size and color, and not be recessed.

7.3.3.5 For emergencies a means of stopping and moving the packer panel away from the pinch point (prior to the pinch point) shall be provided. Emergency stop controls shall be red, distinctly labeled as to function, and not be recessed.63

Standards Summary: Useful Recommendations

Although the development of ANSI standards seems to have been done by separate committees working in response to specific hazards in different industries, many worthwhile recommendations can be gleaned from them. In reviewing the standards and viewpoints from personal correspondences previously mentioned, the following recommendations with regard to emergency stopping devices can be made:

(1) The master stop control should be located in the same place on each master control panel.

(2) A red colored control should be used consistently for the emergency stopping device and other controls should not be coded red.

(3) Momentary operation of the device should immediately stop hazardous motion and leave the

system in a safe condition.

(4) Restarting of machinery should require use of a separate and distinct operation.

(5) A stop control should be available to each operator at each normal operator's station, and in each hazardous location where operators may be required to work.

(6) Means should be available for manually inching hazardous machine parts forward or backward.

(7) If hazardous machine parts can coast after the emergency stopping device is actuated, a braking system should be incorporated to achieve good stopping performance.

(8) Controls used on similar machines should be standardized in configuration, location, function, and color coding.

(9) Emergency stopping devices should be tested frequently by making use of them during routine stopping of equipment.

(10) Emergency stopping devices should be size and shape coded.

(11) All controls should be conspicuously labeled.

(12) Emergency stop pushbuttons should not be recessed.
Legal Requirements

The previous discussion has focused on the development of voluntary consensus standards applicable to emergency stopping of industrial machines. As written, voluntary standards developed by standards setting organizations were never binding unless federal, state, or local laws incorporated them within their codes of regulations. Before the Occupational Safety and Health Act of 1970 (OSHAct, Public Law 91-596), enactment of health and safety laws had been left principally to the individual states.64 Some federal legislation existed including: the Service Contract Act of 1965, the National Foundation on Arts and Humanities Act, the Federal Metal and Non-metallic Mine Safety Act, and the Contract Workers and Safety Standards Act (Construction Safety Act), but these were applicable only to a limited number of employees such as those who worked on federal contracts or in specific industries.65 The rest were covered only by state laws and each state had a different set of health and safety regulations which might have included codes derived from many different sets of consensus standards. Not only did these standards vary from one state to another but regulations were often lax, inadequate, and ineffectively enforced.66

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64McElroy, p. 21. 65Ibid. 66Ibid.
One major concern of the federal OSHAct was, "...to assure so far as possible every working man and woman in the Nation safe and healthful working conditions..." One of the ways this objective was accomplished was in setting mandatory Occupational Safety and Health standards and requiring compliance by employers and employees. Many previously issued consensus standards were compiled, revised where necessary, and used as the basis for OSHA standards. Current OSHA regulations that apply to emergency stopping devices are found in the Occupational Safety and Health Standards for General Industry (29 CFR Part 1910). The following excerpts from this document apply to emergency stopping of machines and emergency stop devices:

Subpart C -- Machinery and Machine Guarding

1910.211 Definitions

(52) "Stop control" means an operator control designed to immediately deactivate the clutch control and activate the brake to stop slide motion.

1910.212 General requirements for all machines

(No entries applicable to emergency stops)

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68McElroy, p. 27.
1910.213 Woodworking machinery requirements

(b) Machine controls and equipment.
(1) A mechanical or electrical power control shall be provided on each machine to make it possible for the operator to cut off the power from each machine without leaving his position at the point of operation.

(4) Power controls and operating controls should be located within easy reach of the operator while he is at his regular work location, making it unnecessary for him to reach over the cutter to make adjustments...

1910.214 Cooperage machinery

(Revoked at 43 F.R. 49726, October 24, 1978)

1910.215 Abrasive wheel machinery

(No entries applicable to emergency stops)

1910.216 Mills and calenders in the rubber and plastics industries.

(b) Mill safety controls --- (1) Safety trip control. A safety trip control shall be provided in front and in back of each mill. It shall be accessible and shall operate readily on contact. The safety trip control shall be one of the following types or a combination thereof:

(i) Pressure-sensitive body bars. Installed at front and back of each mill having a 46-inch roll height or over. These bars shall operate readily by pressure of the mill operator's body.

(ii) Safety triprod. Installed in the front and in the back of each mill and located within 2 inches of a vertical plane tangent to the front and rear rolls. The top rods shall be not more than 72 inches above the level on which the operator stands. The triprods shall be accessible and shall operate readily whether the rods are pushed or pulled.

(iii) Safety tripwire cable or wire center cord. Installed in the front and in the back of each mill and located within 2 inches of a vertical plane tangent to the front and rear rolls. The cables shall not be more than 72 inches above the level on which the operator stands. The tripwire cable or wire center cord shall operate readily whether cable or cord is pushed or pulled.
(c) Calender safety controls --- (1) Safety trip, face. A safety trip rod, cable, or wire center cord shall be provided across each pair of in-running rolls extending the length of the face of the rolls. It shall be readily accessible and operate whether pushed or pulled. The safety tripping devices shall be located within reach of the operator and the bite.

(2) Safety trip, side. On both sides of the calender and near each end of the face of the roll, there shall be a cable or a wire center cord connected to the safety trip. They shall operate readily whether pushed or pulled.

(e) Trip and emergency switches. All trip and emergency switches shall not be of the automatically resetting type, but shall require manual resetting.

1910.217 Mechanical power presses

(b) Mechanical power press guarding and construction.

(7) Machines using part revolution clutches

(ii) A red color stop control shall be provided with the clutch/brake control system. Momentary operation of the stop control shall immediately deactivate the clutch and apply the brake. The stop control shall override any other control, and reactuation of the clutch shall require use of the operating (tripping) means which has been selected.

(8) Electrical. (i) A main power disconnect switch capable of being locked only in the Off position shall be provided with every power press control system.

(ii) The motor start button shall be protected against accidental operation.

1910.218 Forging machines

(No entries applicable to emergency stops)
Subpart R -- Special Industries

1910.261 Pulp, paper, and paperboard mills.

(c) Handling and storage of pulpwood and pulp chips.

(15) Belt conveyors.

(iv) Every belt conveyor shall have an emergency stop cable extending the length of the conveyor so that it may be stopped from any location along the line, or conveniently located stop buttons within 10 feet of each work station, in accordance with American National Standard B20.1-1957.

(k) Machine room.

(1) Emergency stops. Paper machines shall be equipped with devices that will stop the machine quickly in an emergency. The devices shall consist of push buttons for electric motive power (or electrically operated engine stops), pull cords connected directly to the prime mover, control clutches, or other devices, interlocked with adequate braking action. The devices shall be tested periodically by making use of them when stopping the machine and shall be so located that any person working on the machine can quickly disconnect the machine from the source of power in case of emergency.

(1) Finishing rooms.

(2) Emergency stops. Electrically or manually operated quick power disconnecting devices, interlocked with braking action, shall be provided on all operating sides of the machine within easy reach of all employees. These devices shall be tested by making use of them when stopping the machine.

(7) Rotary cutter.

(v) Electrically or manually operated quick power disconnecting devices with adequate braking action shall be provided on all operating sides of the machine within easy reach of all operators.
1910.262 Textiles.

(c) General safety requirements.

(1) Means of stopping machines. Every textile machine shall be provided with individual mechanical or electrical means for stopping such machines....

(h) Slashers.

(1) Cylinder dryers.

(iv) Pushbutton control. Slashers operated by pushbutton control shall have start and stop buttons located at each end of the machine, and additional buttons located on both sides of the machine, at the size box and the delivery end. If calender rolls are used, additional buttons shall be provided at both sides of the machine at points near the nips, except when slashers are equipped with an enclosed dryer.

(2) Enclosed hot air dryer.

(ii) Push-button control. Slashers operated by push-button control shall have one start button at each end of the machine and stop buttons shall be located on both sides of the machines at intervals spaced not more than 6 feet on centers....

(aa) Sanforizer and palmer machine. A safety trip rod, cable, or wire center cord shall be provided across the front and back of all palmer cylinders extending the length of the face of the cylinder. It shall operate readily whether pushed or pulled. This safety trip shall be not more than 72 inches above the level on which the operator stands and shall be readily accessible.

(bb) Rope washers.

(2) Safety stop bar. A safety trip rod, cable or wire center cord shall be provided across the front and back of all rope washers extending the length of the face of the washer. It shall operate readily whether pushed or pulled. This safety trip shall be not more than 72 inches above the level on which the operator stands and shall be readily accessible.
1910.263 Bakery equipment.

(e) Mixers.

(1) Horizontal dough mixers.

(iii) Each mixer shall be equipped with an individual motor and control,...

(g) Moulders.

(3) Stopping devices. There shall be a stopping device within easy reach of the operator who feeds the moulder and another stopping device within the reach of the employee taking the dough away from the moulder.

(h) Manually fed dough brakes.

(2) Emergency stop bar. An emergency stop bar shall be provided, and so located that the body of the operator will press against the bar if the operator slips and falls toward the rolls, or if the operator gets his hand caught in the rolls. The bar shall apply the body pressure to open positively a circuit that will deenergize the drive motor. In addition, a brake which is inherently self-engaging by requiring power or force from an external source to cause disengagement shall be activated at the same time causing the rolls to stop instantly. The emergency stop bar shall be checked for proper operation every 30 days.

(i) Miscellaneous equipment.

(7) Conveyors.

(iii) Where hazard of getting caught exists a sufficient number of stop buttons shall be provided to enable quick stopping of the conveyor.

(1) Ovens.

(3) Safeguards of mechanical parts.

(i) Emergency stop buttons shall be provided on mechanical ovens near the point where operators are stationed.69

As can be seen from these entries, federal regulations covering emergency stopping devices on industrial machines have generally been extracted from those consensus standards covering processes where there has been a long established need for such devices and a strong emphasis on the emergency stop within the standard (such as on mills and calenders). In those areas such as mechanical power transmission where there is currently no emphasis on emergency stopping of equipment within the consensus standard, there is also no federal regulatory requirement. Furthermore, within the general requirements for all machinery (29 CFR 1910.212) there is no reference made to an emergency stopping device nor the need for providing the capability to quickly stop machines. It appears that the importance of quickly stopping equipment during emergencies has not been recognized or has somehow been ignored; it is not a consistent, mandatory federal requirement.

**Military Standards**

Military standards have often proved to be very specific and detailed when specifying equipment requirements. Perhaps this results due to a need for consistency among many thousands of units purchased and from a desire to advantageously apply ergonomic principles. It is expected that military personnel may engage in life-threatening activities and this is how they are trained. In order
for soldiers to respond quickly and effectively under emergency situations they are conditioned with the desired response and this is reinforced through frequent practice. Furthermore, the advantage of reinforcing prelearned human expectancies cannot be ignored. Manipulation of controls is a function humans learn from a very young age and it would not be sensible to violate long established expectancies between control movements and system response. Therefore, a significant emphasis on machine controls has been included in manuals of military specifications. The following excerpts from the Military Standard Human Engineering Design Criteria for Military Systems, Equipment and Facilities, MIL-STD-1472C are applicable to emergency stopping devices:

5.4.1.3 Arrangement and Grouping.

5.4.1.3.3 Location of Primary Controls. The most important and frequently used controls shall have the most favorable position with respect to ease of reaching and grasping...

5.4.1.3.4 Consistency. The arrangement of functionally similar, or identical, primary controls shall be consistent from panel to panel throughout the system, equipment, or vehicle, ...

5.4.1.4 Coding.

5.4.1.4.1 Methods and Requirements. The use of a coding mode (e.g., size and color) for a particular application shall be governed by the relative advantages and disadvantages of each type of coding. Where coding is used to differentiate among controls, application of the code shall be uniform throughout the system...
5.4.1.4.2 **Location Coding.** Controls associated with similar functions should be in the same relative location from operator work station to work station and from panel to panel.

5.4.1.4.3 **Size-Coding.** No more than three different sizes of controls shall be used in coding controls for discrimination by absolute size. Controls used for performing the same function on different items of equipment shall be the same size...

5.4.1.4.4 **Shape-Coding.** Primary use of shape coding for controls is for identification of control knobs or handles by "feel;" however, shapes shall be identifiable both visually and tactually...

5.4.1.4.5 **Color-Coding.**

5.4.1.4.5.1 **Choice of Colors.** Controls shall be black (17038, 27038, or 37038) or gray (26231 or 36231). If color coding is required, only the following colors identifiable by FED-STD-595 shall be selected for control coding.

a. Red, 11105, 21105, 31105
b. Green, 14187
c. Orange-Yellow, 13538, 23538, 33538
d. White, 17875, 27875, 37875
e. Blue, 15123 shall be used if an additional color is absolutely necessary.

5.4.1.4.5.4 **Control Panel Contrast.** The color of the control shall provide contrast between the panel background and the control.

5.4.1.8 **Prevention of Accidental Activation.**

5.4.1.8.3 **Rapid Operation.** Any method of protecting a control from inadvertent operation shall not preclude operation within the time required.

5.4.3 **Linear Controls.**

5.4.3.1 **Discrete Linear Controls.**

5.4.3.1.1 **PushButtons (Finger or Hand Operated).**

5.4.3.1.1.1 **Use.** Push buttons should be used when a control or an array of controls is needed for momentary contact or for activation of a locking circuit, particularly in high-frequency-of-use situations.
5.4.3.1.1.2 **Shape.** The push button surface should normally be concave (indented) to fit the finger. When this is impractical, the surface shall provide a high degree of frictional resistance to prevent slipping.70

The following excerpts applicable to emergency stopping devices are from the *Military Handbook Human Factors Engineering Design for Army Material, MIL-HDBK-759A(MI)*:

1.1 CONTROLS

1.1.1 General Criteria

1.1.1.3 Arrangement and Grouping

1.1.1.3.1 **Primary Controls** - The most important and frequently used controls should have the most favorable positions with respect to ease of reaching and grasping...

1.1.1.3.4 **Emergency Controls** - Emergency function controls should be located where they can be identified and reached quickly. However, their location should not be such that accidental use or inadvertent contact could result in serious system malfunction and/or ultimate injury to personnel.

1.1.1.3.5 **Consistency** - When functionally similar control interfaces appear in more than one operator station within the same or similar systems, control locations and arrangements should also be the same or at least similar.

1.1.1.4 **CODING.**

1.1.1.4.1 **Factors to be Considered.** Many methods of coding are available. The choice of coding should be based on such factors as:

(a) Types of coding already being used.

(b) Kinds of information to be used.

(c) Nature of the tasks to be performed, and the conditions under which they will be performed

(d) Number of coding steps or categories available (e.g., the number of different knob shapes available, and how many of those shapes users can discriminate easily).

(e) Need for redundant or combination coding.

(f) Standardizing coding methods.

Any coding method that is selected should be used consistently, and with consistent meaning, throughout the system. Consideration should be given to coding used in other systems which the operator may be employed (either separately from or in conjunction with the system being designed). The method should allow controls to be identified easily by sight or touch and discrimination from each other by color, size, shape and location.

1.1.1.4.2 Color.

1.1.1.4.2.3 Emergency Controls. All emergency controls should be coded red. To give these emergency controls the visual emphasis they demand, only a bare minimum of other, less important controls should be color coded. Colors used to code critical controls should contrast sharply with those used for non-critical controls.

1.1.1.4.2.5 Control-Panel Contrast. Control color should contrast with the panel on which they are mounted.

1.1.1.4.3 Shape.

1.1.1.4.3.1 Design Coding - The primary reason for shape coding controls is to facilitate identification by "feel." However, shapes should be identifiable both visually and tactually. When shape coding is used, the coded feature should not interfere with the ease of control manipulation. Shapes should be equally identifiable regardless of the position of the control knob or handle....

1.1.1.4.3.2 Similar Functions. Controls with similar purposes or functions should have the same shape.
1.1.1.4.3.3 Dimensions. When operators must distinguish controls by touch alone, the shape of the control should be free of sharp edges or corners and at least:

(a) Height: 13 mm or larger
(b) Width: 13 mm or larger
(c) Depth: 6.5 mm or larger

1.1.1.4.4 Size.

1.1.1.4.4.1 Discrimination of sizes. When coding controls by size, it is important to make sure sizes differ enough that users are not likely to confuse them. Users can learn to discriminate two or three different sizes of controls; if more coding steps are needed, another coding system should be used. When coding knobs with diameters between 13 mm and 100 mm by size, each knob's diameter should be at least 20% larger than the next smaller one.

1.1.1.4.4.2 Similar Functions. Code sizes should be consistent when controls have similar functions on different items of equipment.

1.1.1.5 Labels.

1.1.1.5.1 General. Controls should have labels (on panel or control) that:

(a) Identify what they control.
(b) Show how to operate the control.

1.1.10 Push Button Switches (Hand-Operated)

1.1.10.1 Application - Push button controls should be used primarily when a simple switching between two conditions are required, selection of alternate on-off functions from an array of related conditions, or subsystems functions, ...

1.1.10.5 Push Button Cap Shape - Cap surfaces should, in general, be flat, but with rounded edges. However, for proper finger centering, which must be insured, the cap surface may be concave. General cap shapes may be round, square, or rectangular as long as they provide adequate finger, thumb or hand contact area, and are compatible with identification or legend requirements.
1.3.6 Control/Display Integration.

1.3.6.6 Importance of Use. Controls and displays which are critical to operation should be placed in preferential positions...

1.3.6.8 Emergency Use. Emergency displays and controls should be located where they can be seen and reached with minimum delay (e.g., warning lights within a 30-degree cone about the operator's nominal line of sight; emergency controls close to the nearest available hand in its nominal operating position.\textsuperscript{71}

\textbf{Military Standards Summary}

As can be seen from these excerpts, military requirements for system controls are very much influenced by human factors principles (ergonomics). The relationships of human factors to emergency response are covered in detail in chapter III so they will not be examined here. However, some important principles can be gleaned from these military requirements; in review, the following recommendations with regard to emergency stopping devices can be made:

(1) The most important controls, including emergency controls, should have the most favorable positions on a control panel.

(2) Consistency in location, size, and shape should

be maintained from panel to panel throughout each system.

(3) Consistency between systems is highly desirable.

(4) No more than three different sizes of controls should be used.

(5) Emergency controls should be coded red.

(6) A minimum of other controls should be color coded to provide emphasis to emergency controls. Most controls should be black or gray.

(7) Control panels should be colored to provide good contrast with controls.

(8) Methods of protecting controls from inadvertent activation should not impair operation within the time required.

(9) Pushbuttons should be shaped to fit the finger/hand or surfaces should provide a good grip.

(10) Shape coded controls should be discriminable both visually and tactually.

(11) Minimum pushbutton size for tactual discrimination should be 13 mm (each edge, diameter, etc.) and 6.5 mm in depth.

(12) Size coded controls should be limited to three different sizes. Each knob diameter should be 20% or more larger than the next smaller diameter.

(13) Controls should be labeled.
CHAPTER III

HUMAN FACTORS AFFECTING AN EMERGENCY RESPONSE

Response Time: Human-Machine Systems

The question: how fast can a human being respond in an emergency is universally asked. Everyone working under the forces of nature or the laws of physics governing man-made machines needs to respond to changing environmental and mechanical conditions. In normal daily events there might not be any life-threatening emergency requiring an immediate response; and no one needs to know exact times required to perform mundane tasks, but a general understanding of human limitations, especially the delays that occur within a human-machine system during emergency response is required.

After many accidents a statement is made regarding what should have been done to prevent the damage. Often these comments seem ridiculous in contrast with the serious effects of the event, but the notion that "hindsight is clearer than foresight" does present one important concept: the realization that if someone had reacted correctly before some critical time, the disaster could have been avoided, or loss and suffering could have been minimized. In other words, there is always some time period during which a correct response can change the outcome of an
impending disastrous event. Machines can be stopped before they break down. Water can be drained before a dam breaks and towns can be evacuated before a volcano erupts. Clearly, the question then becomes: does the human being in a position to avert this disaster have the ability to recognize the danger and the time to make the correct decision and respond?

Any human emergency response assumes that the following processes have occurred: receptor stimulation, neural conduction to the brain, perception and recognition, neural conduction to the muscles, and muscular contraction. These activities take time. "The human operator has a limited response speed, frequency, and flexibility." In effect there is a minimum time delay that can be expected from any person required to detect an input signal, process the information, select a course of action, and complete the required physical motions. This is known as the response speed. There is also a limitation to the frequency of data input that can be analyzed and the number of responses that can be made from that data in any increment of time. Lastly, human flexibility is limited in the number of sensory channels that can be simultaneously processed (i.e., audible, visible, tactile, etc.).

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73 Ibid., p. 221.

74 Ibid.
Total response time of any human-machine system has been reported to consist of various delays and lags that are operator and system imposed; these are:

1. Display lags and delays
2. Human input acquisition and receptor delays
3. Neural transmission delays
4. Central processing delays
5. Muscle activation time
6. Movement time
7. System dynamics lags and delays

Items (1) and (7) represent delays that result due to the mechanical and electrical characteristics of the system design. Items (2) through (6) represent delays that result due to the human factor in the human-machine system and these must be considered in the design of any emergency controls.

**Operator Delays During Response to Emergency Stimuli**

Human input acquisition and receptor delays occur as a function of the person's level of vigilance, the form, intensity, quality, and surround of the input signal, and as a function of the chemical/electrical transduction pro-
cess of the particular sense organ.  

Neural transmission delays occur as a result of the time required for neural impulses to traverse the chain of individual nerve cells (neurons). This is a biochemical energy conversion process. For any human stimulus-response action two neural transmissions are required: the afferent, the impulse that travels from the receptor to the cerebral cortex, and the efferent that travels from the cortex to the voluntary muscles. Delays occur as a function of fiber composition, diameter, length, and the number and complexity of synaptic connections.

Central processing delays occur as a result of the time required to perceive, recognize, discriminate, and identify a particular emergency situation as different from the norm. These are the result of the thinking and decision making processes and generally are the most variable. When the complexity of the situation increases such as when there is a choice of responses that can be made, the time required for central processing can increase dramatically.

Muscle activation time is defined by Wargo as the time required for peak muscle tension to be developed after the myoneural junction is stimulated. This time is known to vary as a function of muscle type, mass, and

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76 Wargo, p. 223.
77 Ibid.
78 Ibid.
79 Ibid., p. 224.
80 Ibid.
81 Ibid.
innervation (the arrangement or disposition of nerves within the muscle). 82

Movement time occurs as a result of the distance between the body part to be used for control and the control device. Delays occur as a function of distance, muscle activation time, mass of the body part, inertia, and design of the control device. Frequently, movement time is divided into two segments: the time required to complete the gross movement, and the time to make fine adjustments; these would be designated "primary" and "secondary" movements. 83 Wargo estimates that primary movements tend to reduce error to within 10% and secondary movements to within 1% of the original distance; a minimum movement time of 0.3 second can be expected when making even a one inch motion with the hand, more than half the total response time. 84

Reaction Time Experiments

In laboratory experiments the simple reaction time (RT) is defined as the time lag between stimulus onset and the first visible sign of a response (i.e., the first detectable movement). 85 Movement time is excluded. The disjunctive or choice reaction time is defined as the time

82 Wargo, p. 224. 83 Ibid., p. 233. 84 Ibid. 85 Ibid., p. 225.
lag between stimulus onset and first visible sign of response when the correct response depends on which of a variety of stimuli is presented. For example: if the presentation of a red or green colored light means that a subject should press a corresponding red or green emergency stop button, this would be a choice reaction time measurement. Wargo summarizes operator delays for the simple and choice reaction times as follows:

<table>
<thead>
<tr>
<th>Delay Basis</th>
<th>One Choice</th>
<th>Disjunctive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Receptor Delays</td>
<td>1-38</td>
<td>1-38</td>
</tr>
<tr>
<td>Afferent Transmission</td>
<td>2-100</td>
<td>2-100</td>
</tr>
<tr>
<td>Delays</td>
<td>70-100</td>
<td>90-300</td>
</tr>
<tr>
<td>Central Process Delays</td>
<td>70-100</td>
<td>90-300</td>
</tr>
<tr>
<td>Efferent Transmission</td>
<td>10-20</td>
<td>10-20</td>
</tr>
<tr>
<td>Delays</td>
<td>30-70</td>
<td>30-70</td>
</tr>
<tr>
<td>Muscle Latency and</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Activation Time</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reaction Time or</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Delay</td>
<td>113-328</td>
<td>133-528</td>
</tr>
</tbody>
</table>

(Times in milliseconds)

As can be seen from the table the best simple reaction time that could be expected of an experimental subject

86 Wargo, p. 225. 87 Ibid., p. 224.
would be approximately 0.113 second. Furthermore, Wargo's estimate presupposes that the subject is trained, in position for the response, and also is prewarned a few seconds prior to stimulus presentation; a situation that could hardly be expected under actual emergency conditions. It would be difficult to guess how an industrial operator might compare with these estimates when reacting under an actual emergency condition. It is likely that they have other jobs to do besides vigilance of emergency stopping procedures. They must observe, control, and record many operating parameters during a shift; therefore, an awareness of impending crisis cannot be assumed and the operator could not be expected to have his/her hand resting on the control device prior to the emergency signal.

Receptor delays, neural transmission time, and muscle activation time are factors that would not be expected to vary significantly with subjects performing multiple experimental trials or industrial operators. These delays are functions of the transduction process at the receptor level, the composition and length of particular nerves in the neural pathway, and the rate of biochemical information transmission. Therefore, it would not be expected that any operator training or practice could affect these in any significant way. Central processing delays and movement delays on the other hand would be expected to vary with many factors, such as: the operator's cognizance of the emergency situation, previous training, position
with respect to the control, personal activity, and the
design of the control device. With individuals perform-
ning multiple experimental trials the effects of practice
and fatigue would be expected to affect experimental re-
sults.

Simulating Uncertainty

When testing human responses to emergency signals,
subjects often perform under minimum uncertainty. They
know what signal to expect and the required response.
Experimenters place subjects where response is made easy
and movements are practiced in advance. The emergency is
not real and no damage occurs if subjects respond incor-
rectly or too slowly. As a result, motivation during
testing conditions cannot approach the level encountered
in a crisis where panic can affect the outcome. Often
there is no real comparison between a test subject's re-
sponse and the response of an accident victim. A subject
knows that it's only a test, but a frightened worker
captured in a machine instantly senses the danger; a correct
response in the latter case is imperative, it may save
life or limb. Can a stop button even be reached? Perhaps
not.

A major problem when studying human emergency re-
sponse is how to experimentally produce sufficient un-
certainty to provide meaningful results. Time uncertainty
is the only variable that can be easily controlled by an experimenter and it is by definition the only uncertainty a subject has during simple reaction time tests. Uncertainty results due to subjects' imperfect internal clocks and variability of stimulus presentation. In a classic experiment Klemmer studied the relationship between reaction time and subjects' uncertainty about time of stimulus presentation.

In a first series of tests a prestimulus warning click was given at eleven second intervals with the stimulus flash (neon light) presented thereafter. The time period between click and flash was designated the "foreperiod" and foreperiod mean and variability were changed between tests. In a second series of tests no prestimulus warning was given at all and stimuli were presented at identical intervals during each sequence of trials. Inter-stimulus intervals were then changed for later sequences.

The results showed two important human tendencies:

(1) Reaction time increases with foreperiod variability and with mean foreperiod above some small optimum value (less than one second).

(2) It is not the immediate foreperiod that dramatically affects reaction time but the dis-

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It is doubtful that these short-term observations could be extrapolated to explain human response during very long interstimulus intervals that would be expected for emergencies. Even in those industries that require frequent emergency stops of machines due to jams, misfeeding of stock, mis-alignments, etc., interstimulus intervals would likely be measured in minutes or hours rather than seconds as in Klemmer's experiment. In any event, there is one clearly established factor: that expectation can influence a person's state of readiness and can potentially shorten response time. In an industrial setting such prestimulus warnings could occur as changes in pitch of machine sounds, increased vibrations, gauge changes, etc., and these could warn an alert operator to an impending emergency. However, there is no guaranty that this will occur; a sudden entanglement in a machine might occur without any conscious expectation.

Human Expectation in Emergencies

This problem of expectation was studied by Johansson and Rumar who tested automobile drivers' response to emer-
The purpose of the experiment was two-fold. First they wanted to obtain a correction factor to be applied to brake reaction time data for estimating the difference between situations where braking is expected and unexpected. Second they wanted to determine the distribution of a random sample of drivers when the drivers knew they would be required to brake their vehicles suddenly at some time between two check-points.

The experiment was performed in two parts. During the first part drivers of vehicles along a chosen road were stopped by police and asked if they would participate in the experiment. If they agreed, they were told that at some time during their next ten kilometers of travel they would hear a loud horn and at that signal they were to immediately step on the brake. They were not to completely stop their cars but when the horn stopped they were to release the brake and continue on their way. The horn signal was initiated by an experimental assistant located five kilometers up the road. The assistant recorded the reaction time of each driver by pressing a stop key at the instant the vehicle's brake lights were seen. The human variability of the assistant was estimated at less than 4% of total recorded variability and his mean response time was subtracted from each.

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of the data.

For the second part of the experiment, five experienced drivers who had also participated in the first phase of the experiment were chosen. Each driver's vehicle was fitted with an electronic timer that would initiate an alarm signal (buzzer) and record the elapsed time for a braking response. The interstimulus intervals were set to be in excess of one hour and, since the cars were used mostly for short trips, drivers did not know during which trip a signal could be expected; intersignal variability was known to be from a minimum of about one hour to a maximum of more than a week which depended solely on the car's use.

The results showed that the histogram of reaction times for 321 expectant drivers (first phase of the experiment) had a positively skewed appearance, although the authors did not report this observation. The median brake reaction time was 0.66 second with a range of 0.3 to 2.0 seconds. Mean reaction time was not reported but can be estimated at about 0.74 second from the histogram supplied.\(^91\)

For part two of the experiment all five drivers tested showed longer brake reaction times when the signals occurred unexpectedly; however, it appears that the authors did not test for statistical significance between

\(^{91}\)Johansson and Rumar, pp. 25-26.
means, preferring rather to work with observed medians. A correction factor was computed from the data and indicated that the unalerted brake reaction time would be about 1.35 times longer than the alerted time.\textsuperscript{92}

Due to the small number of drivers used for part two of the experiment, and the authors' lack of rigor in statistical testing it is questionable if the data obtained show truly significant differences between the expectant and unexpectant conditions. However, the fact that the distribution obtained in part one appears to be positively skewed is worth noting. The question might be asked: is the observed skewness of drivers' reaction times related to expectancy? In other words, when comparing response time distributions from the expectant and unexpectant parts of this experiment would it be found that the unexpectant case is more positively skewed? Unfortunately the authors did not supply the distribution of data from part two of the experiment so this comparison cannot be made.

The answers to these questions could provide some insight into how humans respond under true emergency conditions. Real emergencies often occur with near zero expectancy (i.e., they are almost totally unexpected). Those persons who know what to do respond immediately; those who don't know, hesitate. Still others may freeze.

\textsuperscript{92}Johansson and Rumar, p. 26.
Therefore, it seems that the distribution of human response times for unexpected occurrences should be skewed.

Infrequent Stimuli

Since emergency response appears to be highly dependent on human expectation and previous training the questions remain: how is response affected when stimuli occur very infrequently? What improvements could be seen if subjects were conditioned to respond over an extended time period? Warrick, Kibler, and Topmiller approached these questions by asking secretaries to press a one inch diameter pushbutton as quickly as possible after hearing an emergency buzzer. The buttons were located at the lower left sides of the typewriters and identical arrangements were made for five secretaries. The signal intensity was measured to be at least thirteen decibels above background noise level while typing but it was determined by the experimenters that the sound did not elicit "startle response."

The experiment lasted over 120 working days and each subject received 48 signals at random times. Of the 48 signals only 36 were presented while secretaries were actually typing and responses to these were used as data.

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93Melvin J. Warrick, Austin W. Kibler, and Donald A. Topmiller, "Response Time to Unexpected Stimuli," Human Factors, 7(1) (February, 1965), 81-86.
The other responses were discarded; their inclusion in the experiment served to increase temporal uncertainty. Signals were presented with a mean interstimulus interval of 2.5 days and a standard deviation of 1.73 days. Also, as part of the experiment, two sets of control trials were run in blocks of twenty trials; this was done at the end of every twenty working days. One set was run with the women typing but they were alerted two to five seconds ahead of signal presentation. The other set was run with the same alerted condition but subjects had their fingers resting lightly on the stop buttons.

The results indicated a slight but consistent improvement in performance over the six month duration of the experiment for the unexpectant condition. The 10th, 50th, and 90th percentile response times for the last six unexpected signals were 0.51, 0.61, and 0.82 second. The mean for all data in the unalerted condition was not given by the authors but was calculated from the frequency distribution as 0.70 second. In considering the first block of six trials per subject (first four weeks) as representing minimum practice, 90% of the unalerted response times were shorter than 1.0 second. As training increased, the last block of six trials per subject (last four weeks) showed 90% of the unalerted response times were shorter than 0.8 second.\footnote{Warrick, Kibler, and Topmiller, pp. 84-86.}
The Startle Response

In the preceding discussion it has been seen how temporal uncertainty and human expectation can affect times for response to emergency signals. In general, many observed experimental response times have been somewhat longer than Wargo estimated. Considering a reaction time of 0.33 second (from Wargo's maximum simple reaction time estimate) and an expected movement time of 0.30 second for simple hand motions, the total would be 0.63 second.95 Nonetheless, many experiments, including the Warrick, Kibler, Topmiller study indicate that some subjects' response times to emergency signals can exceed this estimate. In fact, the above authors removed one subject's data from the computations because her response times (median = 1.58 seconds) consistently exceeded the 90th percentile of the distribution for the other five subjects.96 Is it fair to assume that her data do not represent normal expected variability within the human population? Certainly not; but it's true her data might seriously bias the mean of an extremely small sample (6 subjects).

Although these intersubject differences could be attributed to normal human variability which might include

95Wargo, pp. 224, 233.
96Warrick, Kibler, and Topmiller, pp. 83-84.
physical or mental differences between subjects, the possibility exists that subjects' emotional states could also affect the response. Perhaps the above mentioned subject was naturally slow to respond due to an unhurried emotional state. In this case the alarm might not have been sufficiently intense for her to experience the true sensation of emergency.

It has been shown that reaction time becomes shorter as stimulus intensity increases.\footnote{Warren H. Teichner, "Recent Studies of Simple Reaction Time," \textit{Psychological Bulletin}, 51(2) (1954), 132.} Furthermore, if a subject is experiencing a continuous stimulus, it has been shown that reaction time becomes shorter as the magnitude of change in stimulus intensity increases.\footnote{Ibid., p. 133.} The most extreme example of this phenomenon could occur in an industrial accident where stimulus intensity could increase dramatically from some low level (i.e., an impulse). The sudden shock of an electrical explosion could be an example. Teichner, however, claims that the observed decrease in response time is a non-linear effect.\footnote{Ibid., p. 132.} The question then becomes: what type of function is the response? It is here that the experimental data are not quite clear. One possibility suggested by Teichner is a parabolic function.\footnote{Ibid.} If this were the case then response times could be expected to increase
with louder or more sudden stimuli after some minimum is reached. This could explain the freezing effect as demonstrated by some persons in extreme emergencies.

Motor effects of very strong audible stimuli were studied by Davis (i.e., the startle response).\(^{101}\) In his experiment subjects were asked to lie down and relax in a noise-free environment. Active electrodes were placed two to three inches above the elbows on both forearms and normal background activity potentials were determined. After approximately five minutes of relaxation a sudden sound stimulus (shock wave) of 500 hertz was generated. Three levels of approximately 90, 95, and 99 decibels were used in the experiment. Subjects had been previously instructed to do nothing in response to the sounds. Stimulus duration was four seconds for test A and two seconds for test B.

The first test was designed to study the effects of stimulus intensity and duration on muscular action potentials while the second was to observe the effects of pre-stimulus tension (a weight held in the hand) on the response. The following results were obtained:

(1) The startle response consists of two distinct responses designated by Davis as a and b.

(2) The a-response has a latency of about 0.1 second, peaks during the next 0.1 second, and almost disappears during the next 0.5 second.

(3) The a-response rapidly adapts and practically disappears with six or more stimulations.

(4) The a-response varies with stimulus intensity and has a threshold below which it would probably not appear.

(5) The b-response reaches a maximum at about 1 second after stimulus onset, remains at that level for about 1 second, and then declines slowly.

(6) The b-response appears not to be affected by stimulus intensity or repetition.

(7) Both a- and b-responses are related to the state of muscular tension existing just prior to stimulus onset.\textsuperscript{102}

Everyone has felt the startling effect of a sudden event so the results of Davis' work are not that surprising. But the notion that there may be two combined and distinct responses is interesting indeed. In considering the a-response, it is particularly short-lived and could explain the visible jump humans emit when surprised. How-

\textsuperscript{102}Davis, pp. 274-275.
ever, a problem could develop with human response to startling emergencies due to tensions induced in muscles not essential for making the response. Studies of extraneous tension during reaction time have generated conflicting conclusions when relating tension to time of response. The possibility exists that a startled operator might react slower if the initial shock is sufficient to elicit an a-response.

The b-response was shown to be much longer in duration and appeared to be unrelated to stimulus intensity or repetition. It could be a prolonged state of readiness to react brought on by the stimulus. Since it does not appear to die out with repetition, in those industries where operators are subjected to repeated loud sounds (a punch press operator for example), it could bring on a level of tension and annoyance incompatible with proper emergency response.

Visual Feedback

In most reaction time studies subjects respond to a signal by reaching to and activating some type of control. The verification that the response is complete usually occurs due to a combination of visual, audible, and tactile feedback. But what of the time period during which

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103 Teichner, pp. 139-140.
the reaction takes place? It has often been suggested that human response, control of precise hand and arm motions, is analogous to "servo-response." In other words, human response involves the continuous comparison of input and output with the error between the two used as the basis for control. Arm motions, under this theory, are guided by a series of visual error measurements between the actual hand position and the desired target; changes in position result from an effort to reduce this error to zero. It is further assumed that motions made without visual feedback (i.e., blindfolded) require some form of mental imagery as a substitute.

The value of this visual feedback was questioned in an experiment by Taylor and Birmingham. They devised an experiment to suddenly disrupt subjects' visual feedback on a manual tracking task. In a first test subjects were presented with a visual target which jumped quickly to the left or right and could be brought back to center with proper manipulation of a joystick. After several successful maneuvers of the target suddenly the joystick was disconnected and the target would no longer respond. The experimenters observed that the subjects' now futile response pattern did not change even though the target could not be brought back to center. For a second test

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the target was suddenly made to respond in the opposite direction. The subjects' initial response pattern did not change although a second opposite motion of the joystick was ultimately made.\textsuperscript{105}

These studies led the experimenters to reject the servo hypothesis and conclude that visual feedback during a first reaction time period could not affect a response already in progress. Once a quick response was started it ran to completion; any adjustments were made during a later and distinct time period.\textsuperscript{106}

Further analysis of the servo hypothesis was made by Chernikoff and Taylor.\textsuperscript{107} They devised an experiment to test reaction time to kinesthetic stimulation (sudden motion of a body part). The kinesthetic stimulus was provided by attaching a subject's arm to a splint which was held by an electromagnet. The splinted arm was allowed to drop from a high starting point and the subject responded by either stopping the arm motion (one part of the experiment) or pressing a button with the opposite hand. In the first part of the experiment a subject's response was indicated by the onset of the change in acceleration as measured electronically.

The results indicated: "that kinesthetic reaction time is too long to permit continuous voluntary control  

\textsuperscript{105}Chernikoff and Taylor, p. 1. \textsuperscript{106}Ibid. \textsuperscript{107}Ibid., pp. 2-8.
of short duration hand and arm movements by information furnished through feedback." The authors proposed a dual hypothesis of control where "volitional processes" issue orders for body movements and "nonvoluntary lower centers" execute the movements without further instruction.

The human factors demonstrated in these two important experiments bear a direct relationship to human emergency response. In an industrial accident requiring a manual activation of an emergency stopping device, a human being's initial response will likely follow through to completion, whether or not the response is in error (i.e., if a stopping device is missed or not pushed hard enough). If an error is made another separate and distinct response will be required after feedback confirms the failure. If the accident involves an entanglement in a machine which could impart enough energy to throw the person off balance, the probability of missing the stopping device could greatly increase. A correct initial response would require instant human recognition of body position and acceleration with respect to the machine and an evaluation of where the body will be (with respect to the stopping device) when the response is initiated. In other words, the victim will, in effect, be required to hit a moving target; not because the stopping

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108 Chernikoff and Taylor, p. 8.  
109 Ibid.
device is in motion, but rather, because his/her body is in motion with respect to the target. The difficulties in performing this feat while simultaneously coping with the fear and pain of entanglement could cause delay or ineffectual response if the stopping device is not in a familiar position, readily accessible, and easily activated.

Motor Reaction

One of the motor reactions commonly required in any human control operation is the movement of a limb (often an arm) as quickly as possible from one position in space to another. The purpose of the motion, however, is more than just to accurately locate the limb in space; frequently the hand or foot is required to operate some type of mechanical control such as a knob, switch, push-button, or lever. Therefore, it is often desired to reach the control location both as quickly as possible and with a minimum of error and tremor.

It has already been stated that positioning motions can be divided into primary and secondary movements. Primary or gross movements merely transport the limb to the


111 Ibid.
general vicinity of required activity while secondary or fine adjustments are necessary to compensate for any residual error. In an experiment by Brown and Slater-Hammel these primary and secondary motions were studied.

For the experiment subjects were asked to move a pointer, at the sound of a buzzer, as quickly and accurately from one position in space to another along a marked board. Through a reduction pulley arrangement, motions of the pointer were transferred to a pen on a strip recorder, thereby providing a continuous record of pointer velocity and acceleration. The results showed that in all records the onset of the stimulus was followed by a brief interval (the reaction time), then a rapid acceleration and an apparent uniform period of high velocity before decelerating to zero; smooth changes were noted between phases of increasing acceleration, relative uniform velocity, and deceleration. Most records showed that the primary movement ended with the pointer either short of or beyond the terminal line and secondary movements resembled the familiar graphs of underdamped, critically damped, or overdamped oscillations.\footnote{Brown and Slater-Hammel, pp. 84-95.}

For the experiment the following important conclusions were reached:

\begin{enumerate}
\item The primary movement, which consists of a rapid
initial acceleration and a period of relatively uniform velocity may on occasion terminate at the exact desired point, but usually does not.

(2) A secondary corrective motion will usually be required which may take on one of the typical patterns of damped oscillation.

(3) Increases in length of movement were associated with corresponding increases in duration of primary movement, velocity of movement, and variability in both time and speed.

(4) Secondary corrective movements remained relatively constant for total movements within the range of approximately 10 to 40 centimeters.

(5) Short excursion primary movements were usually followed by long duration secondary movements.¹¹³

The important concept of this experiment in relation to emergency stop motions is that overshoot or undershoot of a limb in motion will occur in the majority of cases. If the emergency stopping device is not sufficiently large to allow for error, the initial movement of the hand (or foot) may miss the device causing a delay in activation.

¹¹³Brown and Slater-Hammel, pp. 94-95.
The discussion of relevant human factors so far has focused on some of the aspects of actually reaching for a control device. This assumes that the operator knows where the control is and does not need to select the device from among other controls that may be located in the same vicinity. For example: the secretaries in the Warrick, Kibler, Topmiller experiment did not need to discriminate between controls. If the typewriter keys are excluded, there were no other devices to be confused with the stop button during emergency response. When the signal was given there was only one thing to do; no decision had to be made. Likewise, in the Johansson and Rumar experiment drivers did not need to discriminate. To an experienced driver reaching for the brake pedal is a normal event and the only mental process required during the experiment was an association of the audible signal with a need for a braking response.

However, in the industrial environment things may not be that easy; controls are becoming increasingly more complex. It is not uncommon to find seemingly incomprehensible arrays of lights, switches, and knobs on the same panel; lights flash different colors, knobs and switches control different functions, and alarms sometimes call for immediate attention. How then can an operator in an emergency quickly decide which control to use?
Quite often training is an important factor. As was shown in the experiment with secretaries, response time significantly decreased with practice over the six month period. The effect has also been noted in other studies of simple reaction time.\textsuperscript{114} However, the simple reaction time does not require any complicated decision making process; Teichner proposed that any improvement observed with practice might be due, not to the effect of learning on the reaction itself, but on learning the proper preparatory interval.\textsuperscript{115}

The choice reaction time would more nearly correspond to an industrial environment where operators need to decide when and what response is required depending on conditions observed. Many studies have found a significant correlation between the number of choices and the time needed to react.\textsuperscript{116} It has been determined that decision reaction time varies as a direct function of the number of choices available.\textsuperscript{117} The following data have been reported assuming each choice has an equal probability of occurrence:

\begin{itemize}
\item \textsuperscript{114} Teichner, p. 139.
\item \textsuperscript{115} Ibid., pp. 139-140.
\item \textsuperscript{116} Wargo, p. 225.
\item \textsuperscript{117} Ernest J. McCormick and Mark S. Sanders, \textit{Human Factors in Engineering and Design} (New York, 1982), p. 198.
\end{itemize}
<table>
<thead>
<tr>
<th>Number of Choices</th>
<th>Reaction Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.20</td>
</tr>
<tr>
<td>2</td>
<td>0.35</td>
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<tr>
<td>3</td>
<td>0.40</td>
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<tr>
<td>4</td>
<td>0.45</td>
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<tr>
<td>5</td>
<td>0.50</td>
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<td>6</td>
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<td>7</td>
<td>0.60</td>
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<tr>
<td>8</td>
<td>0.60</td>
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<tr>
<td>9</td>
<td>0.65</td>
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<tr>
<td>10</td>
<td>0.65</td>
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</tbody>
</table>

It is here that the effects of training have not been clearly established as most studies concerning choice reaction times allow subjects the advantage of practice runs before experimental data is taken. However, industrial engineers have long recognized the importance of practice in repetitive motions and the improvement in time of performance is firmly established.\(^{119}\) In general, the reduction in time is attributable to a general familiarity with the required movements and a reduction in the number of consecutive eye fixations required.\(^{120}\) After practicing

\(^{118}\) McCormick and Sanders, p. 198.


\(^{120}\) Ibid.
a less defined visual picture of terminal location is needed during movement and grasping; a better coordination results. Learning curve theory has shown that the effects of practice generally produce a hyperbolic curve when plotting cumulative trials versus cumulative average time; also, it may take many hundreds of trials before an operator's learning curve begins to flatten out.\textsuperscript{121} In an industrial environment requiring an emergency stop motion, faster response would be expected if the operator was familiar with the exact motions required. This would seem to indicate that the emergency stop motion should be utilized during routine stopping of equipment. This would be especially true if the emergency stopping response had to be discriminated from among a variety of other normal motions.

**Discrimination**

The ability to recognize the required control from among all other non-essential devices in the immediate vicinity is an important task within the context of a manual emergency stop. As was previously mentioned, practicing a movement has always shown improvements in speed of discrimination, coordination, reaction, and a general

reduction in the amount of visual feedback required to complete a response. Just as a trained automobile driver can learn to reach instinctively for required controls, so too can the industrial operator. However, with the complexity of modern equipment it cannot be assumed that all operators have had the necessary training or could instantaneously produce an emergency stop motion when required to do so. Therefore, for those persons not capable of instinctive response, the ability to discriminate becomes very important.

Color coding has always been an important factor in proper discrimination of controls. Historically, the emergency stop control has been colored bright red to be consistent with human expectations from other coding schemes using red as the symbol for danger or stop. Red as significant to danger is clearly established and is derived from blood; in war, red flags as symbols of combat have been used for many centuries. Red has also been found superior for distant discrimination even though its apparent brightness shifts with low illumination.

Color as a coding dimension for displays has been an effective means for reducing search time.

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In an experiment by Hitt et al subjects were asked to search numerals, letters, geometric shapes, colors, and configurations for five types of tasks: identification, counting, comparing, locating, and verification. Both color and numeric codes were shown to be superior in the locate task.\textsuperscript{125} In a second experiment, the same group found that color coded targets on maps were located and counted significantly faster than when numerals and enclosed shapes were used as a coding dimension.\textsuperscript{126} In an experiment by Shontz et al with color coding for information location (again using maps) it was found that subjects were able to locate checkpoints significantly faster than if non-coded maps were used.\textsuperscript{127}

Although color coding has proven effective in providing ease of discrimination among targets, it has also been found that the nature and number of coded but non-searched objects in a display (clutter) can seriously degrade the response time performance.\textsuperscript{128} A search situation invariably involves more than one stimulus in a field of view with only one target of superior importance. Furthermore, the same targets may become unimportant in succeeding trials. Therefore, any coding scheme that in-

\textsuperscript{125}Jones, p. 359. \textsuperscript{126}Ibid. \textsuperscript{127}William D. Shontz, Gerals A. Trumm, and Leon G. Williams, "Color Coding for Information Location," Human Factors, 13(3) (June, 1971), 237-246. \textsuperscript{128}Jones, pp. 359-360.
creases discriminability may also increase the distracting effect of non-targets if it is applied equally to all objects in the display. For example: an industrial control panel may consist of five pushbuttons with five respective warning lights. If all objects on the panel are the same size and merely differ in color, then the nine non-searched objects, all brightly colored and distinct, could increase confusion during an emergency response. A panicked operator might try inadvertently to push a warning light rather than its corresponding pushbutton.

In studying this effect, Smith found that when targets differed both in size and contrast, median search time was significantly shortened than for contrast or size differences alone.\textsuperscript{129} Weitz reported a similar observation; he found that the response time to control levers was faster if they differed in both color and shape than if they differed only in color or shape.\textsuperscript{130} Eriksen and Hake expanded the experiment to include brightness so their targets differed in three dimensions. The results showed that multidimensional stimuli were much easier to discriminate than when only single dimensional differences were used.\textsuperscript{131}

\textsuperscript{129}Jones, p. 360.


\textsuperscript{131}Ibid., p. 159.
Geometric forms have also been studied in regard to this question of discriminability. Sleight studied the relative discriminability of geometric forms when they constituted a complex panorama with which subjects had to deal. Both efficiency in terms of sorting time and the relative attention-getting value were considered. In all, six each of twenty-one different geometric figures were used (see figure 3-1) for a total of 126 objects. The task of the experiment required subjects to sort each set of these forms and place them in compartments on a display board as quickly and accurately as possible. All geometric shapes were sized to be the largest that would fit into a one inch circle; areas were therefore not the same. The following results were obtained:

(1) Discriminability was approximately ten times faster for the first ranking figure compared with the last as measured by sorting time.

(2) On the basis of significant differences it was possible to identify four separate groups of geometric forms each of which was equally discriminable. The best group consisted of: swastika, circle, crescent, airplane, cross,

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Experimental Geometric Forms


Figure 3-1
and star.

(3) A high positive correlation was found between sorting time and ranking based on subjects' order of selection (attention-getting value).\textsuperscript{133}

In general, the results of these studies seem to indicate that an emergency stop device will be more easily and quickly discriminated from other controls on a panel if it differs in color, size, and shape. Furthermore, the vicinity of the emergency stopping device should not be cluttered with other controls which might reduce discriminability under emergency conditions. Evidence from human experimentation suggests that relatively unimportant or seldomly used controls on the same panel should receive a lower level of coding, thereby reducing distraction during emergency response. Since the circle was shown to be one of the most discriminable shapes in Sleight's experiment, the total evidence of these studies suggests that a large, red, round, pushbutton on a panel of smaller, non-red objects could be superior in terms of ease of discrimination during emergency response.

\textsuperscript{133}Sleight, p. 328.
Summary

The preceding discussion of human factors has focused on the effects normal human tendencies may have on an emergency response. A lifetime of observation might induce an engineer to surmise that some people would be naturally slow or error prone in producing an emergency response and not much could be done to improve their performance. Although this might seem to be confirmed when experimental reaction time data show skewing of response times, the truth is, much can be done during the design of equipment to compensate for these slower individuals if normal human tendencies are studied and the principles applied. According to Wargo, a human being "... is placed in a system's control loop when any one or any combination of, ..., sensing, pattern recognition, decision making, and planning ability is unequaled by existing electro-mechanical devices of comparable cost, weight, and size." Therefore, if positive human traits are to be exploited, then an allowance must be made for error, especially in those areas where human judgement or response might prove faulty. In other words, when utilizing human beings as control operators the good must be accepted with the bad and equipment designed accordingly.

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134 Wargo, p. 221.
Therefore, with these thoughts in mind, the following major chapter conclusions are summarized:

(1) Almost every disaster has some critical time period during which a response can minimize or avert damage.

(2) Every human response consists of various processes including: receptor stimulation, recognition, decision, neural conduction, muscle activation, etc. These processes take time.

(3) Any human response consists of a reaction time and a movement time which are distinct and separable quantities.

(4) Expectation can dramatically influence a person's state of readiness and can seriously affect response time.

(5) The distribution of human emergency response times during periods of low expectancy could be severely skewed due to those persons who do not immediately know what to do.

(6) Consistent improvements in performance are generally seen when human beings practice response motions.

(7) Humans are often startled by rapid changes in stimulus intensity and this may or may not improve response time performance due to extraneous muscle tensions developed.
(8) Repeated loud sounds can increase muscular tension levels in humans for indefinite time periods. This could prevent an immediate recognition of an emergency thereby slowing or preventing emergency response.

(9) Visual feedback does not seem to control responses already in progress. If an error is made, a second and distinct reaction time will likely be needed to make any corrections.

(10) Kinesthetic feedback appears to take too long to allow continuous control of short duration limb movements. It appears that volitional processes issue orders for body movements and non-voluntary processes execute these movements without further instruction.

(11) Motor reaction of a limb will almost always consist of a gross movement and an oscillatory secondary movement.

(12) An industrial control response would more nearly correspond to a choice reaction time. Choice reactions have been shown to require dramatic increases in decision time with total number of choices available.

(13) Under choice reaction time conditions effects of practice could be expected to improve response time and accuracy.

(14) Color coding has been shown to be superior in
improving discriminability of objects in a display if all objects are not coded equally.

(15) Multidimensional coding has proven to be superior to single dimensional coding in improving discrimination.

The following recommendations are made about design and placement of emergency stopping devices and machine design to be consistent with human expectations and established ergonomic principles.

(1) Provide audible warnings of impending system malfunctions requiring manual emergency stops whenever practical.

(2) Allow operators to practice the emergency stop motions regularly by utilizing these motions for routine stopping of equipment.

(3) Utilize the minimum power necessary, including mechanical power and electrical voltage to produce the desired result.

(4) Minimize audible vibration of equipment.

(5) Locate the emergency stopping device in a familiar position and make it easily activated and readily accessible.

(6) Standardize the location of emergency stop controls on different pieces of equipment.

(7) Make the emergency stop device sufficiently
large to minimize misses when undershoot or overshoot of the response limb occurs.

(8) Color code the emergency stop device red. Do not use red coding on any other control.

(9) Make the emergency stop device round whenever practical.

(10) Make the emergency stop device larger than other controls on a panel.

(11) Segregate the emergency stop device from other controls on a panel.
CHAPTER IV

THE EXPERIMENTAL METHOD

Introduction

One major difficulty encountered in any experiment which would attempt to analyze human responses to emergencies is how to accurately reproduce the desired condition in a laboratory setting. For this study, the problem of simulating the industrial accident requiring manual activation of an emergency stopping device was considered.

It was hoped that the methods used by previous experimenters would suggest some practical way to approach this problem. However, the nature of the task and the seriousness of the event under study have forced experimenters to remain far short of generating actual emergencies. Situations that would approach the severity of a runaway industrial machine, a human arm caught in a gear, or a major electrical short-circuit cannot be safely controlled or reproduced; therefore, they cannot be systematically studied without a serious risk of injury to subjects and experimenters. Because of the dangers and complexities there has been a necessary reluctance to study this very important problem. Furthermore, the data that are collected are often very specific and do not
apply to varied industrial situations.

Many factors in the environment can contribute to the overall response time of an individual during an accident. How fast can a human being respond to an emergency stimulus and take the proper corrective steps is a very practical and frequently asked question. The truth is, we can't really say for sure because of the effects of unforeseeable variables. Has the operator been forwarned to an impending crisis or has the situation gone critical unexpectedly? Has the operator been exposed to similar emergencies before? Are there extraneous stimuli present that could impede recognition of an emergency signal? What is the operator's level of motivation and is he/she tired or distracted? These and other human factors can be expected to affect the person's response time to an industrial accident. Furthermore, with industrial operators often required to perform many duties simultaneously, he/she might not even be physically within reach of the emergency stopping device; thus the problem is often seriously compounded.

Therefore, it is the purpose of this experiment to test human response times to actuate different types of emergency stopping devices (pushbuttons) that are commonly used on industrial equipment. Statistically significant differences in response times and miss frequencies are related to design and a modification of the standard mushroom style button is made in an effort to reduce miss
Subjects

Thirty-one subjects with ages ranging from 16 to 61 years participated in the experiment. The mean age was 33.2 years with a standard deviation of 13.8 years. Sixteen subjects were male, fifteen were female and none were considered by the experimenter to have any qualifications or training that would make their response times to emergency stopping devices non-representative of the population in general. Some exceedingly fast and some exceedingly slow subjects' individual and average response times were noted among those sampled. These were attributed to normal human variability, differences in motivation (subjects' attitudes and recognition of the importance of an emergency response), and deliberateness (subjects' attempts to perform accurately by utilizing conscious deliberate control of arm motions). It was assumed that all data collected represented normal variability within the general population and no attempts were made to eliminate any subject's average or individual response times.

Design

The experimental design consisted of two different emergency stop pushbuttons that were mounted on individual
consoles. The first console contained a standard 7/8 inch collar protected pushbutton that had been modified to allow collar removal. See figures 4-1 and 4-2. The second console contained a standard 7/8 inch collar protected pushbutton that was fitted with a standard 3 inch diameter mushroom head. See figures 4-3 and 4-4. The mushroom head was allowed to rock within its mount thereby allowing an emergency stop activation to occur by either rocking the button or pressing straight on. An alternate 3 inch diameter experimental mushroom head was designed by the experimenter and built to accept an identical set of mounting hardware. See figures 4-4 and 4-5.

The experiment was divided into two phases. During phase I each subject was tested for response times to four different arrangements. These were called tests A, B, C, and D. During phase II subjects were tested on four different arrangements designated tests E, F, G, and H. Phase I and phase II were completed for each subject at a different sitting and all subjects performed phase I testing before proceeding to phase II. Variability was from one to six weeks between phases.

For each test arrangement (A - H) the subject was seated in front of a console and was directed to actuate the device upon hearing an audible signal. After several trial runs to familiarize the subject with each arrangement the experiment began and each emergency stop arrangement was activated twenty times in response to randomly timed
Standard Pushbutton - Exploded View

Collar Guard

Locknut

Pushbutton

Bushing

Spring

Housing

Figure 4-1
Standard 7/8 Inch Collar Protected Pushbutton With Modification

Figure 4-2
Figure 4-3
Standard 3 Inch Diameter Mushroom Head Pushbutton and Experimental Design

Figure 4-4
Figure 4-5
emergency signals.

Subjects' attention during the experiment was diverted from the emergency stopping task by having an assistant ask them questions from a popular game of trivia. Therefore, in addition to staying alert for the alarm signal, each subject was required to continuously answer a stream of questions that were completely irrelevant to the immediate experimental task. In this way a diversity of mental activity was obtained and concentration on response time was interrupted.

Randomness was achieved by varying the number of questions asked between trials. A random number table was used to generate lists of random numbers between 0 and 4 and these lists were used to determine the number of questions to be asked between trials. Initiation of the audible signal occurred during the asking or answering of the last question according to the experimenter's discretion. Since the experimental assistant was trained not to rush the subject with a flurry of questions, quite often a discussion about some particular answer would develop, thereby increasing normal variability between questions. Although intertrial elapsed time was not recorded, no trials were observed to take longer than three minutes to complete.

Ordering of arrangements presented was randomized during each phase of the experiment to reduce the effects of practice and fatigue on the results. There are twenty-
four possible combinations of four arrangements and each of the first twenty-four subjects was given a different combination. Combinations were chosen at random for subjects twenty-five and up.

**Apparatus**

The materials used in the experiment were red emergency stop pushbuttons commonly used on industrial devices. The buttons were arranged on two identical consoles as shown in figures 4-6 and 4-7. For phase I the four experimental arrangements consisted of:

- **Test A** - 7/8 inch collar protected button
- **Test B** - 7/8 inch button with collar removed
- **Test C** - 3 inch standard mushroom button
- **Test D** - 3 inch standard mushroom button (subjects were instructed to use their non-favored hand for response)

Spring tension and travel distance were adjusted to be equal on both consoles. Activation force required was 3 pounds straight on and activation distance was 1/8 inch. These parameters were measured with a Dillon 25 pound capacity, 1/4 pound division compression force gauge, a vernier caliper, and an electronic ohm-meter to verify electrical switch contact.

For phase II of the experiment subjects were fitted
First Console

Test A

Test B

Figure 4-6
Second Console

Figure 4-7
with a surgeon's style rubber glove on their favored hand. The glove and the emergency stop pushbutton under test were thoroughly sprayed with silicone lubricant before each test was started. Pushbutton surfaces used for phase II testing had been previously prepared by sanding to bare metal with 400 grit paper and painting with four coats of glossy red spray enamel. Paint was baked dry and buttons were examined to ensure identical surfaces. Spring tension was adjusted within each mounting mechanism to increase required activation force to 7-1/2 pounds. Activation distance remained unchanged. The four experimental arrangements consisted of:

Test E - 3 inch standard mushroom button
Test F - 3 inch experimental button
Test G - 3 inch standard mushroom button
  (Subjects were blindfolded)
Test H - 3 inch experimental button
  (Subjects were blindfolded)

The tester's console for activation of the audible alarm and timer is shown in figure 4-8. The wiring of this console and its interface with the experimental consoles and timer is shown in figure 4-9. The timer used was a Lafayette Instrument Company model 58007 with a precision of 0.01 second. The alarm was a Floyd Bell Associates continuous tone device.

An overall block diagram of how the experiment was
Tester's Console

Figure 4-8
Wiring Diagrams for Normally Open and Normally Closed Pushbuttons

Figure 4-9
conducted is shown in figure 4-10. The design of the consoles resulted in both the audible alarm and timer being activated by the experimenter through the operation of one switch. Likewise, both the alarm and timer were stopped simultaneously by activation of the pushbutton on the subject's console.

Procedure

Each subject was seated in front of a pushbutton console and was told that he/she was in control of an industrial machine. This machine could be any type of device he/she could imagine, such as: an industrial robot, automatic arc-welder assembling automobiles, a nuclear reactor, a conveyor, hydraulic press, etc. Each subject was then given the following instructions:

(1) Please face the console with your hands placed on the table to the sides of the console. You may not rest them directly on the console.
(2) You will be asked questions concerning everyday subjects which have been taken from a popular trivia game.
(3) At random times during the questioning you will hear an emergency signal which sounds like this: (experimenter momentarily activates the alarm).
(4) Upon hearing the alarm you are to press the
Block Diagram

Figure 4-10
emergency stop button as quickly as you can to silence the alarm.

(5) Please activate the device (experimenter activates the alarm, subject presses the button).

(6) If you miss or do not press the button hard enough and the alarm continues, please press it again until the alarm stops.

(7) Do you have any questions?

Subjects were allowed to ask questions about the experiment and practice several activations of the emergency stopping device. When they were ready the testing began. After twenty trials were completed on the first arrangement and response times recorded on the data sheet the experimenter replaced the first arrangement with the second. Again, the subject was allowed to make several practice activations of the device and when he/she was ready the testing began. Third and fourth arrangements were done identically.

The experimental assistant began asking questions each time that the subject indicated he/she was ready to begin a test. Using a list of random numbers the experimenter counted questions and activated the alarm and timer. Upon proper activation of the emergency stopping device by the subject the alarm and timer were stopped. The experimenter then recorded each response time in the
appropriate column on the data sheet and reset the timer for the next trial. During each trial the experimenter carefully observed the response of the subject and noted any deviations on the data sheet. If the subject was distracted and failed to respond immediately to the alarm, a notation of "distracted" was recorded next to the response time. If the subject needed two or more tries to silence the alarm then a "miss" was recorded and if the subject experienced visible manual difficulty but only needed one try then the notation "slipped" was recorded. The experimenter recorded a deviation only when mentally certain that one had actually occurred. When any uncertainty existed the trial was considered normal. All response times, regardless of recorded deviations, were recorded as registered and every response was considered a legitimate trial.

The conditions in the room where the experiment was conducted simulated an ideal industrial environment. It was well lighted and subjects faced their control consoles. The experimental assistant sat directly alongside the subject and the experimenter sat behind the subject's field of view.

**Statistical Analysis**

For each phase of the experiment subjects were asked to respond to audible signals by immediately pressing an
emergency stopping device, thereby deactivating an armed electrical circuit. The total elapsed time for the system response (including the human element) was recorded as the response time and sets of twenty trials for each subject were used to compute an average. Subjects activated different devices and/or responded under different experimental conditions depending on the testing arrangement. For example: by comparing tests A and B it can be seen that both tests utilized the same 7/8 inch pushbutton device but the mechanical conditions were changed; namely, the protective collar was removed for the second arrangement. For another pair of tests, subjects activated different devices but mechanical conditions were left unchanged. For example: by comparing tests B and C it can be seen that there was a change from a 7/8 inch unguarded pushbutton to a 3 inch unguarded mushroom style pushbutton.

It is assumed that the protective collar used on the 7/8 inch pushbutton was included in the design to prevent accidental activations (bumping); but one of the disadvantages to a guarded pushbutton is the requirement for an operator to use a single finger for activation. The blind frightened swipe of a palm during an extreme emergency might not be reliably expected to activate this type of device. In other words, it might be hypothesized that a guarded pushbutton would, on the average, take longer to activate thereby increasing the severity of damage or human trauma in an accident.
The question of interest for the comparison of the guarded and unguarded pushbutton is: can the observed difference in average human response time be attributed to chance or is it statistically significant? Likewise, for the other testing arrangements of this experiment the purpose of the comparisons is to see if observed differences in response times can be considered statistically significant.

Standard statistical methods of testing sample means for significant differences usually require that independent samples be taken. For this experiment that would mean eight different sets of human subjects would be needed, one for each experimental arrangement. However, for identical samples (i.e., humans performing an identical number of trials under different testing arrangements) paired statistical comparisons can be made. The paired situation alludes to the common "before and after" type of test. Therefore, the following paired comparisons of response time data are made for this experiment:

1. A - B; 7/8 inch pushbutton, guarded vs. unguarded
2. B - C; 7/8 inch standard button vs. 3 inch mushroom head, both unguarded
3. C - D; mushroom button, favored vs. non-favored hand
4. E - F; Mushroom vs. experimental mushroom head
5. G - H; mushroom vs. experimental mushroom head
Statistical Procedure for Test Pair: A - B

(1) For n subjects over twenty trials the average response times $R_{iA}$ and $R_{iB}$ are computed.
   $i = (1, 2, \ldots, n)$

(2) Paired differences are computed.
   $D_i = R_{iA} - R_{iB}$

(3) Deviations $d_i = (D_i - \bar{D})$ are assumed normally and independently distributed with population mean equal to zero.

(4) $S_D^2 = \sum_{i=1}^{n} (D_i - \bar{D})^2 / (n - 1)$

(5) $S_D^2 = (S_D^2 / n)^{1/2}$

(6) $t = D / S_D$  \hspace{1cm} d.f. = n - 1

(7) For the paired data:
   $H_0: \mu_D = 0$
   $H_A: \mu_D \neq 0$

the null hypothesis is tested against the alternative hypothesis using the $t$ statistic.

Analysis of Miss Frequencies

When studying human response to different arrangements of emergency stopping devices, the question might occur: could a particular arrangement increase the like-
likelihood of a missed response? In other words, could the
design of the device occasionally prevent a human operator
from completing an emergency stop? For example: in compar-
ing the guarded and unguarded buttons it might be hypothe-
sized that the guard increases the probability that an
operator could fail to activate the device on the first
attempt. If so, the miss would increase the delay in
stopping a machine and could increase the severity of
damage or human trauma in an accident.

The question of interest is: can the observed differ-
ences in frequencies of miss response for this experiment
be attributed to chance or are they statistically signif-
icant? Therefore, the following paired comparisons of
miss frequency data are made for this experiment:

(1) A - B; 7/8 inch pushbutton, guarded vs. unguarded
(2) B - C; 7/8 inch standard button vs. 3 inch mush-
room head, both unguarded
(3) E - F; mushroom vs. experimental mushroom head
(4) G - H; mushroom vs. experimental mushroom head

The statistical procedure used in comparing miss
frequencies is identical to that used for response times.
The variable $M_i$ is used in place of the average response
time $R_i$ in the previous example and the same procedure is
used to test null and alternative hypotheses. For all
comparisons made in this experiment a null hypothesis is
rejected only after the computed $t$ value indicates the
95% level of statistical significance is exceeded.

In counting missed/slipped trials during the experiment it was realized that a rather subjective judgement by the experimenter was required each time a miss/slip was recorded. Although the visible and audible effects of a miss/slip were often very evident, it was concluded that errors could be made in judgement. Furthermore, it was determined that the most detrimental effect of missing or slipping was a lengthened elapsed time of response. If the subject actually missed or slipped on the response but then recovered with sufficient speed to prevent an excessive elapsed time then there would be no detrimental effect. Trials such as these should not be considered a deviation. Therefore, the following procedure was used to eliminate these non-excessive deviations:

(1) Each subject's response times for each test arrangement were used to compute a mean (\( \bar{x} \)) and standard deviation (s) for the twenty trials. Missed/slipped trials were not included.

(2) The value \( \bar{x} + 2s \) was then compared to the response time of each missed/slipped trial.

(3) If the recorded time exceeded two standard deviations above this mean, the elapsed time was considered excessive. If not, then this particular trial was ignored in the miss frequency analysis.
The purpose of this procedure was to ensure that miss responses used in the statistical analysis were truly excessive in terms of elapsed time of response. If only those trials showing elapsed times greater than two standard deviations above the mean were counted as miss responses then 97.7% of other trials (including those where subjects responded slowly due to distraction) would be faster than each miss response. Although this had the effect of eliminating 10% of all missed/slipped trials, it was considered a necessary procedure.

Summary

For the experiment, the following hypotheses about common emergency stop pushbuttons were made:

(1) It was suspected that inclusion of a finger guard around a standard pushbutton could increase both the average human response time for activation and the probability of a miss response.

(2) It was suspected that a large mushroom pushbutton could prove superior to a smaller button in terms of average response time and miss frequency.

(3) It was suspected that further improvements in average human performance could be achieved
by redesigning the standard mushroom push-button.

The experiment was designed to test the validity of these arguments.
EXPERIMENTAL RESULTS

The following results for the eight different arrangements of emergency stop devices were obtained:

Mean Response Times (X) in 1/100 Seconds

<table>
<thead>
<tr>
<th>Arrangement</th>
<th>X</th>
<th>s</th>
</tr>
</thead>
<tbody>
<tr>
<td>A - 7/8 Inch Guarded Pushbutton</td>
<td>83.65</td>
<td>10.40</td>
</tr>
<tr>
<td>B - 7/8 Inch Unguarded Pushbutton</td>
<td>72.75</td>
<td>12.79</td>
</tr>
<tr>
<td>C - 3 Inch Standard Mushroom Pushbutton</td>
<td>67.92</td>
<td>11.57</td>
</tr>
<tr>
<td>D - 3 Inch Standard Mushroom Pushbutton</td>
<td>69.13</td>
<td>13.81</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E - 3 Inch Standard Mushroom Pushbutton</td>
<td>72.30</td>
<td>15.93</td>
</tr>
<tr>
<td>(Opposite Hand)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F - 3 Inch Experimental Mushroom Pushbutton</td>
<td>71.71</td>
<td>11.59</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G - 3 Inch Standard Mushroom Pushbutton</td>
<td>76.19</td>
<td>16.12</td>
</tr>
<tr>
<td>(Greased + Blindfold)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H - 3 Inch Experimental Mushroom Pushbutton</td>
<td>74.73</td>
<td>14.32</td>
</tr>
<tr>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Table 5-1
## Statistical Significance of Observed Differences

<table>
<thead>
<tr>
<th>Test Pair</th>
<th>Test Parameter</th>
<th>Value 1</th>
<th>Value 2</th>
<th>Difference</th>
<th>Significance Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>A - B</td>
<td>Means</td>
<td>83.65</td>
<td>72.75</td>
<td>10.90</td>
<td>99.9%</td>
</tr>
<tr>
<td>B - C</td>
<td>Means</td>
<td>72.75</td>
<td>67.92</td>
<td>4.83</td>
<td>99.5%</td>
</tr>
<tr>
<td>C - D</td>
<td>Means</td>
<td>67.92</td>
<td>69.13</td>
<td>-1.21</td>
<td>not significant</td>
</tr>
<tr>
<td>E - F</td>
<td>Means</td>
<td>72.30</td>
<td>71.71</td>
<td>0.59</td>
<td>not significant</td>
</tr>
<tr>
<td>G - H</td>
<td>Means</td>
<td>76.19</td>
<td>74.73</td>
<td>1.46</td>
<td>not significant</td>
</tr>
<tr>
<td>A - B</td>
<td>Misses</td>
<td>20</td>
<td>8</td>
<td>12</td>
<td>96.7%</td>
</tr>
<tr>
<td>B - C</td>
<td>Misses</td>
<td>8</td>
<td>9</td>
<td>-1</td>
<td>not significant</td>
</tr>
<tr>
<td>C - D</td>
<td>Misses</td>
<td>9</td>
<td>6</td>
<td>-3</td>
<td>not significant</td>
</tr>
<tr>
<td>E - F</td>
<td>Misses</td>
<td>21</td>
<td>14</td>
<td>7</td>
<td>not significant</td>
</tr>
<tr>
<td>G - H</td>
<td>Misses</td>
<td>38</td>
<td>13</td>
<td>25</td>
<td>99.9%</td>
</tr>
</tbody>
</table>

**Note:** Not significant means that the statistical significance did not exceed 95%.
## Computed "t" Values of Paired Comparisons

<table>
<thead>
<tr>
<th>Test Pair</th>
<th>Test Parameter</th>
<th>Computed &quot;t&quot; Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>A - B</td>
<td>Means</td>
<td>9.73</td>
</tr>
<tr>
<td>B - C</td>
<td>Means</td>
<td>3.31</td>
</tr>
<tr>
<td>C - D</td>
<td>Means</td>
<td>1.19</td>
</tr>
<tr>
<td>E - F</td>
<td>Means</td>
<td>0.37</td>
</tr>
<tr>
<td>G - H</td>
<td>Means</td>
<td>1.21</td>
</tr>
<tr>
<td>A - B</td>
<td>Misses</td>
<td>2.26</td>
</tr>
<tr>
<td>B - C</td>
<td>Misses</td>
<td>-0.23</td>
</tr>
<tr>
<td>C - D</td>
<td>Misses</td>
<td>0.83</td>
</tr>
<tr>
<td>E - F</td>
<td>Misses</td>
<td>1.10</td>
</tr>
<tr>
<td>G - H</td>
<td>Misses</td>
<td>3.76</td>
</tr>
</tbody>
</table>

Note: Degrees of freedom (d.f.) = 30.
Response Frequencies

<table>
<thead>
<tr>
<th>Response Time</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
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</thead>
<tbody>
<tr>
<td>(1/100 sec)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>31 - 35</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>36 - 40</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>7</td>
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<td>3</td>
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<td>41 - 45</td>
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<td>7</td>
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<td>11</td>
<td>8</td>
<td>9</td>
<td>10</td>
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<td>46 - 50</td>
<td>3</td>
<td>22</td>
<td>17</td>
<td>37</td>
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<td>51 - 55</td>
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<td>95</td>
<td>80</td>
<td>77</td>
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<td>62</td>
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<td>61 - 65</td>
<td>30</td>
<td>95</td>
<td>122</td>
<td>107</td>
<td>99</td>
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<td>66 - 70</td>
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<td>95</td>
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<td>71 - 75</td>
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<td>76 - 80</td>
<td>110</td>
<td>74</td>
<td>58</td>
<td>60</td>
<td>50</td>
<td>60</td>
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Table 5-4
### Miss Responses

<table>
<thead>
<tr>
<th>Arrangement</th>
<th>Frequency</th>
<th>Mean Response Time ($\bar{X}$)</th>
<th>s</th>
</tr>
</thead>
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<tr>
<td>A</td>
<td>20</td>
<td>122.5</td>
<td>39.20</td>
</tr>
<tr>
<td>B</td>
<td>8</td>
<td>115.0</td>
<td>21.63</td>
</tr>
<tr>
<td>C</td>
<td>9</td>
<td>123.3</td>
<td>20.65</td>
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<td>6</td>
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<tr>
<td>E</td>
<td>21</td>
<td>122.2</td>
<td>29.95</td>
</tr>
<tr>
<td>F</td>
<td>14</td>
<td>128.5</td>
<td>28.55</td>
</tr>
<tr>
<td>G</td>
<td>38</td>
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<td>51.80</td>
</tr>
<tr>
<td>H</td>
<td>13</td>
<td>125.4</td>
<td>17.78</td>
</tr>
</tbody>
</table>

Note: Mean response times in $1/100$ seconds.

Table 5-5
Frequency Distribution: Arrangement A, 7/8 inch Guarded Pushbutton

n = 620
\( \bar{X} = 83.65 \)
\( s = 18.09 \)

Figure 5-1
Frequency Distribution: Arrangement B, 7/8 inch Unguarded Pushbutton

Figure 5-2

n = 620
\( \bar{X} = 72.25 \)
\( s = 16.34 \)
Frequency Distribution: Arrangement C, 3 inch Standard Mushroom Pushbutton

n = 620
\bar{X} = 67.92
s = 15.47

Figure 5-3
Frequency Distribution: Arrangement D, 3 inch Standard Mushroom Pushbutton (Opposite Hand)

Response Time (1/100 seconds)

- $n = 620$
- $\bar{X} = 69.13$
- $s = 17.64$

Figure 5-4
Frequency Distribution: Arrangement E, 3 inch Standard Mushroom Pushbutton (Greased)

Figure 5-5

n = 620
\bar{X} = 72.30
s = 26.01
Frequency Distribution: Arrangement F, 3 inch Experimental Mushroom Pushbutton (Greased)

n = 620
\( \bar{X} = 71.71 \)

s = 19.05
Frequency Distribution: Arrangement G, 3 inch Standard Mushroom Pushbutton
(Greased + Blindfolded)

- $n = 620$
- $\bar{X} = 76.19$
- $s = 24.00$

Response Time (1/100 seconds)
Frequency Distribution: Arrangement H, 3 inch Experimental Mushroom Pushbutton (Greased + Blindfolded)

n = 620
\( \bar{X} = 74.73 \)
\( s = 18.95 \)

Figure 5-8
CHAPTER VI

DISCUSSION AND CONCLUSIONS

Experiment Phase I

For the four different arrangements of emergency stopping devices tested in phase I of the experiment, the following major conclusions were reached:

(1) The inclusion of a protective collar guard around a standard 7/8 inch pushbutton seriously detracts from a human being's ability to quickly and consistently activate the device. This was shown by a 15% increase in average system response time with a statistical significance well in excess of the 99.9% level. Furthermore, inclusion of the guard was shown to increase the frequency of miss response by a factor of 2.5 to 1, this being in excess of the 95% level of statistical significance. The effect of a miss was observed to be an increase in total system response time from an average of 0.84 second to an average of 1.23 seconds or an increase of about 46% for the guarded pushbutton. Probability of a miss response was 0.032 for the guarded pushbutton and 0.013 for the identical button with the guard
removed. Lastly, one subject was observed to miss the guarded pushbutton twice in succession during a single trial. Total response time for this trial was 2.45 seconds. A double miss was not observed at any other time during the 4,960 trials of this experiment.

(2) The 3 inch standard mushroom style pushbutton was observed to have a shorter mean response time than the unguarded 7/8 inch button by about 6.6%; the null hypothesis that the means were the same was rejected at greater than 99.5% level of statistical significance. The null hypothesis that frequencies of miss response were the same for these two devices could not be rejected and, in fact, they were observed to be about equal. Probability of a miss response for the 3 inch standard mushroom pushbutton was 0.015 compared with 0.013 for the 7/8 inch unguarded button.

(3) The null hypothesis that mean response times were the same when using favored versus non-favored hands to activate a 3 inch standard mushroom style pushbutton could not be rejected at greater than 95% level of significance. This occurred in spite of a small observed increase in mean response time (1.8%) when shifting to the non-favored hand. Many more trials would be needed to show a significant difference, indeed
if any difference actually exists. Miss probability was 0.010 for the non-favored hand and it was concluded that mean system response time and miss frequency for this device are not dependent on the hand used for activation.

For phase I of the experiment one obvious conclusion is: a 7/8 inch unguarded pushbutton is superior to a guarded button in terms of the average human-machine system response time for activation. Secondly, the larger mushroom style pushbutton is superior to the smaller button. It is assumed that the larger surface area encourages use of a somewhat faster (although less precise) palm strike and off-center hits are effective in activating this device because of rocking motion. Time consuming secondary movements are thereby minimized. Palm strikes can also be used on the unguarded smaller button but this may not be as obvious. Many subjects were observed using fingertips on this device while very few, if any, used anything but palm strikes on the large mushroom pushbuttons. Finally, a near threefold reduction in miss frequency can be obtained by using an unguarded device. This could become a critical factor during a true emergency response.
Experiment Phase II

During testing for this experiment it was expected that the 3 inch standard mushroom style pushbutton would give superior results in terms of average response time. Indeed, during analysis of phase I data this hypothesis was shown to be statistically significant and did not come as a surprise; but miss frequency did not prove superior with this device. From personal experience and research by the experimenter it was suspected that, whatever type of device is used, under emergency conditions, manual stopping of equipment will always be associated with some probability (no matter how small) that the human being responding will not complete the response. In other words, the person might fail to stop the machine on the first try (miss) under some combination of physical and emotional stress. Furthermore, the developing situation might not allow time for this person to try again. This situation was deemed the most serious, therefore, an effort was made to improve the standard mushroom button design in order to reduce miss frequency.

It has already been concluded that the standard mushroom button allows more rapid activation because of its sensitivity to off-center hits. Also, as shown in the experiment by Brown and Slater-Hammel, secondary movements, similar to those needed to position fingertips in space for the 7/8 inch pushbutton, can often add significantly
to system response time. These movements do not seem to be associated with the palm strikes commonly used on large mushroom pushbuttons; however, occasionally a hit will be sufficiently off-center that a hand will slip off the rounded edge of the button before electrical switch contact is made. The result is a miss.

It was suspected that the surface of curvature should not be consistent along the entire cross section of the device. In other words, if the standard mushroom button were cut vertically through the center and a side view drawn, the surface of the button would form an arc of a perfect circle. It was decided to modify this arc by including a horizontal edge; a button of this shape was manufactured and the resultant forces during off-center hits for the two devices are shown in figure 6-1.

In order to test the hypothesis that the surface of the experimental mushroom head was superior to the standard head, some method of increasing frequency of miss for both devices was needed. It was decided to adjust the system variables as follows:

(1) Spring pressure to activate the device was increased; this had the effect of requiring harder strikes to make electrical switch contact. This condition was not considered unreasonable because, with age, accumulation of dirt, and degradation of sliding surfaces,
Forces on Pushbutton Surfaces

Standard Mushroom

\[ F = \text{Force applied from off-center hit} \]
\[ F_r = \text{Radial Component} \]
\[ F_t = \text{Tangential Component} \]

Experimental Mushroom

Figure 6-1
pressure required for activation of industrial pushbuttons could easily increase.

(2) Surfaces were made extremely slippery by thoroughly coating with silicone spray lubricant. This condition did not seem unreasonable because many manufacturing environments use spray silicone or other lubricants on work parts and machines. Excess lubricant could easily coat the emergency stop button and/or the operator's hands without notice.

(3) Subjects were blindfolded for parts of the experiment. It was thought that this condition would increase the probability that palm strikes would be sufficiently off-center to produce miss responses. This was considered a reasonable simulation of an emergency situation (such as a human entanglement) where the person involved must reach instinctively for the emergency stop device without being able to see it.

The major conclusion from phase II of the experiment was that miss frequencies were higher for the standard mushroom pushbutton design. The null hypothesis that miss frequencies were the same for the standard and experimental designs during blindfolded response was rejected at greater than 99.9% level of statistical significance. It was concluded that the experimental head was superior in prevent-
ing misses during the extreme conditions of this part of the experiment; namely, the high activation force required, slippery surfaces, and lack of visual contact. Miss probabilities were 0.061 and 0.021 for the standard and experimental heads respectively.

Although, in the non-blindfolded condition, miss probabilities were observed to be 0.034 and 0.023 for the standard and experimental heads respectively, the observed difference was not sufficient to reject the null hypothesis at greater than 95% level of significance. It was concluded that many more trials would be needed to show a significant difference in this case.

As expected, average response times for the standard and experimental heads did not differ sufficiently for rejection of the null hypothesis. It was concluded that, since both mushroom heads were 3 inches in diameter, there would be no reason to expect any differences in average response times; therefore, it was concluded that they were equal.

Frequency Distributions

Frequency distributions for each of the eight experimental arrangements are included in chapter V. Analysis of these distributions indicates that there is likely some minimum value of response time before which no human emergency response could ever be expected. Clearly, faster
responses than this minimum, which appears to be about 0.3 second for this experiment, could indicate some anticipatory condition to stimulate response before the alarm. Non-stimulated responses of this type were noted several times during the experiment when subjects pressed the button without any signal being given. However, it is believed that good performance by the experimental assistant at keeping subjects occupied with the auxiliary task prevented anticipation from affecting the results.

These distributions also indicate that there is likely no corresponding maximum value of response time after which no human emergency response could ever be expected. The longest response time observed for this experiment was 4.40 seconds. This occurred during a trial when the subject was deeply engrossed in some particular train of thought. This distracted condition combined with miss responses and periods of indecisiveness could conceivably skew frequency distributions even more seriously under true emergency response situations. No attempt was made to analyze these positively skewed distributions any further than the above speculations.

Conclusion

For this study, many major conclusions were reached regarding emergency stop pushbuttons commonly used on industrial machines. These will not be repeated here; the
reader is referred to the summaries in chapters II and III and the previous discussion. However, the clear superiority of an unguarded pushbutton and especially the large mushroom style button in both average system response time and miss frequency provides the focus for a concluding argument.

Guarded pushbuttons should not be used as emergency stopping devices on machines. If prevention of accidental stopping of machines (bumping) is a machine design criterion, then emergency stop pushbuttons should be guarded by location. Furthermore, the location should be easily accessible and within reach of an operator in the normal operating position. If this is incompatible with the need to prevent bumping of emergency stop buttons, then bumping as a criterion should be sacrificed in favor of operating convenience.

Also, the author has seen many cases where dangerous machinery is stopped and started by two adjacent guarded pushbuttons on one panel; frequently the dual pushbutton station shown in chapter I is used. These should be replaced. The increase in system response time and miss frequency for guarded pushbuttons plus the possibility that a frightened operator could push the wrong button, justify rejection of this popular arrangement as a control panel.

Since the experiment in this study utilized emergency stop pushbuttons mounted on an angled control panel-
el which could be considered an optimum location for activation, no attempt was made to apply the results to buttons mounted in non-optimum locations. This is left for further investigation. However, it could be surmised that the experimental head used in phase II of this experiment might show an even greater improvement in miss frequency when mounted in a less optimum location such as on a vertical panel. On this type of panel the anatomical posture of the wrist might be incompatible with palm strikes; therefore, on vertical panels, operators might be encouraged to use fingertips to activate mushroom pushbuttons. Fingertip strikes would likely require more secondary movement than palm strikes and this could affect miss frequency. Therefore, the hypothesis that the experimental head mounted on a vertical panel could reduce miss frequency remains to be tested.

The focus of this study has been on ergonomic principles and their proper application to design and placement of emergency stopping devices. One might wonder how so much emphasis can be placed on such simple devices; for clearly, there is not much that can be done to improve what is already in use. However, the fallacy of this notion becomes apparent when the results of this experiment are considered. How many machines today still use the standard 7/8 inch guarded pushbutton as an emergency stopping device? Even for such a simple device, improvements can be made when ergonomic principles are ap-
plied and concern for the human operator is given during design of machines.
An important aspect of technical report writing is the solicitation of constructive criticism regarding the research. These comments, when given by persons knowledgeable in the field, can be used not only to evaluate the work but also to generate further interest. Historically it has been shown that questions have often arisen during the course of technical research which could not have been answered without further study. Later experimenters often explored these themes. Therefore, readers' comments are important for evaluation and to promote continued interest in the field.

The following readers have provided comments and their critiques are included for reference:

Professor James L. Smith, Ph.D., P.E.
Industrial Engineering Department
Texas Tech University

Mr. Frank Bastion, CIH
Certified Industrial Hygienist
Clayton Environmental Consultants, Inc.

Mr. Nabil J. Bejjani, MS
Civil Engineer
Louis Berger & Associates
Mr. Robert P. Guinter

Dear Mr. Guinter,

I have read your thesis and found it to be well written and an appropriate research effort for a Master’s degree with an ergonomics specialty. The literature review was extensive and provided the appropriate background for the thesis.

The experimental method was adequate, although it did produce a few questions that I feel should be resolved. At one point you stated that, "the experimenter recorded a deviation only when absolutely certain that one had occurred" (p. 20 of CH 4), yet 5 pages later you describe a procedure to test the "legitimacy of any suspected deviation". These statements appear to be in conflict and I would suggest a brief rationale of why the legitimacy test was felt necessary, and the effect of the procedure on the data, i.e., how many "MISSES" were eliminated using this procedure? Another point that I feel needs to be addressed is the manner in which a "normal diversity of industrial activity was simulated". You hypothesize that "no mental concentration on response time could be maintained", although later on the same page (p. 10, CH 4) you state that, "no trials were observed to take longer than three minutes to complete". Is the three minute maximum trial time long enough to remove all anticipation by the subject and to indeed simulate the "normal diversity of industrial activity"?

The statistical analysis seemed appropriate for the experiment. I would like to see explanations for a couple of items in your results section. First, in Tables 5-2 and 5-3, why weren’t the MISSES for the C-D response comparison included? You appear to discuss the C-D comparison in your Discussion of Results section. Secondly, how can the B-C MISSES in Table 5-2 be "not significant" if in Table 5-3 the "t" value for B-C MISSES was "not computed"? If it was, in fact, not computed, why not offer a brief explanation for its exclusion?
The conclusions seem to logically follow from the results of the experiment. I think that CHAPTER 5, Discussion of Results, is in reality a part of the conclusions. I would suggest that the Discussion of Results section address issues such as what data were included and excluded from analysis and why, and the rationale for the manner in which the data are represented, i.e., tables, response frequencies, and frequency distributions. Finally, a suggestion: Here at Texas Tech we have started to require that students include their raw data in an appendix so that future researchers can use the data if they desire.

Overall, I feel that the thesis was well done and hope that you find my comments helpful. I have enclosed a brief description of our ergonomics program here at Texas Tech to provide you with a little background on the kinds of ergonomics efforts in which I am involved. I would like to receive a final copy of your thesis when it becomes available. If I can be of further assistance, please let me know. Good luck on your defense and with your future endeavors in the ergonomics area.

Sincerely,

James L. Smith, Ph.D., P.E.,
Associate Professor
Dear Professor Smith:

After speaking with my thesis advisor concerning your many valuable comments and suggestions, it was decided that I should write you a formal letter addressing these issues and include a copy with your critique in the final report. Therefore, this letter is in addition to the thank-you letter I already sent and may contain some of the same information.

Concerning the question of raw data being included with the report, it was decided that the quantity of pages would seriously increase the size of an already lengthy report. Therefore, raw data will not be included. However, my advisor requested that the raw data be included with your copy of the final draft and the original data sheets will be kept on file in the Industrial Engineering department here at NJIT. If anyone should need these data for further research the department will make them available on request.

As to the conflicting statements in chapter IV you are absolutely correct. After considering this point I realized that my wording did not accurately convey the idea I was trying to communicate. How could an experimenter sitting behind the subject be "absolutely certain" that a miss/slip had occurred? In reality, there is no way to be absolutely certain unless each response was videotaped and later scrutinized in detail. Since this was not done, the experimenter could only become mentally convinced that a deviation had occurred after considering the visual and audible effects of each response and the recorded elapsed time of each trial. Therefore, each suspected deviation required a mental decision on the part of the experimenter which did allow some small probability of error. I believe this idea is more clearly established in the revised wordings. Also, it was concluded that, even if a subject missed or slipped during a response this event only became important if it seriously increased the total elapsed time
of response. If a miss occurred but then the subject recovered within a sufficiently short time period to stop the clock quickly, then the trial should not be included with the miss frequency analysis because, clearly, it would not have seriously degraded a true emergency response. Only those misses/slips that seriously increased the elapsed time of response were wanted. This was the reason a procedure for eliminating non-excessive deviations was devised. Hopefully, this idea is now more clearly conveyed after rewording.

Tables 5-2 and 5-3 have been expanded to include the data for B-C and C-D misses that were not included in your copy of the draft. After reading your comments, I decided that a "t" test of this information was indeed required if the result was later to be reported as "not significant." It was not a good scientific method to assume a statistical result no matter how trivial the computation or obvious the result might appear. Also, the typographical error in table 5-3 was corrected; it was B-C misses that should have been labeled "not computed," not A-B misses. Now all "t" values have been computed and reported in the table.

Your comments about the discussion and conclusions have resulted in these two chapters being combined. Also, except for the procedure to eliminate non-excessive missed/slipped trials from the miss frequency analysis, there was no attempt made at any time to eliminate any subjects' individual or averaged response times. The comments on pages 80 and 108 reflect my opinions on this matter.

Finally, for the rationale of data representation in chapter V, these tables and figures were included to represent the data in every way that seemed logical and informative. During my literature search I found that many experimenters failed to include significant information about their data. Perhaps this reflects a need for fewer pages and concise data representation for journal publication. In writing a thesis, I am not restricted in this manner and my tables and figures were included so that future experimenters will not be hampered when reviewing my research (as I was when reviewing others').
Again, I would like to express my gratitude for your timely and extensive comments concerning my research effort. I have had ample time to address each issue you raised and many pertinent changes to the final draft have been made. I expect to have copies of the final draft made within the next two weeks and I will send you one shortly thereafter. Thanks again and I extend my very best regards.

Very truly yours,

Robert P. Guinter
Dear Bob:

I read your thesis 'Emergency Stop Devices For Industrial Machines And The Human Factors Of Emergency Response' and found it an interesting and informative study of an important safety issue.

Clearly, there is more that can be done to minimize the incidence and severity of industrial machine accidents. The lack of uniformity in emergency stop devices points up the need for safety and design professionals to cooperate in incorporating ergonomic principles in the design and retrofit of industrial machines.

The experiments described affirmed the dogmatic belief that small, guarded stop buttons are more difficult to successfully activate than large, unguarded buttons. Beyond this, however, the study defines and quantifies different human response factors involved. For example, the total human response time includes contributions due to recognition of the emergency, the motion to activate the stop device, the possibility of missing or slipping-off the stop button, the possibility of identifying the wrong button, and the physical action required such as single digit versus palm activated buttons. This detailed treatment brings to light new ideas such as the proposed revised mushroom button design which can decrease the response time.

I have a suggestion regarding the motivation of experiment subjects. Ideally, subjects will respond in the experiment the same as they would in an emergency situation. The question is how to elicit crisis motivation without endangerment. A possible solution would be to choose the subject population from a group that is motivated by monetary gain (e.g., college students). The subject would compete for a reward of some sort. I'm not certain just how this would be implemented, but I think the idea of trying to simulate some of the emotions which motivate a real-life operator in a crisis situation could benefit future experiments.
I believe this thesis is a worthy addition to the body of information concerning industrial safety. My best wishes for your continued success.

Sincerely,

B.F. Bastian, CIH
Clayton Environmental Consultants, Inc.
May 5, 1986

Mr Robert Paul Guinter

Dear Mr Guinter:

I had the pleasure to read your Master Thesis on "Emergency Stop Devices and Human Response".

The work was done with professionalism reflecting a well structured handling and discussion of a very relevant and up-to-date topic in Ergonomics. Moreover, the good syntax helped the refined English writing style in presenting the subject matter as a clear and easy to understand one, although some ideas were stated in an ambiguous way. The formatting and presentation are inviting and clean, except for some drawings (figures) which lack explanation and mainly captions.

Although not displayed in a standard form, the scientific aspect of the experiments and their results are accurate and sufficiently elaborate for the purpose of the study. The statistics part could include a tabulation of Means, Standard Deviations and Ranges (i.e. minima and maxima) of the corresponding results and observed data, in order to be more technical.

But most of all, as the intent of this thesis is to serve as a reference material to the industry, an economical additive, coupled with a sharp safety measure advice against vandalism will make your findings even more attractive to Management in the industrial world.

All the aforementioned remarks do not interfere with the intrinsic value of the research work, which is very informative about the subject treated. It is thoroughly backed by relevant references and exhaustively encompasses all the sides of the "Emergency Stop Devices and Human Response" issue.

I wish you good luck, with confidence,

yours truly,

Nabil J. Bejjani
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