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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

cal	caliber	J	joule
cu ft	cubic foot	L	liter
cu in	cubic inch	lb	pound
ft	foot	min	minute
ft/s	foot per second	m/s	meter per second
g	gram	oz	ounce
gal	gallon	pct	percent
g cm/s	gram centimeter per second	psi	pound per square inch
gpm	gallon per minute	psig	pound per square inch gauge
gr	grain	rpm	revolution per minute
in	inch	s	second

EVALUATION OF THE SAFETY OF ONE-HOUR COMPRESSED OXYGEN SELF-RESCUERS—RESULTS OF DESTRUCTIVE TESTING

By R. W. Watson,[1] A. L. Furno,[2] W. J. Doyak,[3] and R. L. Brewer[4]

ABSTRACT

At the request of the Mine Safety and Health Administration (MSHA) the Bureau of Mines evaluated the potential hazards of three compressed oxygen self-contained self-rescuers (SCSR's) designed for use in underground coal mines.

The evaluation followed the lines used in a similar investigation of chemical self-rescuers and involved laboratory experiments as well as field trials designed to simulate a mining environment. They included bullet impact, bonfire, feeder-breaker impact and feed-through, and mining machine runover tests.

The work showed that the units were not inherently unsafe but that under certain conditions of extreme abuse they can present a potential ignition or explosion hazard. This, coupled with a survey of reported damage on SCSR's currently deployed in underground mines, which indicated a relatively high frequency of incidents leading to the destruction of the units, led to new recommendations on the deployment of SCSR's. The recommendations formulated by MSHA state that the units should be either properly worn by the miner, stored in heavy containers, or otherwise protected from situations in which they might be accidentally ruptured or destroyed, such as runover by mobile mining equipment.

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INTRODUCTION

A Federal regulation (30 CFR 75.1714), which went into effect on June 21, 1981, requires that every person who goes into an underground coal mine in the United States must be supplied with an SCSR. An SCSR is a self-contained, closed-circuit, emergency breathing apparatus designed for mine escape purposes.

All SCSR's intended for in-mine use must be approved by the National Institute for Occupational Safety and Health (NIOSH) and the Mine Safety and Health Administration (MSHA) under a schedule given in 30 CFR 11, Subpart H for 60-min-duration breathing apparatus. Both chemical oxygen and compressed oxygen SCSR's have received NIOSH-MSHA approval; as of July 1, 1982, five different SCSR's were commercially available: CSE AU-9A1, Drager OXY-SR 60B, MSA-60-min SSR, OCENCO EBA 6.5, and PASS 700.[5]

The Drager and the MSA SCSR's are chemical units which utilize potassium superoxide (KO_2) for producing oxygen. An evaluation of the potential safety hazards of these two units has been reported (1).[6] The results of the investigation showed that the chemical SCSR's were rugged and would probably survive massive roof fall and crushing by mobile mining equipment, including continuous mining machines, without releasing significant quantities of KO_2. It was shown that the KO_2 did not pose any significant hazard even if released under these circumstances. However, in experiments involving a feeder-breaker, short-lived fires were observed when the KO_2 canister contained in the chemical SCSR's was punctured while being fed through the breaker assembly. An analysis of the probability of this type of event showed it to be too low to preclude the use of chemical SCSR's in underground coal mines.

With the commercial introduction of compressed oxygen SCSR's in 1982, the Bureau of Mines conducted an evaluation of the potential hazards of the three approved compressed oxygen SCSR's. The evaluation followed along the lines of the chemical SCSR investigation and involved some preliminary laboratory experiments as well as field trials designed to simulate a mining environment; they included bonfire, bullet impact, drop weight, simulated roof fall, feeder-breaker impact and feed-through, and mobile equipment runover trials. The results of this evaluation are summarized in this report.

PHYSICAL DESCRIPTION OF THE UNITS TESTED

In some of the destructive testing to be described, the qualitative behavior of the three SCSR's (CSE AU-9A1, OCENCO EBA 6.5, and PASS 700) differed from unit to unit. These differences depended to a large degree on the physical makeup of the individual units and particularly on features that influenced accidental oxygen release, such as the material and construction of the bottles and the gas manifolds used to control the normal flow of oxygen from the bottles. For this reason it is desirable to give a brief physical description of the three units with emphasis on those features that might affect the gross response of the SCSR's to various forms of physical abuse. The three SCSR's are shown in figure 1, and the pertinent design and construction details are summarized in table 1.

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[5]Reference to specific products does not imply endorsement by the Bureau of Mines.

[6]Underlined numbers in parentheses refer to items in the list of references at the end of this report.

TABLE 1. - Physical characteristics of three self-rescuers

Dimension	CSE AU-9A1	OCENCO EBA 6.5	PASS 700
Overall size............in..	11.5 × 8.5 × 4.5	11.9 × 8.6 × 4.6	19.5 × 14.5 × 7.5
Carrying weight.........lb..	11.0	7.7	18.9
Case material..............	Aluminum	Plastic	Plastic
Case thickness..........in..	0.052	0.082	0.145 outer, 0.082 inner.
Bottle:			
Material..................	1006 steel	6061-T6 aluminum, fiberglass-epoxy.	6351-T6 aluminum
Wall thickness........in..	0.180	0.094 + 0.09[1]	0.215
Length................in..	7.9	7.9	10.9
Diameter..............in..	2.75	3.53	4.38
Volume.............cu in..	32.6	48.8	103.0
Service pressure....psig..	3,500	3,000	2,015
Oxygen capacity....cu ft..	4.6	5.54	8.7
Orifice diameters, in:			
A - Neck fitting..........	0.125	0.070	0.060
B - Frangible disc........	0.125	0.125	0.180
C - Gauge fitting.........	0.125	0.070	0.125
D - Gauge stem............	0.015	0.005	0.030

[1]0.094-in aluminum inner shell; 0.09-in fiberglass overlay.

The CSE unit is contained in an aluminum case having a wall thickness of 0.052 in and overall dimensions of 11.5 by 8.5 by 4.5 in; the carrying weight is approximately 11.0 lb. The compressed oxygen is contained in a 0.180-in-thick-wall, 1006 alloy steel bottle having a length of 7.9 in and an outside diameter of 2.75 in. The volume of the bottle is 32.6 cu in, which is sufficient to contain 4.6 cu ft of oxygen at a service pressure of 3,500 psig.

The OCENCO unit has a carrying weight of 7.7 lb and is contained in a 0.082-in-thick plastic case which is 11.9 by 8.6 by 4.6 in overall. The OCENCO uses a composite bottle consisting of a 0.094-in-thick inner shell of 6061-T6 aluminum alloy which is overwrapped with epoxy-impregnated fiberglass; the thickness of the fiberglass overlay is roughly 0.09 in. The composite bottle is 7.9 in long and 3.53 in in diameter and has a volume of 48.8 cu in. It holds 5.54 cu ft of oxygen at a service pressure of 3,000 psig.

The PASS unit has overall dimensions of 19.5 by 14.5 by 7.5 in and a carrying weight of 18.9 lb. It is contained in an outer plastic case having a 0.145 in-thick-wall. The bottle, which is 10.9 in long and 4.38 in in diameter, is additionally protected by a 0.082-in-thick inner plastic case which serves as the breathing volume in place of an air bag. The PASS bottle is made of 0.215-in-thick 6351-T6 aluminum alloy and has a volume of 103 cu in; it is designed to hold 8.7 cu ft of oxygen at a service pressure of 2,015 psig.

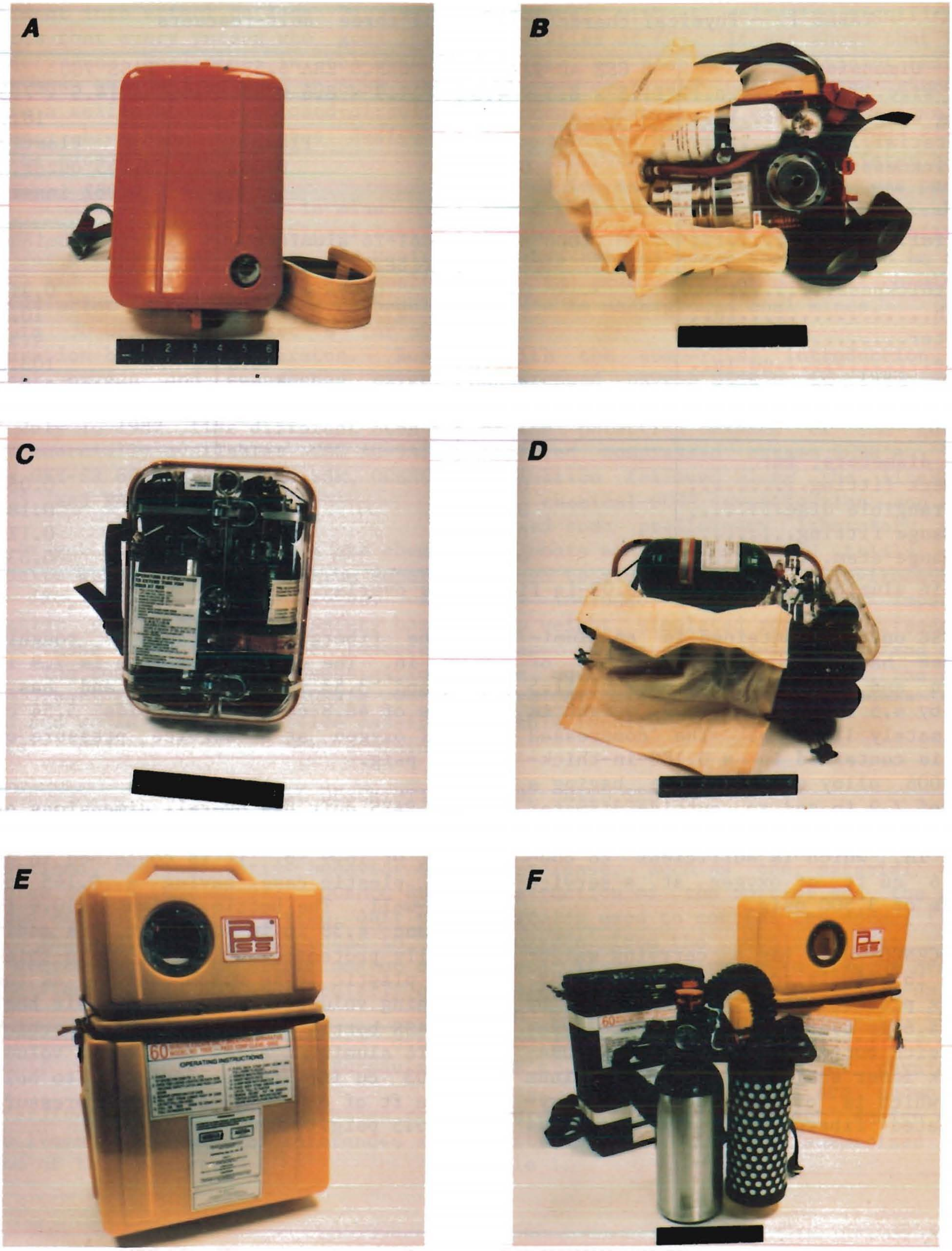

FIGURE 1. - The three self-rescuers used in test program. *A-B*, CSE; *C-D*, OCENCO; *E-F*, PASS. The orange exterior case of the CSE unit is of aluminum; the transparent case of the OCENCO unit and the yellow case of the PASS unit are plastic.

All the bottles are equipped with a gas control manifold consisting of an on-off valve, a pressure gauge, and a frangible disc assembly, all integrated into a single unit screwed into the top of the bottle. Damage to any of these components can lead to the escape of oxygen even with the valve in the off position. The oxygen release rate is governed by the diameter of the various orifices supplying the damaged component(s). Referring to figure 2, it can be seen that the flow of gas is first restricted by the internal diameter (*A*) of the fitting used to couple the manifold to the neck of the bottle. As shown in table 1, this diameter is ordinarily equal to or smaller than the effective frangible disc diameter (*B*) and serves as the principal flow control when the frangible disc is ruptured.

For a given bottle the orifice in the gauge fitting (*C*) is no smaller than the neck orifice and did not serve to further restrict flow in cases where the gauge fitting was sheared from the manifold. However, flow to the gauge proper is limited by a very small diameter restriction (*D*) in the stem of the gauge. This led to the very slow release of oxygen in certain tests where there was damage to the internal components of the gauge, particularly in trials involving fire.

On comparing the various orifice diameters in table 1, it can be surmised that failure of the frangible disc or gauge fitting would result in relative oxygen release rates ranging from high to medium to low for the CSE, OCENCO, and PASS units, respectively. This follows from the fact that the orifice in the neck fitting would serve to control the flow. The corresponding order for gauge failure, per se, would be PASS, CSE, and OCENCO. This is in qualitative agreement with the impressions gained from witnessing the destructive tests.

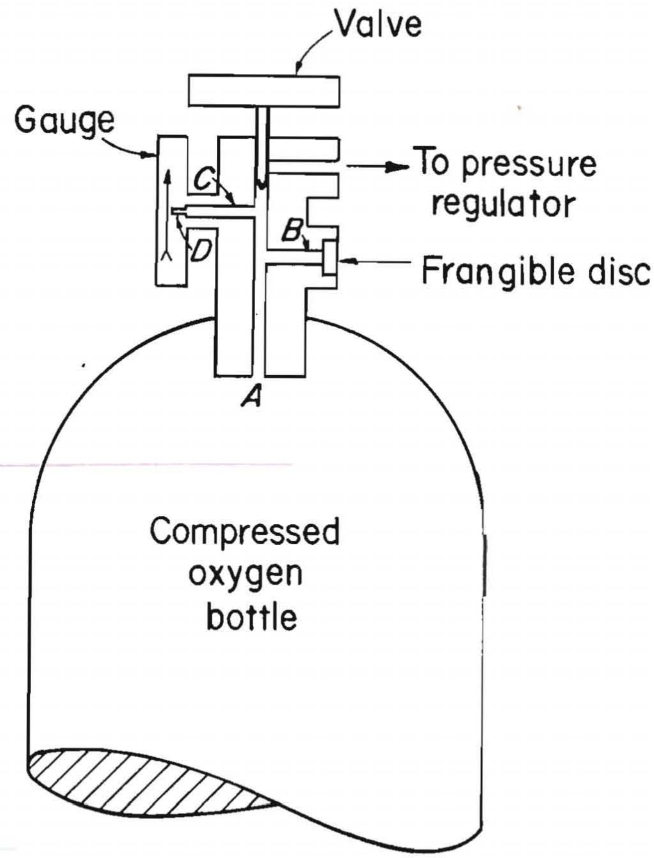

FIGURE 2. - Principal features of gas manifold on compressed oxygen bottles.

PRELIMINARY EXPERIMENTS

To assure the safety of the personnel involved in conducting the hazard evaluation, as well as to obtain a good grasp of the nature of the hazards, a number of preliminary experiments leading to destruction of the SCSR's were conducted. They consisted of bonfire trials where the bottles or units were burned to destruction, bullet and drop weight impact tests leading to bottle perforation, and a few experiments where the bottles were pressurized to the point of frangible disc failure. They were all conducted in closed testing chambers or at safe distances to protect personnel from potentially hazardous missiles and served to lay the ground rules for range safety in conducting the more complex mine simulation trials. The preliminary experiments also shed considerable light on the nature of the hazards that might be posed by accidents leading to the destruction of SCSR's.

BONFIRE TRIALS

All three compressed oxygen bottles are equipped with safety relief devices, in the form of frangible burst discs, in order to comply with regulations pertaining to safety in the transportation of compressed gas bottles (2). These devices are designed to prevent the buildup of pressure within the bottle due to excessive heat or overfilling. To observe the functioning of the burst disc and to determine the effect, if any, of the presence of the external case and accessories on the normal functioning of the disc, a series of six bonfire trials was conducted with compressed oxygen bottles from the three devices under consideration as well as with complete units.

For this purpose the articles were positioned on a steel grate placed over a 3-ft-square by 1-ft-deep steel box containing 45 gal of water on which was floated 10 gal of JP4 jet fuel. The fuel was ignited with a 1/2-oz black powder ignitor and allowed to burn to completion, which normally took about 30 min. The bottles and units were equipped with two thermocouples to record the temperature-time histories of the trials. One thermocouple was placed directly on the center of the bottles to record average bottle surface temperature; the other was placed in the vicinity of the burst disc to record temperatures there.

The experimental setup is shown in figure 3, and the results from the tests are summarized in table 2. Selected photographs from tests 43, 44, and 45 are presented in figure 4, and the remnants of the bottles and units from all six bonfire tests are shown in figure 5.[7]

[7]Nearly 250 tests were conducted; only those significant to the present report are discussed.

TABLE 2. - Summary of bonfire trials

Test	Test item	Venting time,[1] s		Elapsed time, s	Frangible disc	Remarks
		Start	Finish			
43	CSE bottle...	53	80.5	27.5	Burst.....	Slow venting starting at t = 53 s; very rapid venting at t = 80 s.
44	OCENCO bottle	42	65	23	...do.....	Slow venting starting at t = 42 s; fast venting at t = 50 s.
45	PASS bottle..	72	100	28	...do.....	Fast venting at t = 72 s; slowed at t = 87 s.
76	CSE unit.....	172	460	288	Intact....	Sporadic venting throughout.
77	OCENCO unit..	128	142	14	Burst.....	Slow venting starting at t = 128 s; fast venting starting at t = 139 s.
78	PASS unit....	346	420	74	Intact....	Fairly slow venting starting at t = 346 s; sporadic from t = 368 to t = 420 s.

[1]Measured in seconds after start of bonfire.

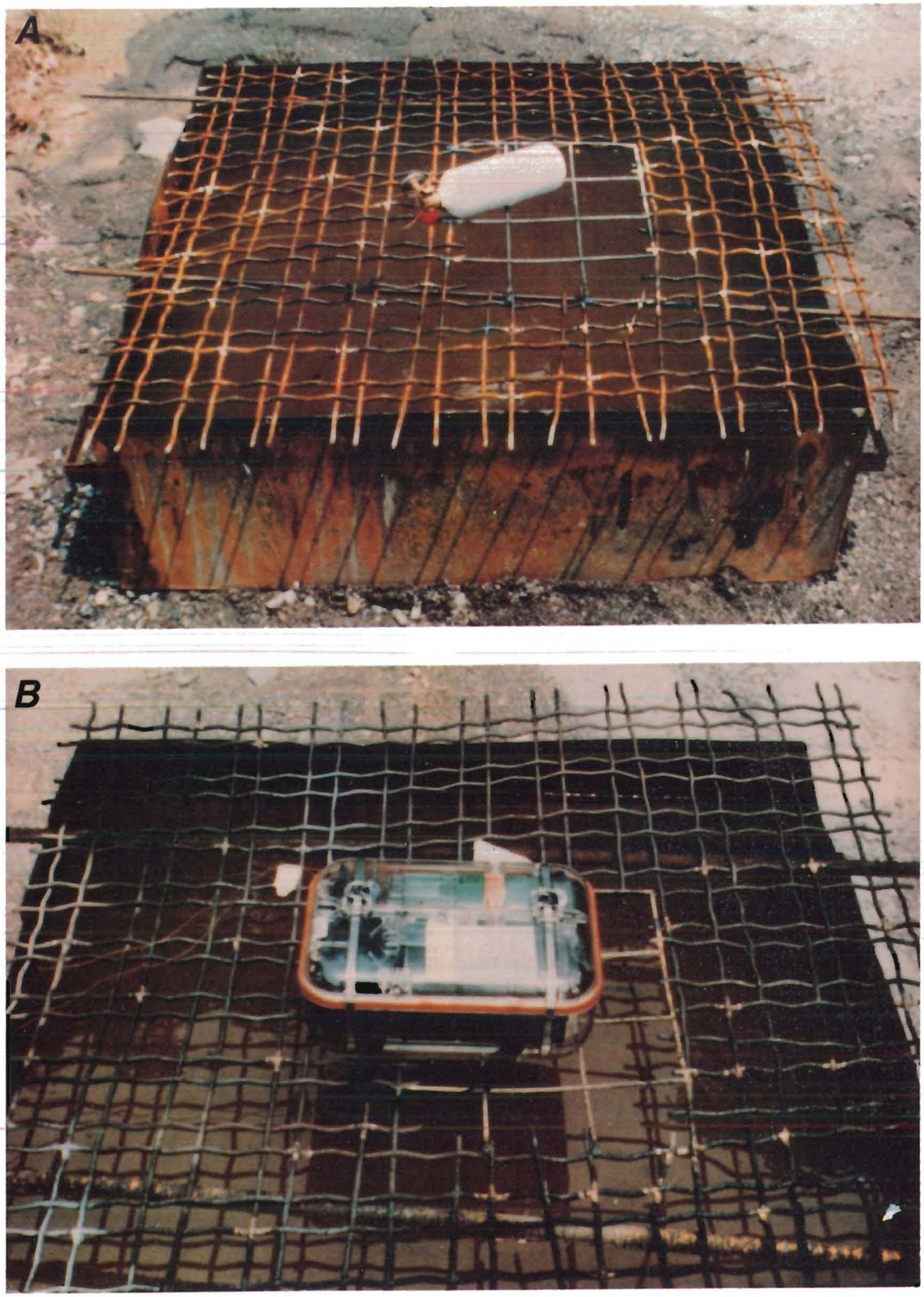

FIGURE 3. - Experimental setup used in bonfire trials with *A*, compressed oxygen bottles and *B*, complete units. The white CSE bottle is constructed of steel.

FIGURE 4. - Selected photographs from bonfire test 43 with a CSE bottle (*A-B*), test 44 with an OCENCO bottle (*C-D*), and test 45 with a PASS bottle (*E-F*). The large fireball in panel *B* and the intense white flames in panels *D* and *F* are associated with the rapid release of oxygen.

FIGURE 5. - Flame-blackened bottles recovered from bonfire tests 43, 44, and 45 (*A-C*) and remains of units recovered from tests 76, 77, and 78 (*D-F*).

During the bonfire trials it was observed that there were two distinct modes of oxygen release. One was associated with the thermal failure of the pressure gauges, which by necessity are constructed with rather delicate interior components. The other was due to the rupture of the frangible discs which, of course, are designed to provide quick gas release. Since the diameter of the gauge orifice is small in comparison to that supplying the frangible disc, failure of the gauges resulted in the relatively slow release of oxygen, while failure of the frangible discs produced a more violent release of gas. Furthermore, in view of the thermal mass of the gauge in comparison with the mass of the material making up the pressure relief system, one might expect the gauge to fail first. Gauge failure apparently happened in all six trials with the possible exception of test 45. This can be seen from an examination of table 2, where it is shown that gauge failure was the only means of oxygen release in tests 76 and 78 (no disc rupture) and that in tests 43, 44, and 77 the rapid release of oxygen associated with disc failure was preceded by a period of slower release. In test 45 fast venting began at t = 72 s and lasted until t = 87 s, when the venting slowed until completion at t = 100 s; there was no initial period of slow venting. Failure of the disc alone or the gauge and disc together could account for these observations. In any case, all of the bottles (units) were vented by one means or the other before internal pressures could build to a point leading to bottle failure. The temperature of the bottles and the temperature in the vicinity of the burst disc followed one another fairly closely and ordinarily reached 500° C or higher before venting occurred.

It is interesting to note that in the two cases where the bottles vented through the gauge orifice alone (tests 76 and 78), it took the CSE bottle approximately four times longer to vent than the PASS bottle: 288 s versus 74 s. Referring back to table 1, it can be seen that the gauge-orifice diameter of the PASS unit is twice that of the CSE unit. The corresponding cross-sectional areas are in the ratio of 4 to 1, which would lead to a fourfold difference in vent times in the first approximation.

Some of these events were fairly spectacular, as evidenced by the photographs in figures *4B*, *4D*, and *4F*. The photograph in figure *4B* was taken 80 s after the ignition of the JP4 fuel, corresponding to the time of very rapid venting associated with the failure of the burst disc. The photograph in figure *4D* was taken about 57 s after ignition and that in figure *4F* about 70 s after ignition, both during periods of fast venting. As anticipated in the discussion of the orifice sizes in table 1, the CSE bottle appeared to vent most rapidly upon disc failure and the OCENCO bottle appeared to vent more rapidly than the PASS bottle. None of the trials produced any missiles of serious consequence, although the bottles from tests 43 and 77 were projected 9 and 12 ft, respectively, from the test stand.

BULLET IMPACT TRIALS

While the bonfire tests did not produce missiles of any consequence, the possibility of bottle fragmentation during mechanical failure was still of some concern. In a similar vein, the oxygen release was more or less controlled in the bonfire trials, leaving unanswered questions concerning the potential hazards associated with the more violent release of oxygen.

In an attempt to address these questions, a simple ballistic pendulum was used to measure the impulse associated with the rapid release of oxygen effected by perforating the bottles with high-velocity projectiles (bullets). Other bullet impact trials were conducted to simply determine whether the bottles fragmented or whether the full units produced dangerous missiles during bottle failure. In the latter case, the trials resembled those called for by the Department of Transportation in issuing approvals for the transport of certain compressed gas bottles (3).

The experimental setup for the impulse measurements was a crude ballistic pendulum to which the bottle was attached as shown in figure 6. It consisted of a 4-ft by 8-in by 8-in oak log which was suspended from the ceiling of a test chamber by two 6-ft-long steel supports. The pendulum initially weighed 103 lb, but in certain tests the weight was increased to 206 lb by the addition of a steel block, as indicated in figure 6. This was done to keep the deflection of the pendulum within the range of the recording device, which consisted of a spring-loaded steel pen that traced pendulum deflection on a thin sheet of painted plexiglass.

In practice an oxygen-filled bottle was attached to the front of the pendulum with strong fiber bands and impacted with a bullet fired from a rifle through a port in the wall of the test chamber. Tests were conducted with 0.22-cal Hornet bullets having a mass of 45 gr and a nominal velocity of 2,500 ft/s; with 0.30-cal M2 ball ammunition having a mass of 150 gr and a nominal velocity of 2,800 ft/s; and with 0.50-cal brass cylinders having a mass of 210 gr and velocities variable from 300 to 5,000 ft/s (4). For comparison purposes, a few tests were made with bottles filled with nitrogen gas compressed to 3,500 psi. Results from tests with CSE, OCENCO, and PASS bottles are presented in table 3 in terms of momentum transfer (impulse) calculated from the observed values of pendulum deflection.

Before discussing the implications of the impulse measurements tabulated in table 3, it is desirable to discuss some of the qualitative features of the impact experiments with the compressed oxygen bottles. First, no bottle fragmentation, per se, was observed in any of the bullet impact trials. The bottles remained intact and exhibited only bullet entrance holes and exit holes in cases where the bullet perforated the back wall of the bottles. In tests 16-1 and 16-2, which involved relatively low impact velocities, the projectile merely bounced off the bottle, causing only minor surface damage.

TABLE 3. - Results of bullet impact trials using ballistic pendulum

Test	Bottle type	Bullet type	Impulse,[1] g cm/s	Exit perforation
6	CSE..............	0.22-cal Hornet..............	8.0×10^6	No.
7	CSE..............	...do........................	8.8×10^6	No.
8	CSE..............	...do........................	No measurement	No.
12	CSE..............	...do........................	6.5×10^6	No.
202[2]	CSE..............	...do........................	4.8×10^6	No.
203[2]	CSE..............	...do........................	4.6×10^6	No.
3	CSE..............	0.30-cal M2 ball.............	3.7×10^6	Yes.
10	OCENCO...........	0.22-cal Hornet..............	6.5×10^6	Yes.
13[3]	OCENCO...........	0.22-cal Hornet (1,220 ft/s).	7.8×10^6	No.
14	OCENCO...........	0.30-cal M2 ball.............	4.9×10^6	Yes.
16-1[4]	OCENCO...........	0.50-cal cyl (490 ft/s)......	0	No.
16-2[4]	OCENCO...........	0.50-cal cyl (820 ft/s)......	0	No.
16-3	OCENCO...........	0.50-cal cyl (1,640 ft/s)....	8.9×10^6	Yes.
11	PASS.............	0.22-cal Hornet..............	1.6×10^7	Yes.
15[3]	PASS.............	0.22-cal Hornet (1,620 ft/s).	1.2×10^7	No.

[1]Measured values less projectile momentum.
[2]Bottle filled with nitrogen at 3,500 psi.
[3]Reduced powder load.
[4]Projectile did not penetrate bottle.

FIGURE 6. - Ballistic pendulum used to determine impulse associated with bottle puncture. White CSE bottle strapped to oak log is impacted by bullet traveling from left to right; red sheet in background is used to record pendulum deflection.

In cases where oxygen-filled bottles were perforated, television tapes of the events showed that the impacts were accompanied by a bright flash and a spectacular shower of sparks; in addition, loud, explosionlike reports were audible. The visual effects are shown in figure 7, which is a photographic reproduction of several of the frames from the television tape of test 6, which involved the impact of a 0.22-cal Hornet bullet on a CSE bottle. Subsequent examination of the bottles showed that bullet entrance (and exit) holes were significantly larger than expected, and there was evidence of molten metal around the periphery of the holes as well as inside the bottles.

This is illustrated in figure 8, which shows the bottles recovered from tests 7, 10, 11, and 202, all of which involved the impact of 0.22-cal Hornet bullets at a nominal velocity of 2,500 ft/s. Tests 7, 10, and 11 were conducted with oxygen-filled bottles, while test 202 was made with a CSE bottle filled with nitrogen pressurized to 3,500 psi. The OCENCO bottle from test 10 was cut open to more clearly define the impact damage to the aluminum liner, which was obscured by the fiberglass overlay.

From figure 8, it is obvious that the presence of oxygen leads to significantly more impact damage to the bottles. It is also apparent that a high-temperature combustion reaction had occurred from the presence of molten aluminum or steel in the vicinity of the point of impact. This reaction is apparently initiated by the local heating of the metal during the first stages of perforation and persists until the oxygen is vented through the perforation, which is expanding as a result of the wall material being consumed.

It is of some interest to estimate the amount of material involved in the observed combustion reactions; this will be done for the 0.22-cal Hornet impacts on the three bottle types. Crude estimates of weight loss from bottle weight measurements before and after perforation indicated that the CSE bottle lost roughly 15 g of weight, the OCENCO bottle lost 35 g; and the PASS bottles lost roughly 60 g. With a knowledge of the bottle wall thicknesses given in table 1, hole diameters corresponding to the weight loss can be calculated, taking into account the density of the wall material. These turn out to be 0.9, 3.2, and 2.8 in for the CSE, OCENCO, and PASS bottles, respectively. These values are in good agreement with the values of 0.9 in and 2.5 in (average) observed for the diameters of the holes in the CSE and PASS bottles in figure 8. The hole in the OCENCO bottle was very irregular, but its total cross-sectional area was close to that of a 3.2-in-diameter circle. The agreement between the observed hole diameters and the diameters calculated from weight loss measurements indicates that the major portion of the material represented by the holes in the bottles is consumed in the combustion reaction and not just displaced during the perforation process.

One further item of interest is the energy released by the combustion reactions observed in the bullet impact experiments. If the heats of combustion of aluminum and steel (iron) are taken to be 7,000 and 1,600 calories per gram, respectively, the weight loss observed in the 0.22-cal Hornet trials equates to an energy release of 0.024, 0.245, and 0.420 mega-calories for the CSE, OCENCO, and PASS bottles, respectively. This observation will be of some importance in discussing the ignition potential of these reactions later in the report.

Let us now return to the impulse measurements obtained in the impact experiments, which are summarized in table 3. The total impulse transferred to the bottles (and pendulum) represents the sum of the momentum associated with the striking bullet, the release of the pressurized gas, and the release of energy during the combustion reaction that occurs during the penetration process. The contribution of the bullet can easily be calculated from the known mass and velocity of the bullet and represents only a fraction

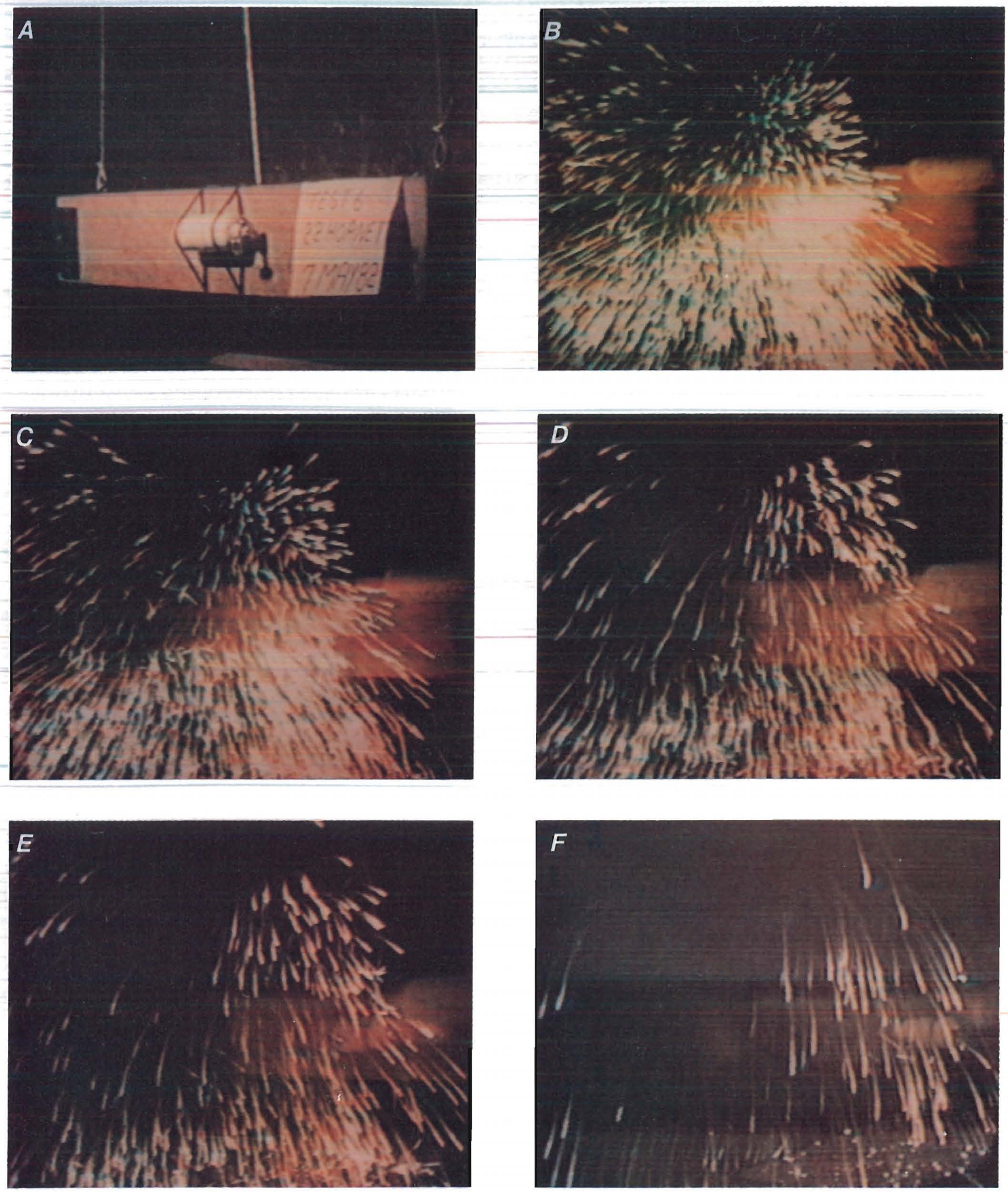

FIGURE 7. - Luminescent streamers associated with bullet impact on a CSE bottle in test 6.

FIGURE 8. - Bullet impact damage to compressed oxygen bottles (top) compared with damage to bottle filled with compressed nitrogen (bottom). Grayish sludge in OCENCO bottle (top center) is molten aluminum.

of the observed values. For example, the forward momentum of the 0.22-cal Hornet (45 g at 2,500 ft/s) is 0.22×10^6 g cm/s, while that of the 0.30-cal M2 ball (150 gr at 2,800 ft/s) is 0.83×10^6 g cm/s; the observed values are on the order of 10^7 g cm/s.

The second contribution, that of the escaping gas, can also be calculated in principle, from a knowledge of the quantity and pressure of the stored gas together with certain simplifying assumptions concerning the nature of the gas release. However, in cases where both sides of the bottle are perforated, the full momentum of the escaping gas is not transferred to the system comprised of the bottle and pendulum owing to the release of gas through the exit hole, which detracts from the total forward momentum. The momentum transferred to the system by the combustion reaction cannot be easily calculated owing to a lack of information on the partition of energy between the pendulum-bottle system and the combustion products.

To avoid these difficulties, a few measurements were made with CSE bottles filled with nitrogen gas pressurized to 3,500 psi. Since the 0.22-cal Hornet is only capable of penetrating one side of the CSE bottle and since no combustion reaction is observed with nitrogen-filled bottles, the measured impulse values represent the upper limit[8] associated with the release of gas during the purely mechanical rupture of the bottle, a situation that might arise while a person was wearing or near an SCSR. The impulse values with the nitrogen-filled bottles (tests 202 and 203) were in close agreement and averaged 4.7×10^6 g cm/s. It will be noted that, in general, the values of impulse observed with the oxygen-filled bottles were significantly higher than the values recorded with the nitrogen-filled bottles. This is due, of course, to the extra impulse resulting from the combustion reaction. In addition, the observed values of impulse were generally higher when only one side of the bottle was perforated, in keeping with our discussion of the impulse associated with gas release. The impulse values observed in the tests with the PASS bottles were somewhat higher than those observed with the CSE and OCENCO bottles. This is associated with the fact that the PASS bottle contains more oxygen than the other two bottles and possibly with the fact that more material was involved in the combustion reaction, as indicated by the weight loss and hole diameter measurements. All this is rather academic in terms of the hazard posed by the mechanical failure of a bottle in a unit being worn, but it does add some insight to the nature of the combustion reaction observed during the high-velocity penetration process.

As was pointed out, the value of 4.7×10^6 g cm/s does represent a reasonable upper limit for the impulse associated with the mechanical failure of the pressurized bottles and can be used to estimate the hazards of this mode of failure. If all of the impulse of the escaping gas is transferred to the bottle alone (rocket effect), the resultant velocity would be high enough for the bottle to constitute a hazardous missile. For example, the CSE bottle and gauge assembly weighs approximately 1,670 g (3.68 lb). An impulse of 4.7×10^6 g cm/s would produce a bottle velocity of 28.1 m/s, or in more convenient terms 92.2 ft/s.

Studies at the Lovelace Foundation (5) indicate that there is a near 100-pct probability for skull fracture resulting from the impact of a 10-lb nonpenetrating missile traveling at 23 ft/s. Since a 3.68-lb bottle traveling at 92.2 ft/s has about six times the kinetic energy of a 10-lb missile at 23 ft/s, there is little doubt that serious injury and possibly death would result from the impact of a rocketing bottle on a vulnerable part of the human body. However, since the bottles are rigidly constrained in more massive SCSR units, there is little if any chance for an encounter of this type. A somewhat more probable, albeit highly unlikely, event would be the mechanical failure of a bottle in a complete SCSR, resulting in the propulsion of the entire unit. Using the CSE unit as an example, the transfer of an impulse of 4.7×10^6 g cm/s to a complete unit which weighs approximately 11.0 lb would result in a velocity of about 31 ft/s. Referring to the Lovelace results, this too would represent a hazardous missile. However, in view of the construction of the

[8]During mechanical rupture of a bottle the total impulse would be less than that associated with bullet impact because in the latter case the escape of gas is more nearly unidirectional than in the former.

units, it is extremely doubtful that all of the momentum available in the escaping gas would be transferred to the unit because of the high likelihood of nondirected gas release, which would significantly reduce the magnitude of the momentum transferred to the unit. Thus, mechanical failure of a bottle within an isolated unit is not viewed as an event of serious consequence.

The last case to consider is the mechanical failure of a bottle within a unit while the unit was being worn. Assuming that this would happen to a 150-lb man, the maximum resultant man-unit velocity would be about 2.3 ft/s. This is equivalent to the velocity obtained by a body falling 1.0 in and is far too low to present a serious hazard. Results presented in reference (5) indicate that whole-body impacts at 10 ft/s or below are "mostly safe."

Besides the impact trials with the ballistic pendulum, some additional bullet tests were conducted on an outdoor range in order to improve photographic coverage and to obtain a better idea of the range of the missiles produced during the tests. Tests were performed on oxygen-filled bottles placed at an inclination of 45° relative to the path of the bullet and with complete units impacted at normal incidence. The tests conducted at 45° incidence resembled, to a large degree, the bullet test called for in reference (3). Most of the trials were conducted with 0.30-cal M2 ball ammunition fired from an M1 rifle at a range of about 85 ft. A few preliminary trials were conducted with 0.22-cal Hornet ammunition to test the marksmanship of a volunteer rifleman; it was not good enough for the purpose at hand so the experimental setup shown in figure 9*A* was adapted, which consisted of a stable gun mount and a velocity-measuring station downstream of the rifle barrel. For the tests at 45° incidence the bottles were strapped to an 8- by 8-in log cut to the appropriate angle as shown in figure 9*B*. For tests at normal incidence the units were strapped in place on similarly sized logs as depicted in figure 9*C*.

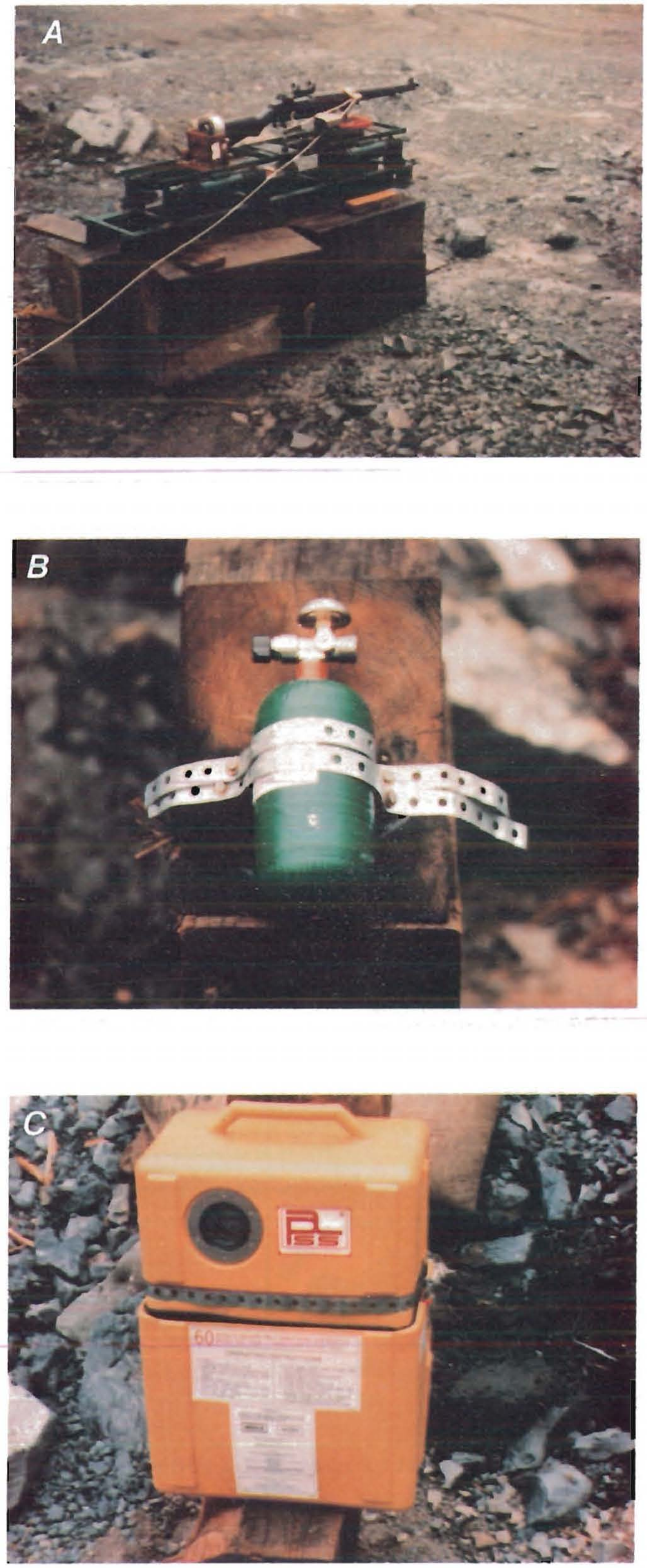

FIGURE 9. - Experimental setup used in outdoor bullet impact tests. *A*, Rifle mount and velocity station; *B*, bottle mounted at 45°; *C*, unit mounted for normal impact.

The results of the outdoor bullet impact tests are summarized in table 4, which gives the experimental configuration along with some remarks concerning each test. In general, the results were not different from those observed in the impact tests with the ballistic pendulum: violent combustion reactions were observed in all cases where the oxygen-filled bottles were perforated. Figures 10*B*, 10*C*, and 10*D* illustrate the characteristic enlargement of the bullet entrance holes in the bottles recovered from tests 46, 47, and 48; figure 10*A* is a photograph of one particularly spectacular event (test 47). The white smoke is presumably aluminum oxide resulting from the combustion of a portion of the aluminum bottle.

Strictly speaking, none of the bottles fragmented, and in this sense they presumably would have passed the bullet impact test prescribed in reference 3 since the criterion for passing this test is absence of bottle fragmentation. However, as the remarks in table 4 indicate, the tests did generate various missiles (bottles and case components) having appreciable range--up to 137 ft for the OCENCO bottle from test 47. The observed ranges of the various missiles are in

TABLE 4. - Results of bullet impact trials with bottles at 45° incidence and units at normal incidence

Test	Test item	Bullet type	Incidence	Remarks
46	CSE bottle.....	0.30-cal M2 ball...	45°......	Bottle perforated; violent combustion reaction; bottle projected 33 ft.
65	CSE unit.......	0.22-cal Hornet....	Normal...	Bullet hit valve neck, resulting in slow O_2 release and mild burning.
66	...do..........	...do..............	...do....	Bottle perforated; violent combustion reaction.
154	...do..........	0.30-cal M2 ball...	...do....	Bottle perforated; violent combustion reaction; bottle and part of case projected 90 ft; part of case 30 ft.
47	OCENCO bottle..	...do..............	45°......	Bottle perforated; violent combustion reaction; bottle projected 137 ft.
74	OCENCO unit....	...do..............	Normal...	Bottle perforated; violent combustion reaction; bottle projected 55 ft, filter 66 ft, and case 20 ft.
48	PASS bottle....	...do..............	45°......	Bottle perforated; violent combustion reaction; bottle projected 97 ft.
75	PASS unit......	...do..............	Normal...	Bottle perforated; violent combustion reaction; bottle and filter projected 15 ft, case top 15 ft, case bottom 28 ft.

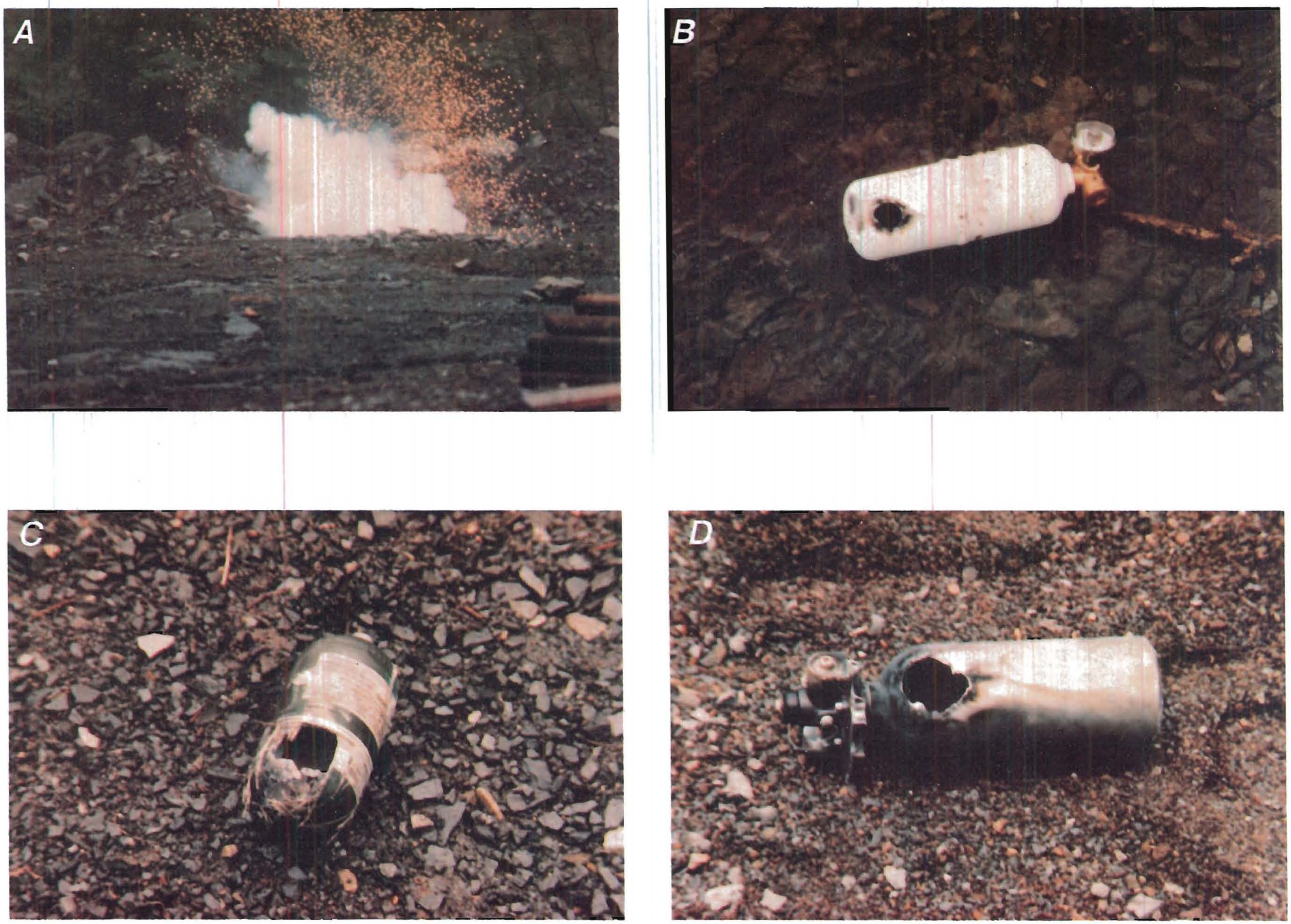

FIGURE 10. - Results of bullet impact tests. *A*, Still photograph of test 47 showing orange sparks and white cloud of aluminum oxide; *B*, CSE bottle from test 46; *C*, OCENCO bottle from test 47; *D*, PASS bottle from test 48.

good agreement with values anticipated from the results of the impulse studies previously described. For example, the impulse associated with the perforation of a CSE bottle was sufficient to produce a bottle velocity of about 92 ft/s. At low projection angles (ca. 15°) this velocity is capable of projecting the bottle 144 ft. Test 154, with a CSE unit, resulted in the projection of the bottle and part of the case to a distance of 90 ft.

DROP WEIGHT TESTS

In view of the combustion reactions observed under conditions of high-velocity impact, it was deemed necessary to determine if similar reactions could be induced at impact velocities approaching those associated with coal cutting equipment; i.e., in the range of a few tens of feet per second. For this purpose a drop weight tester was devised which consisted of a 28-in-long by 6-in-diam cylindrical steel billet weighing 231 lb, which could be dropped from heights up to 12 ft producing velocities up to 28 ft/s. A conventional coal cutting pick with a tungsten carbide tip was inserted in the lower face of the steel billet to simulate impact by coal cutting equipment. With this arrangement impact energies up to 3,770 J, corresponding to a drop from 12 ft, were available. For comparison purposes, the 0.22-cal Hornet bullet weighing 45 gr and traveling at 2,500 ft/s possesses a translational kinetic energy of 850 J. It will be recalled that this bullet was capable of penetrating one side of the CSE bottle. This same energy is available with the 231-lb drop weight falling from a height of 2.7 ft. It was therefore anticipated that the drop weight tester would be capable of penetrating all three bottles with ease. The apparatus would also provide a reasonable simulation of coal cutting equipment insofar as impact energy is concerned. For example, a 1,000-lb coal cutting drum having a diameter of 3 ft and rotating at 60 rpm has a rotational kinetic energy of 940 J, well within the capabilities of the drop weight tester.

A photograph of the lower portion of the test rig is shown in figure 11*A*. Figure 11*B* shows a bottle in a fixture ready for testing, and figure 11*C* shows a SCSR positioned to assure impact on the compressed oxygen bottle contained in the unit. In some cases, as shown in figure 11*C*, approximately 100 g of pulverized coal in a plastic pouch was positioned over the impact point in order to observe whether the impact reactions were capable of igniting dispersed coal dust clouds. The results of 25 drop weight tests are summarized in table 5, which gives the experimental configuration and the observed damage associated with the individual tests.

To simplify presentation of the data, a damage code has been introduced for describing the results of the various tests. The definitions of the degrees of damage, including those listed in table 5, follow:

Degree 1e. - Bottle perforated with violent combustion reaction.

Degree 1f. - Bottle perforated with attendant nonviolent combustion reaction.

Degree 2. - Bottle perforated and oxygen released.

Degree 3. - Valve or gauge damaged, resulting in oxygen leak.

Degree 4. - Superficial damage with no oxygen leak.

This code will be used here and throughout the remainder of the report. It will be noted that none of the drop tests listed in table 5 resulted in degree 1f or degree 3 damage; these degrees are used later in the report and are defined here for completeness.

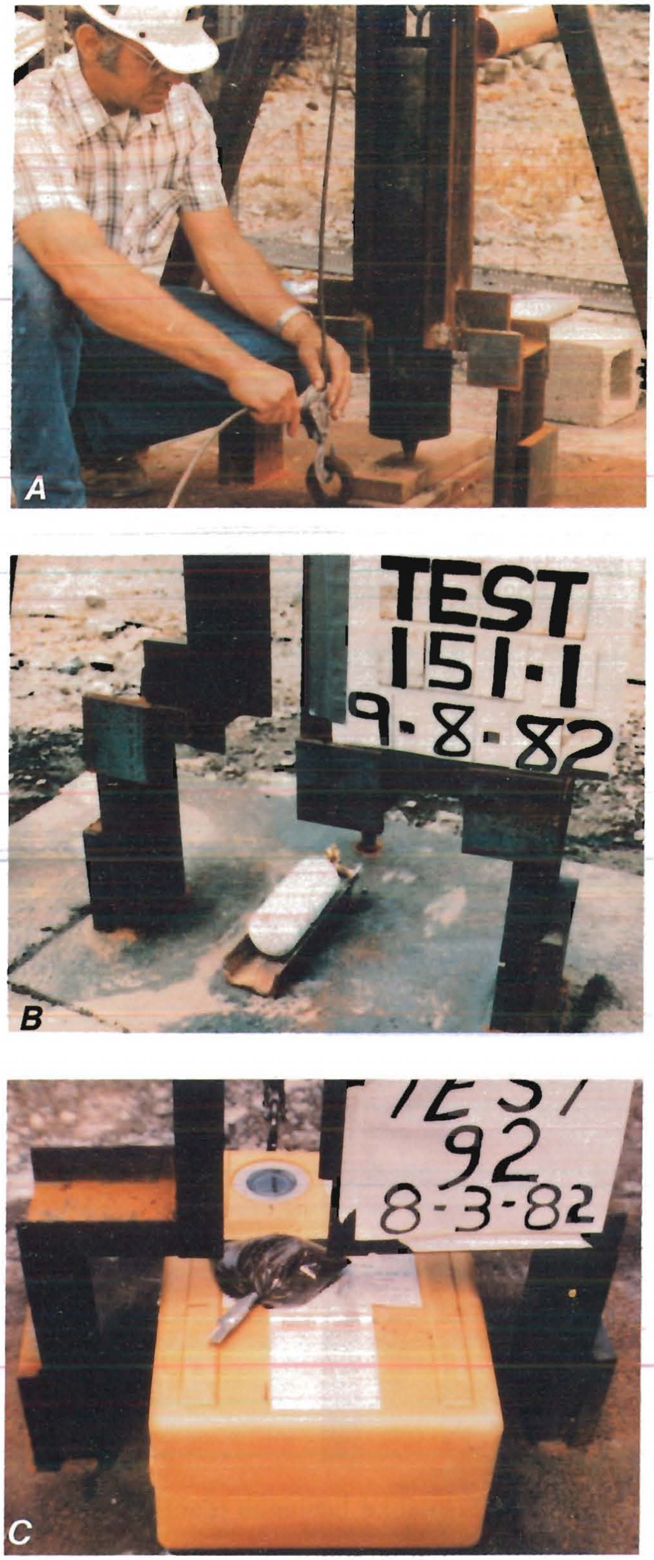

FIGURE 11. - *A*, Lower portion of drop weight tester; *B*, CSE bottle positioned for testing; *C*, PASS unit positioned to assure impact on the bottle. Plastic bag at impact point in panel *C* contains coal dust.

TABLE 5. - Summary of 231-lb drop weight trials

Test	Test configuration: Drop height, ft	Test configuration: Coal dust	Damage[1]
	CSE BOTTLE		
31	3.0	No	2
69	3.0	Yes	4
151-1	4.0	No	2
70	4.0	Yes	1e
161	6.0	No	1e
68	6.0	Yes	1e
20	12.0	No	1e
67	12.0	Yes	1e
	CSE UNIT		
94	6.0	No	2
93-2	12.0	No	1e
90	12.0	Yes	1e
	OCENCO BOTTLE		
153	1.0	No	1e (very small flame).
152	1.5	No	1e (small flame).
30	3.0	No	1e
32	3.0	No	1e
18	12.0	No	1e
	OCENCO UNIT		
185	3.0	No	1e
149-1	6.0	No	1e
91	12.0	Yes	1e
	PASS BOTTLE		
33	3.0	No	2
150	4.0	No	2
160	6.0	No	1e
34	12.0	No	1e
	PASS UNIT		
148	6.0	No	2
92	12.0	Yes	1e

[1]Damage code:
- 1e - Bottle perforated; violent combustion reaction.
- 2 - Bottle perforated; oxygen released.
- 4 - Superficial damage; no oxygen leak.

The qualitative differences between the various degrees of damage observed in the drop weight impact trials are illustrated in figure 12 through 15. Figure 12 shows selected frames from a high-speed camera sequence taken of test 93-2, which involved a 12-ft drop on a CSE unit and resulted in degree 1e damage. The unit

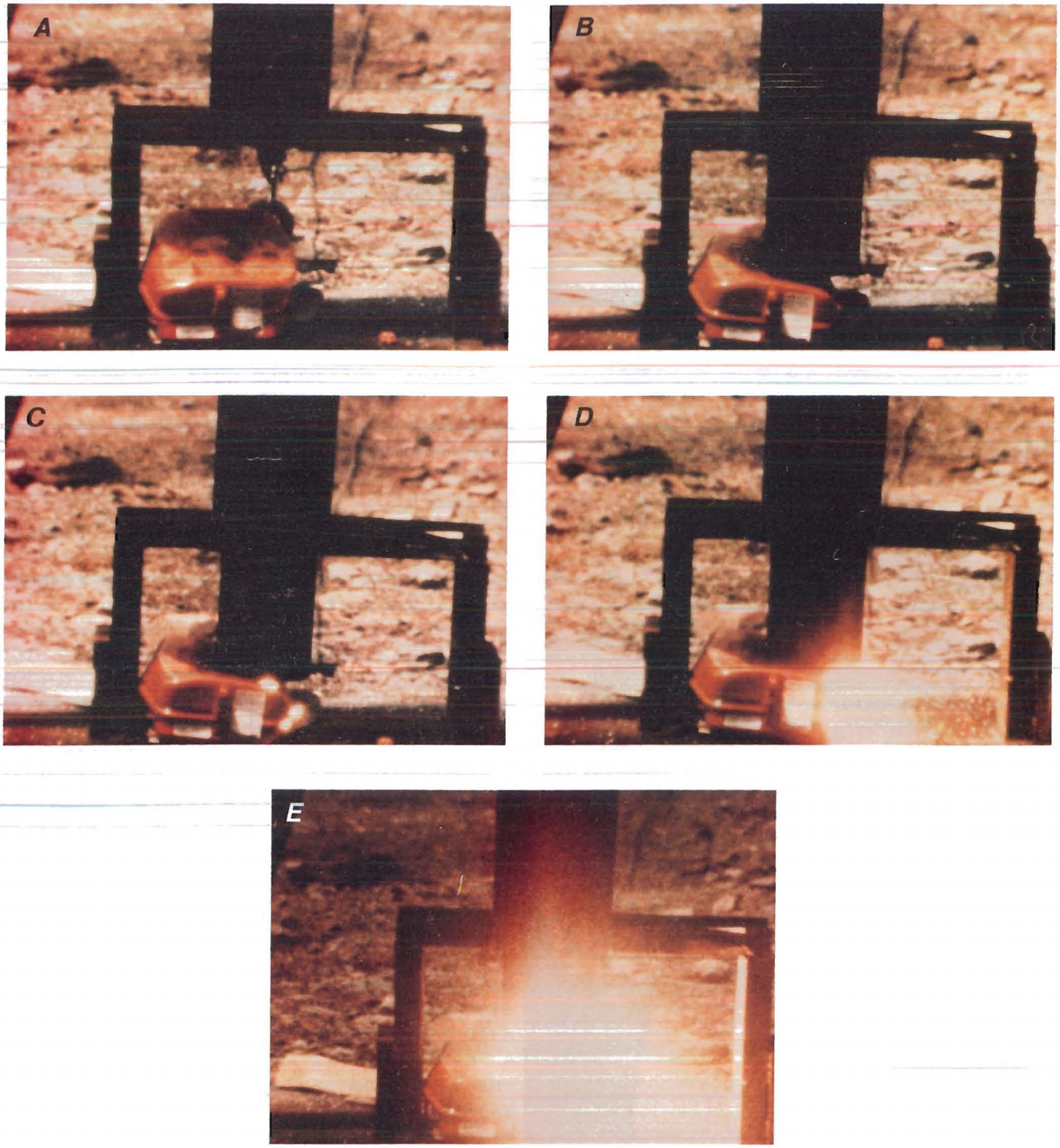

FIGURE 12. - Drop weight impact test 93-2 with a CSE unit. Intense luminous reaction starts in panel *C* and grows in panels *D* and *E*.

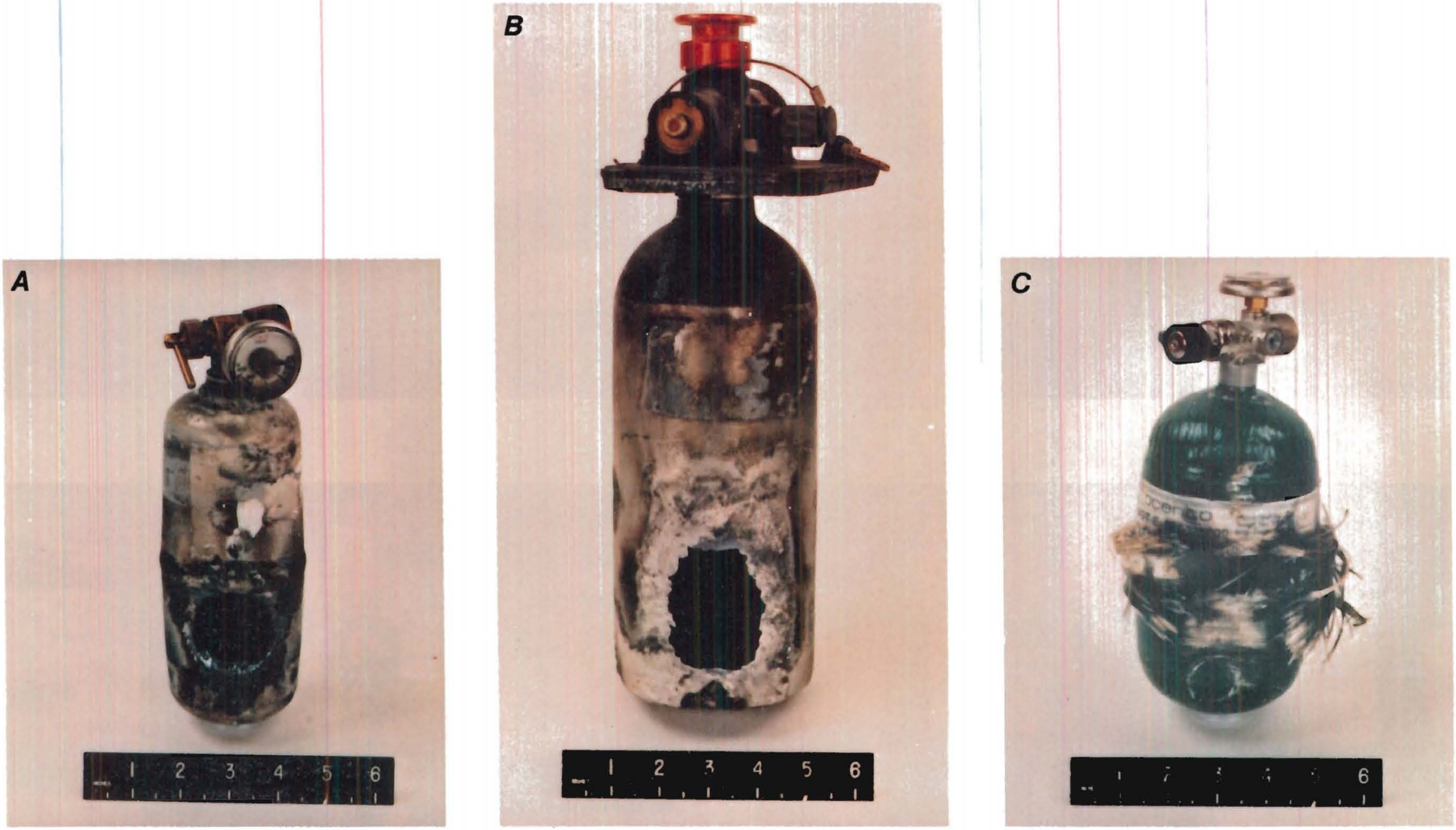

FIGURE 13. - Bottles recovered from tests (*A*) 20, (*B*) 34, and (*C*) 18, illustrating damage of degree 1e. Discoloration around perforations is characteristic of combustion reaction.

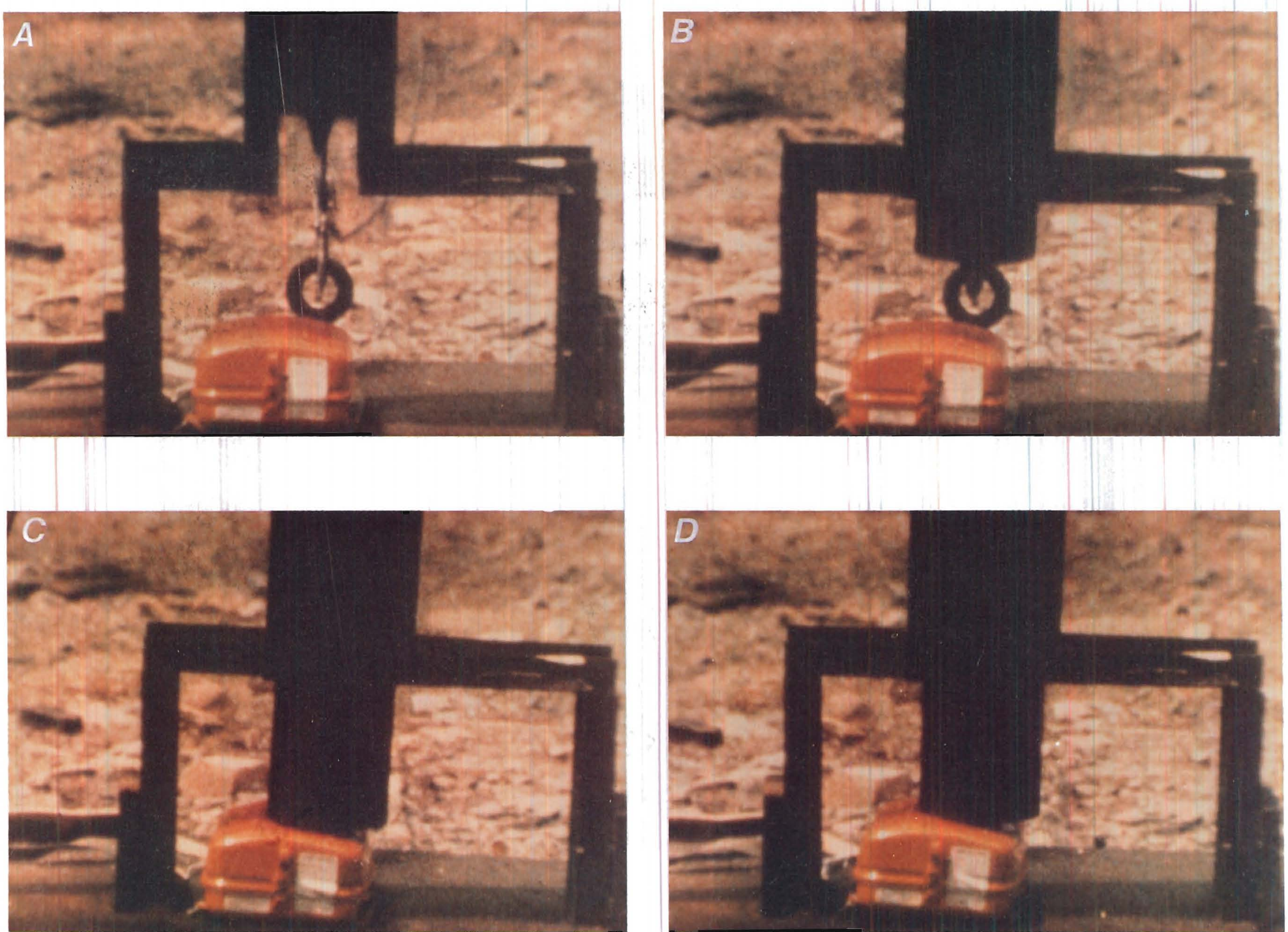

FIGURE 14. - Test 94: CSE unit showed no luminous reaction and was judged to suffer degree 2 damage.

FIGURE 15. - Bottles recovered from drop weight tests (*A*) 94, (*B*) 148, and (*C*) 69, illustrating degree 2 damage (*A*-*B*) and degree 4 damage (*C*). The puncture holes did not display any excess size or discoloration associated with an impact induced combustion reaction.

is about to be struck in panel *A* and has been impacted in panel *B*. A combustion reaction starts in panel *C* and proceeds through panels *D* and *E*.

Figure 13 shows the bottles recovered from tests 20, 34, and 18, which involved 12-ft drops on CSE, PASS, and OCENCO bottles, respectively. All three bottles show the enlarged perforations and signs of molten or burnt material characteristic of degree le damage.

Selected frames from a sequence of high-speed photographs of test 94 which resulted in degree 2 damage are shown in figure 14; the test involved a 6-ft drop on a full CSE unit. Panels *A* and *B* show the approaching drop weight, while panels *C* and *D* show the case (and bottle) being punctured. As can be seen, there was no evidence of any combustion reaction. Figure 15*A* shows the bottle recovered from test 94.

The bottle recovered from test 148, which involved a 6-ft drop on a PASS unit and also resulted in degree 2 damage, is shown in figure 15*B*. In both cases the holes are clean and relatively small in diameter, conforming with the shape of the impacting bit; there is no evidence of molten material, and based on the high-speed photographic evidence, none was expected. Figure 15*C* shows the CSE bottle recovered from test 69, which was made from a drop height of 3.0 ft and resulted in only a slight indentation in the bottle with no oxygen leak, i.e., degree 4 damage.

Having defined and illustrated the varying degrees of damage observed in the drop weight trials, we are now in a position to discuss the general findings of the experimental results in table 5. It will be noted that all units and bottles suffered degree le damage at sufficiently high impact energies (drop heights). Specifically, at a drop height of 12 ft, degree le damage was observed with all three units and bottles. It is also evident that the CSE and PASS cases afford some protection to the bottles against le damage. This is based on the observation that at a drop height of 6 ft the CSE and PASS units suffered only degree 2 damage, whereas the bottles from the units suffered degree le damage in tests from the same drop height. Intuitively, one would expect the same thing to be true of the OCENCO unit, but there is insufficient data to support this conclusion. However, the data clearly indicate that the drop height for producing degree le damage with the OCENCO bottle (or unit) is significantly lower than that required to produce equivalent damage to the CSE or PASS bottles (or units). With the OCENCO bottle, degree le damage was observed at heights as low as 1 ft, whereas with the CSE and PASS bottles the threshold height for a le event appears to be between 4 and 6 ft if the result of test 70, which was augmented with coal dust, is discounted.

It is instructive to calculate the energies and velocities associated with the threshold conditions for degree le damage. After dropping 1 ft, the approximate threshold for the OCENCO bottle, the 231-lb weight has a velocity of about 8 ft/s and a kinetic energy of 313 J. Drops from a height of 5 ft, which is the approximate threshold for the CSE and PASS bottles, result in a velocity of 17.9 fps and a kinetic energy of 1,564 J. For comparison, a 1,000-lb cutting drum having a diameter of 3.0 ft and a rotational velocity of 60 rpm has a peripheral speed of 9.4 ft/s and as previously mentioned a rotational kinetic energy of 940 J. It would thus appear that at least some of the bottles could be perforated by coal cutting equipment, possibly resulting in degree le damage.

Another interesting feature of the data in table 5 is the fact that the threshold height for bottle perforation without reaction (degree 2 damage) for the CSE bottle appears to be about 3 ft. This corresponds to a kinetic energy of 941 J, about the same energy as for the 0.22-cal Hornet bullet (850 J), which was capable of penetrating one side of the CSE bottle, a near-threshold condition. This adds some credence to the speculation, which was based on relative energetics, concerning the ability of coal cutting equipment to perforate the bottles.

One final feature of the data of table 5 that deserves mention is the results of the tests where coal dust was placed over the point of impact. This was done to determine if the impact reactions had the capability of igniting a coal dust cloud dispersed at the moment of impact. An examination of figure 16, which shows selected frames from a sequence of high-speed photographs of test 92, indicates that a significant portion, if not all, of the coal dust is ignited by the combustion reaction associated with bottle perforation. This is not suprising since the energy required to ignite *predispersed* coal dust is estimated to be about 0.06 J, which is orders of magnitude less than the previously deduced values of thermal energy associated with the combustion reactions.

FRANGIBLE DISC FAILURE TESTS

At this point in the test program there were reports of several incidents involving the accidental failure of the frangible discs on SCSR's purchased for mine use. The discs are ordinarily designed to burst at about 1.3 to 1.5 times the operating pressure of the bottle. The field reports concerning disc failure were not detailed enough to learn whether there were any real safety problems involved. Since the oxygen release rate through the disc orifice was expected to be lower than that associated with bottle rupture, which was determined to be a marginal safety problem, no real problem resulting from disc failure was anticipated. Nevertheless, several tests were performed to determine the course of events resulting from disc failure on bottles contained in complete SCSR's.

For this purpose a bottle from each of the three SCSR's under investigation was equipped with a high-pressure fitting, carefully repacked into the SCSR, and gradually filled with compressed air until the frangible disc ruptured. Observations were made on the behavior of the units when the disc failed.

The first test, performed with a PASS unit, resulted in disc failure at approximately 2,930 psig internal bottle pressure. This is about 1.5 times the operating pressure of the PASS bottle (2000 psig). When the disc ruptured, the seal provided by the rubber gasket that joins the two portions of the exterior case failed, allowing the release of oxygen; no physical movement of the unit, which was lightly constrained by the high-pressure tubing used to fill the bottle, was detected.

The second test was conducted with an OCENCO unit. In this case the disc failed at 4,470 psig, which is about 1.5 times the operating pressure of 3,000 psig; disc rupture resulted in gasket failure very much like that observed in the test with the PASS unit. Again, there was no physical movement of the unit.

The third and last test was conducted with a CSE unit. Disc failure occurred at 4,850 psig, which is about 1.4 times the operating pressure of 3,500 psig; the buildup of pressure within the sealed case sheared the rivets that hold the lid clamp, and the top of the case was blown off. It landed some 5 ft from the test stand and was not judged to have sufficient velocity to pose a serious threat to a person nearby. Thus none of the tests indicated that accidental failure of the pressure relief devices within the SCSR's represented any serious hazard to man.

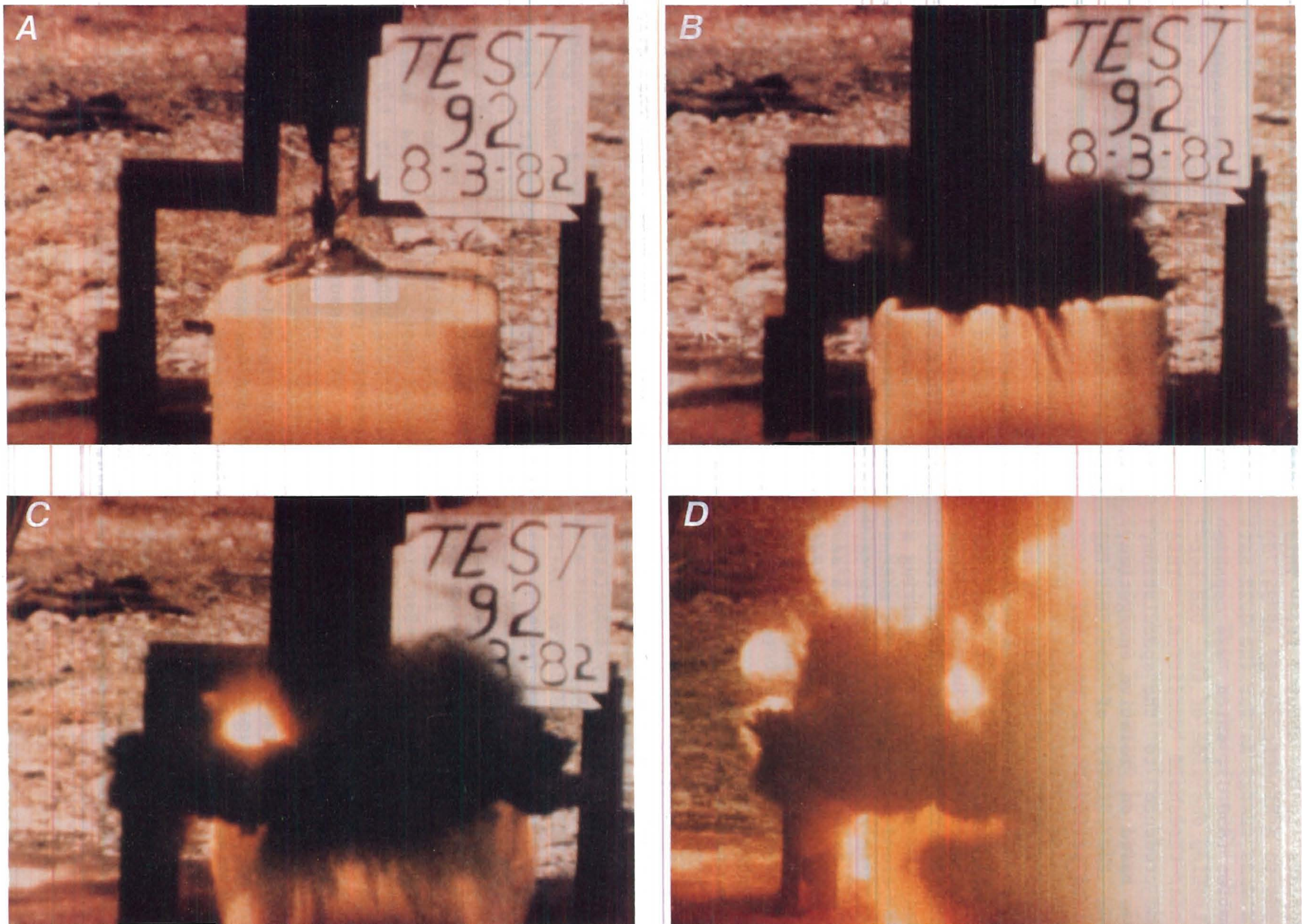

FIGURE 16. - Drop weight test 92 with a PASS unit showing ignition of added coal dust. The black cloud in panel *B* is coal dust dispersed at impact, which ignites in panels *C* and *D*.

EVALUATION OF IN-MINE HAZARDS

While the bonfire, projectile, and drop-weight impact studies were of enormous value in determining the potential fire and explosion hazards of compressed oxygen self-rescuers under extreme conditions, the projectile and drop weight experiments did not represent creditable in-mine accident scenarios. To obtain a more balanced picture of the potential hazards of the devices in a working mine environment, a number of additional tests of a more practical nature were conducted. These included simulations of mine roof fall and encounters with typical mining equipment, including coal cutting machinery. The results of these experiments will be discussed in the remaining sections of the report.

SIMULATED ROOF FALL

To determine the possible hazards associated with compressed oxygen SCSR's exposed to rooffall, a series of tests was conducted with bottles and full units exposed to the impact of a 1,000-lb cubical block of reinforced concrete dropped from a height of 6.0 ft. Previous work (1) had established that this test configuration represented a fair simulation of a massive roof fall. A few preliminary tests with oxygen-filled bottles alone were conducted with the bottles lying on a wood surface designed to protect the floor of the test chamber. Having ascertained that the impacts would not produce missiles hazardous to the personnel conducting the experiments, the main tests were moved outdoors to facilitate photographic coverage.

Three basic test configurations were used throughout the simulated roof fall experiments; they are illustrated in figures 17*A*, *B* and *C*. Tests were made with the units lying flat (17*A*) or in an upright position (17*B*). Tests were also made with a rock shard affixed to the bottom of the block (17*C*). In this case the units were in the flat position. A clear view of the shard, which was affixed to the block with roof-bolt resin, is shown in figure 17*D*. In all cases the drops were made with the lower edge of the block positioned 6 ft above the rock floor of the test arena.

The experimental results from 7 indoor tests and 10 tests conducted outdoors are summarized in table 6 in terms of the observed degree of damage. Typical damage to the units is further illustrated in figure 18; panels *A*, *B*, and *C* represent "flat" impacts; *D*, *E*, and *F* are from tests in the upright position; and *G*, *H*, and *I* show units recovered from impacts with the rock shard attached to the block.

TABLE 6. - Summary of simulated roof fall trials

Test	Test configuration			Damage[1]
	Surface	Block	Unit	
		CSE BOTTLE		
36	Wood...	Flat...	Flat...	3
		CSE UNIT		
39	Wood...	Flat...	Flat...	3
105	Rock...	..do...	..do...	3
108	..do...	..do...	Upright	3
112	..do...	Pointed	Flat...	3
114	..do...	..do...	..do...	3
		OCENCO BOTTLE		
37	Wood...	Flat...	Flat...	3
		OCENCO UNIT		
40	Wood...	Flat...	Flat...	3
106	Rock...	..do...	..do...	3
109	..do...	..do...	Upright	3
111	..do...	Pointed	Flat...	le
		PASS BOTTLE		
38	Wood...	Flat...	Flat...	3
41	..do...	..do...	..do...	4
41-1	..do...	..do...	..do...	3
		PASS UNIT		
107	Rock...	Flat...	Flat...	4
110	..do...	..do...	Upright	3
113	..do...	Pointed	Flat...	3

[1] Damage code:
- le - Bottle perforated; violent combustion reaction.
- 3 - Valve or gauge damaged; oxygen leak.
- 4 - Superficial damage; no oxygen leak.

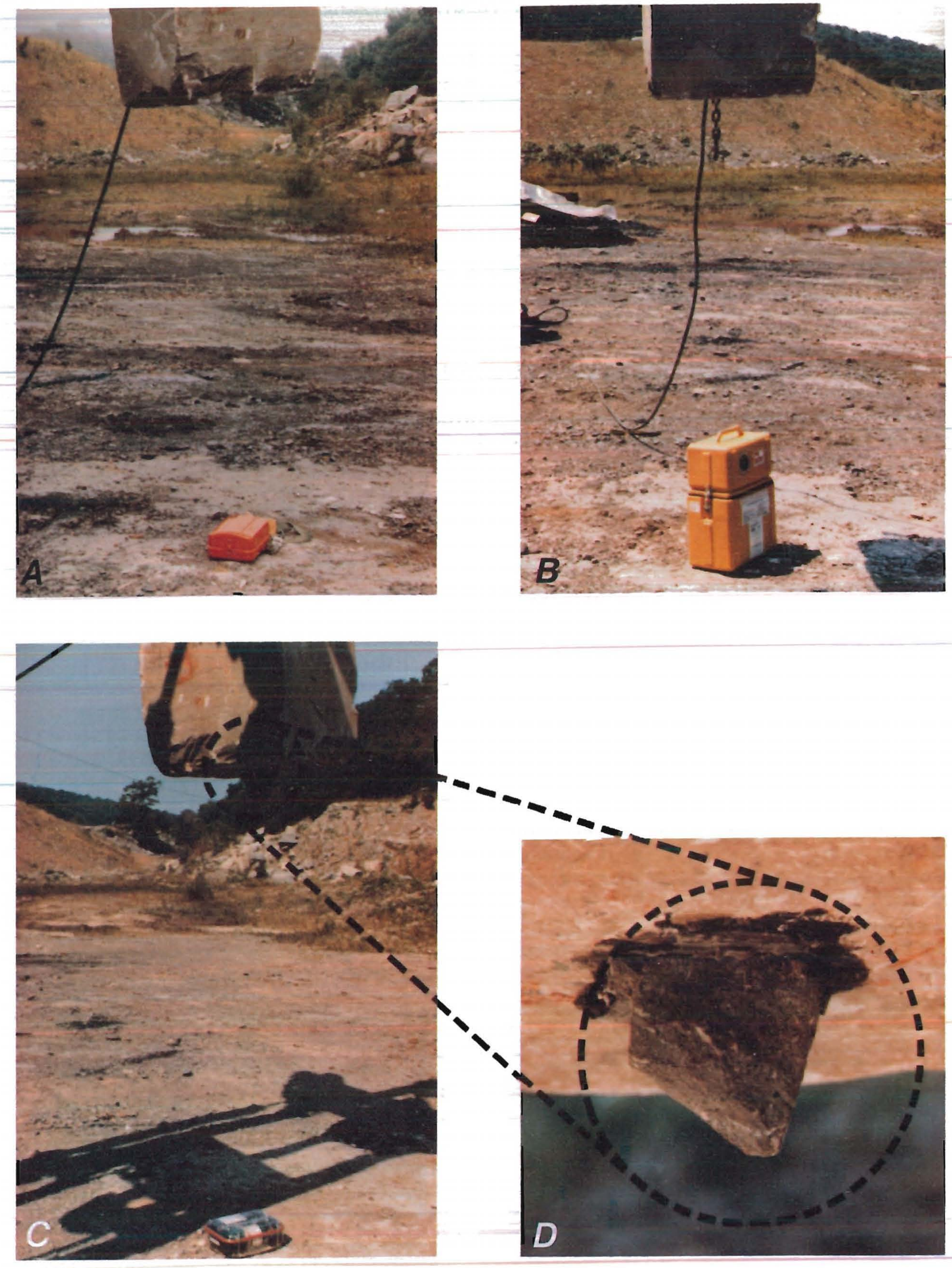

FIGURE 17. - Test configurations used in simulated roof fall trials. The dark brown rock shard in panel *D* was affixed to the bottom of the block in panel *C* with roof bolt resin.

FIGURE 18. - Damage resulting from simulated roof falls with units in the flat position (*A-C*); units in the upright position (*D-F*); and units in the flat position with the rock shard (*G-I*). The rock shard which detached itself from the concrete block is embedded in the orange CSE case in panel *G*.

In all, the bottles and units withstood the rigors of the simulated roof fall rather well. Most of the observed damage fell into the degree 3 category with a damaged valve or gauge leading to the relatively slow release of oxygen. The PASS bottle and unit faired extremely well, suffering only degree 4 damage in two out of six trials and degree 3 in the other four tests. The rugged case undoubtedly contributes to the low level of damage noted here.

In one test (test 111) with "pointed" impact on an OCENCO unit, damage of degree le was observed. The high-speed photographs presented in figure 19 show that this was not a particularly violent event. For comparison purposes a series of high-speed photographs from test 113, which resulted in degree 3 damage to a PASS unit, is presented in figure 20.

The overall conclusion from this series of tests was that a combustion reaction associated with bottle failure could possibly result from roof fall, but that such an event was unlikely.

FEEDER-BREAKER IMPACT TRIALS

As was indicated in the previous hazards evaluation (1), the appearance of a self-rescuer in a feeder-breaker is considered to be a realistic mine accident scenario. Since the drop weight impact test suggested that the compressed oxygen self-rescuers were not immune to puncture by coal cutting equipment, a feeder-breaker was obtained for exploring this possibility. The unit obtained was a Long-Airdox Model MFBM-40 feeder-breaker equipped with a chain conveyor and a rotating head containing 24 cutting bits tipped with tungsten carbide. The bits rotated in a circle having a 15-in diameter; normal operating speed for the head was 60 rpm. The unit is shown in figure 21A along with some of the instrumentation used to document the tests. A closeup view of the cutting head is shown in figure 21B. Feeder-breaker impact tests were conducted with compressed oxygen bottles as well as with complete self-rescuers under a number of different experimental conditions which were basically variations of the same theme.

The initial tests were done with oxygen-filled bottles alone to determine if the Long-Airdox unit was capable of penetrating the bottles. For this purpose the bottles were rigidly positioned on the floor pan of the feeder-breaker in a position directly beneath a pick in order to guarantee a direct hit when the machine was turned on. This was ordinarily accomplished by laying the bottle in a short length of channel iron as shown in figure *22A*. In other cases, the bottles were simply placed on a coalbed beneath a pick and allowed to freely move when struck. This is referred to as a "free" configuration as opposed to the "fixed" configuration and is illustrated in figure *22B*.

Another variation was in the distance the pick travelled before impacting the bottle. In most cases this distance was 3 to 5 in, depending on the bottle dimensions and the exact position of the bottle. However, for a few of the tests, three of the four bits on a bit set were removed in order to allow the remaining bit to transverse a longer arc (~30 in) before impacting the bottle. This allows the machine a longer time to come up to speed, thus intensifying the impact. The bit set with three picks removed is the fourth one from the left in figure 22C.

Another approach to maximizing the intensity of the impacts available with the feeder-breaker consisted of locking the pistons that support the rotary breaker, which ordinarily "floats" over the coal being processed. This was done in a number of trials and is referred to as a "locked" breaker assembly to distinguish it from the "free" floating configuration.

In some cases the bottles were clean (fig. 22A); in others a liberal quantity of pulverized coal was sprinkled over them in order to determine if coal dust ignitions occurred. A dust-covered bottle is located under the modified bit set in figure 22C.

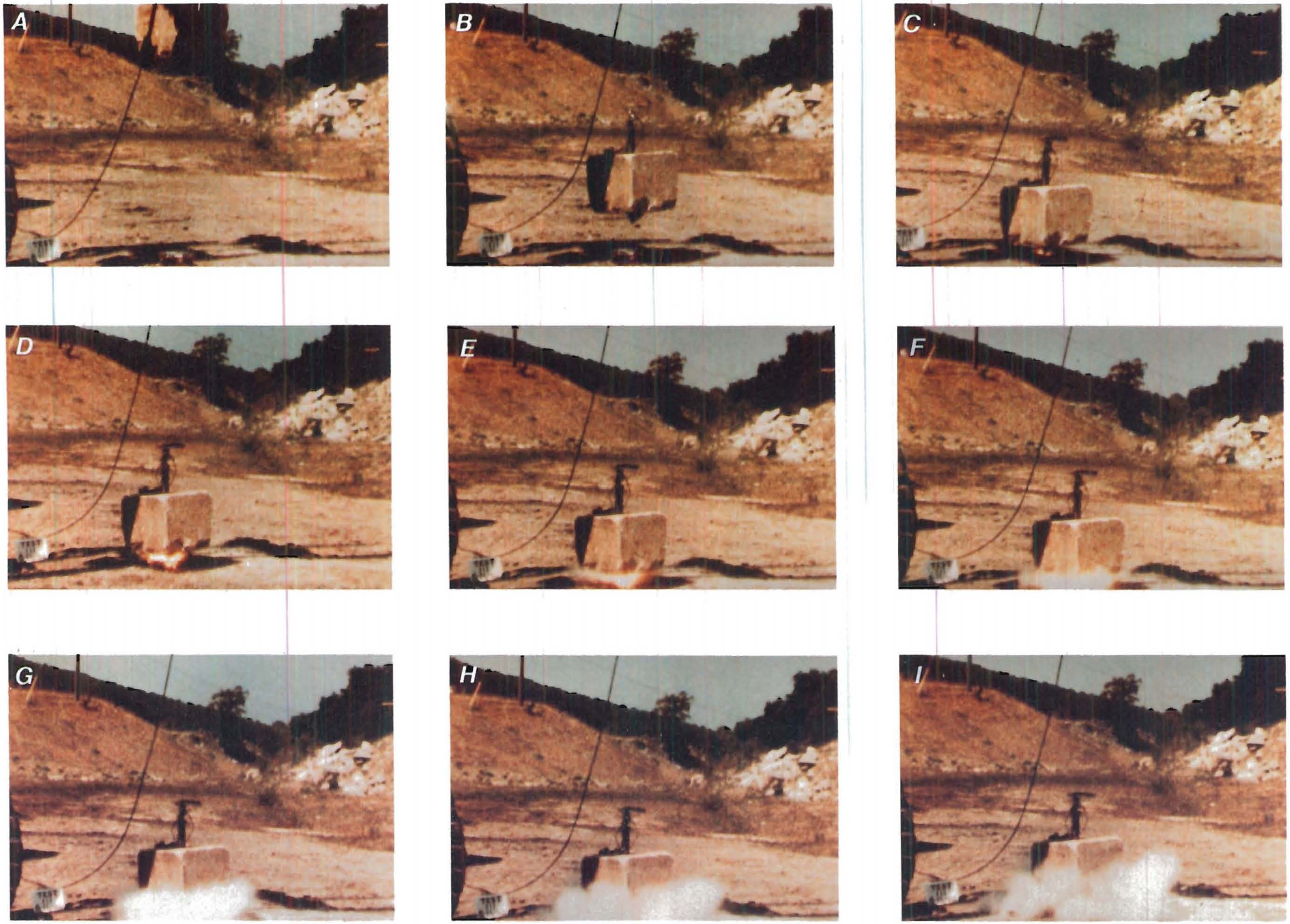

FIGURE 19. - Simulated roof fall test 111 with an OCENCO unit which resulted in damage of degree 1e. The luminous combustion reaction characteristic of 1e damage was first observed in panel *C*.

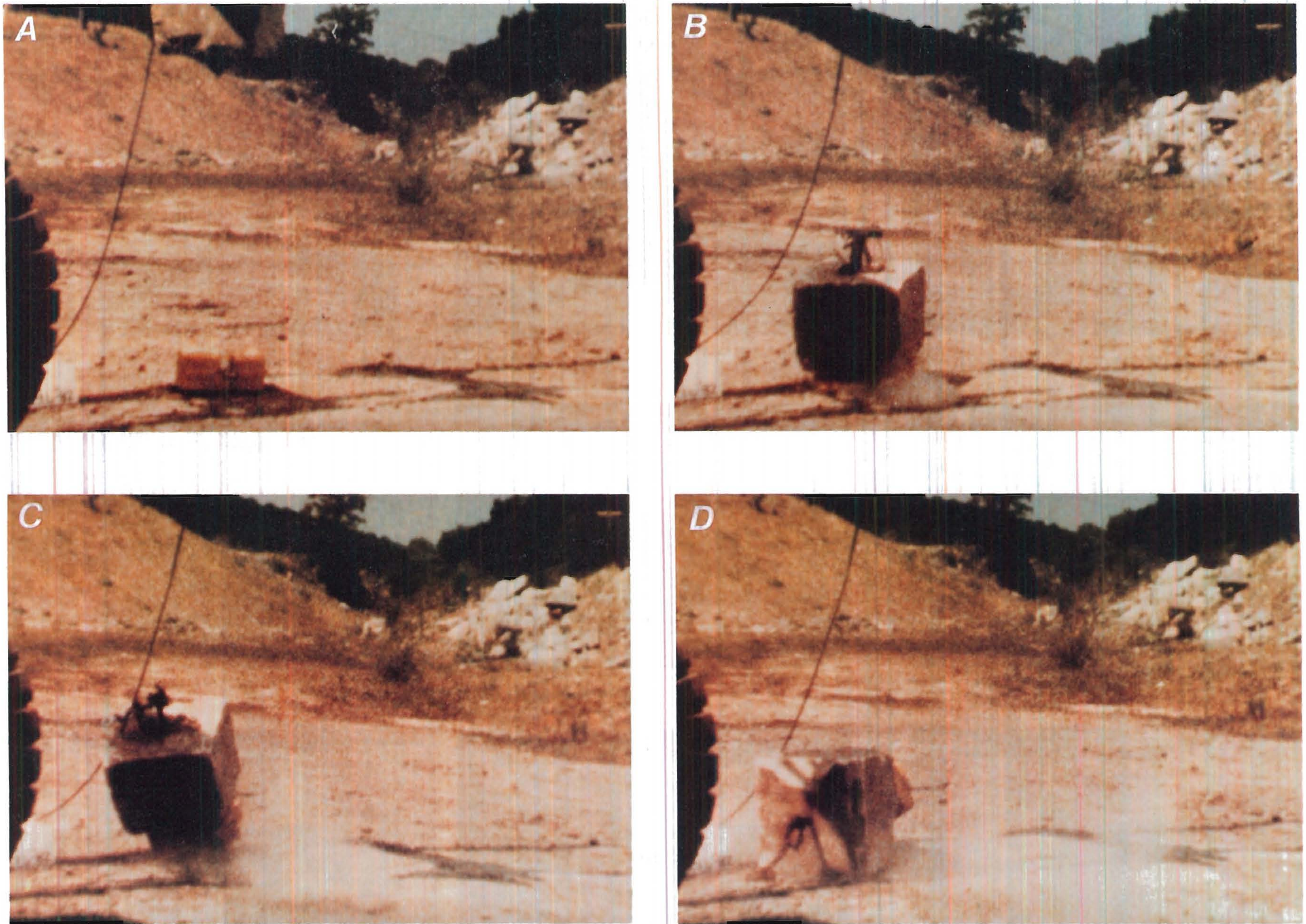

FIGURE 20. - Simulated roof fall test 113 with a PASS unit which resulted in damage of degree 3. While a white dust cloud was observed shortly after impact, there was no evidence of a combustion reaction.

FIGURE 21. - *A*, Long-Airdox feeder-breaker; *B*, cutting head showing picks tipped with tungsten carbide.

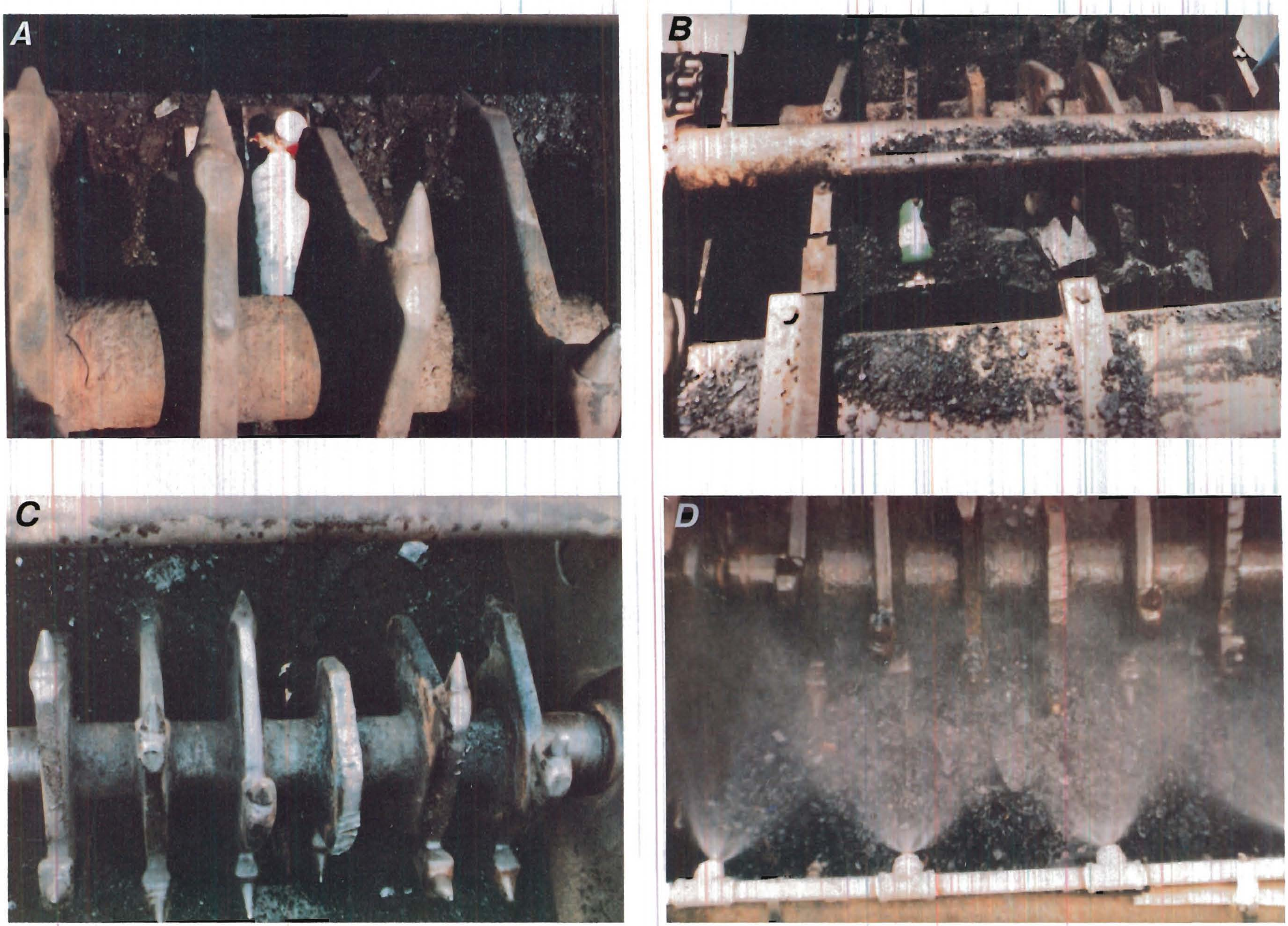

FIGURE 22. - *A*, White CSE bottle in "fixed" position; *B*, green PASS bottle in "free" position; *C*, arrangements for long bit traverse; *D*, water spray system.

A few tests were also performed with a simple water spray system mounted directly over the rotary breaker assembly. The system, shown in figure 22*D*, consisted of four spray nozzles (Spraying System Type BD3) fed by a 1.0-in water line operating at 40 psig. The total water flow rate was about 2.5 gpm, which is typical for spray systems on feeder-breakers. The water sprays were added in an attempt to determine the effect of water on the frequency and intensity of impact reactions.

With the exception of the long bit transverse, the same experimental variations were used in tests run with complete units; table 7 summarizes the results of some 80 impact experiments with bottles and units in the feeder-breaker.

First, it was discovered that all of the bottles could be punctured by the feeder-breaker picks in situations where the pick arc was 30 in and the bottles were held in the fixed position. This occurred in tests 59, 64, and 60 with CSE, OCENCO, and PASS bottles, respectively. In addition, bottle puncture occurred with shorter pick travel with the OCENCO bottle (test 56) and the PASS bottle (tests 57 and 188) held in the fixed position. This is in keeping with the discussion of the results of the 231-lb drop weight experiments, where it was anticipated that at least some of the bottles could be punctured by coal cutting equipment. The OCENCO bottle suffered degree 1e damage in both test 56 and test 64, while the CSE and PASS bottles only suffered degree 2 damage.

Trials resulting in degree 1e damage were fairly spectacular, especially if coal dust was present. This is illustrated in figure 23, which shows a sequence of photographs of test 64. Since the combustion reactions involving the bottle material are very intense (brilliant white light) and fairly localized, it is obvious that a significant amount of the added coal dust was involved in the event depicted in figure 23. For comparison purposes, high-speed photographs from test 57, which resulted in degree 2 damage to a PASS bottle, are presented in figure 24. The whitish cloud which starts to develop in frame *E* of figure 24 is condensed moisture resulting from the rapid cooling effect of the oxygen release.

An important feature of the data in table 7 is the fact that when the bottles were in the free position during impact there were no instances of bottle puncture. In 10 tests with a CSE bottle (116-1 through 116-10) only degree 3 damage was observed. (To conserve material the same bottle was repeatedly impacted in order to estimate the probability of puncture). Eleven trials with an OCENCO bottle (115-1 through 115-11) resulted in degree 4 damage, and 10 tests with a PASS bottle (117-1 through 117-10) resulted in degree 3 damage. Thus, it would appear that unless the bottles are held by some artificial means the probability of impact puncture in the feeder-breaker is low even when the bottles are in a position that guarantees a direct hit.

Examples of the damage inflicted on the bottles in the feeder-breaker impact trials are illustrated in figure 25. The OCENCO bottle from test 56 which resulted in degree 1e damage is shown in figure 25*A*; the PASS bottle from test 57 which suffered degree 2 damage is shown in figure 25*B*. The CSE bottle from test 116 (1-10) and the OCENCO bottle from test 115 (1-11) are shown in figures 25*C* and *D*. The pictures were taken after 10 impacts on the CSE bottle which led to degree 3 damage and 11 impacts on the OCENCO bottle which resulted in degree 4 damage.

Turning to the test results with SCSR units, it was observed that the feeder-breaker was capable of puncturing the bottles within the units provided that the units were held in the "fixed position".[9] Bottle punctures occurred in test 97 with a CSE unit; in tests 79, 80, 96, 102, and 186 with OCENCO units; and

[9]The units were fixed by placing them on the bare floor pan of the feeder-breaker, directly under a pick to assure a direct hit on the bottle, and wedging them with lumps of coal to prevent easy movement.

TABLE 7. - Summary of feeder-breaker impact trials

Test	Pick travel, in	Test configuration: Cutter bar	Item	Coal dust	Water spray	Damage[1]
			CSE BOTTLE			
58	5	Free.........	Fixed.........	Yes........	No..........	4
59	30	Fixed........	...do.........	Yes........	No..........	2
116 (1-10)	5	Free.........	Free.........	No.........	No..........	3
			CSE UNIT			
81	3	Fixed........	Fixed.........	Yes........	No..........	3
83	3	...do........	...do.........	Yes........	No..........	4
97	3	...do........	...do.........	Yes........	No..........	1e
103	3	...do........	...do.........	No.........	Yes.........	4
137	3	...do........	Free..........	No.........	No..........	3
138	3	...do........	...do.........	No.........	No..........	3
139	3	...do........	...do.........	No.........	No..........	4
141	3	...do........	...do.........	No.........	No..........	3
142	3	...do........	...do.........	No.........	No..........	4
			OCENCO BOTTLE			
56	5	Fixed........	Fixed.........	Yes........	No..........	1e
64	30	...do........	...do.........	Yes........	No..........	1e
115 (1-11)		Free.........	Free..........	No.........	No..........	4
			OCENCO UNIT			
79	5	Fixed........	Fixed.........	Yes........	No..........	1e
80	5	...do........	...do.........	Yes........	No..........	1e
96	5	...do........	...do.........	Yes........	No..........	1e
102	5	...do........	...do.........	No.........	Yes.........	1e
186	5	...do........	...do.........	No.........	No..........	1e
133-1	3	...do........	Free..........	No.........	No..........	4
134	3	...do........	...do.........	No.........	No..........	4
134-1	3	...do........	...do.........	No.........	No..........	4
135	3	...do........	...do.........	No.........	No..........	3
136	3	...do........	...do.........	No.........	No..........	4
140	3	...do........	...do.........	No.........	No..........	4
			PASS BOTTLE			
57	4	Free.........	Fixed.........	Yes........	No..........	2
60	30	...do........	...do.........	Yes........	No..........	2
188	4	...do........	...do.........	No.........	No..........	2
117 (1-10)	4	...do........	Free..........	No.........	No..........	3
			PASS UNIT			
86	3	Fixed........	Fixed.........	Yes........	No..........	4
95	3	Free.........	...do.........	Yes........	No..........	4
101	3	...do........	...do.........	No.........	Yes.........	4
187	3	...do........	...do.........	No.........	No..........	2
143	3	...do........	Free..........	No.........	No..........	4
144	3	...do........	...do.........	No.........	No..........	4
145	3	...do........	...do.........	No.........	No..........	3
146	3	...do........	...do.........	No.........	No..........	4
147	3	...do........	...do.........	No.........	No..........	2

[1] Damage code:
- 1e - Bottle perforated; violent combustion reaction.
- 2 - Bottle perforated; oxygen released.
- 3 - Valve or gauge damaged; oxygen leak.
- 4 - Superficial damage; no oxygen leak.

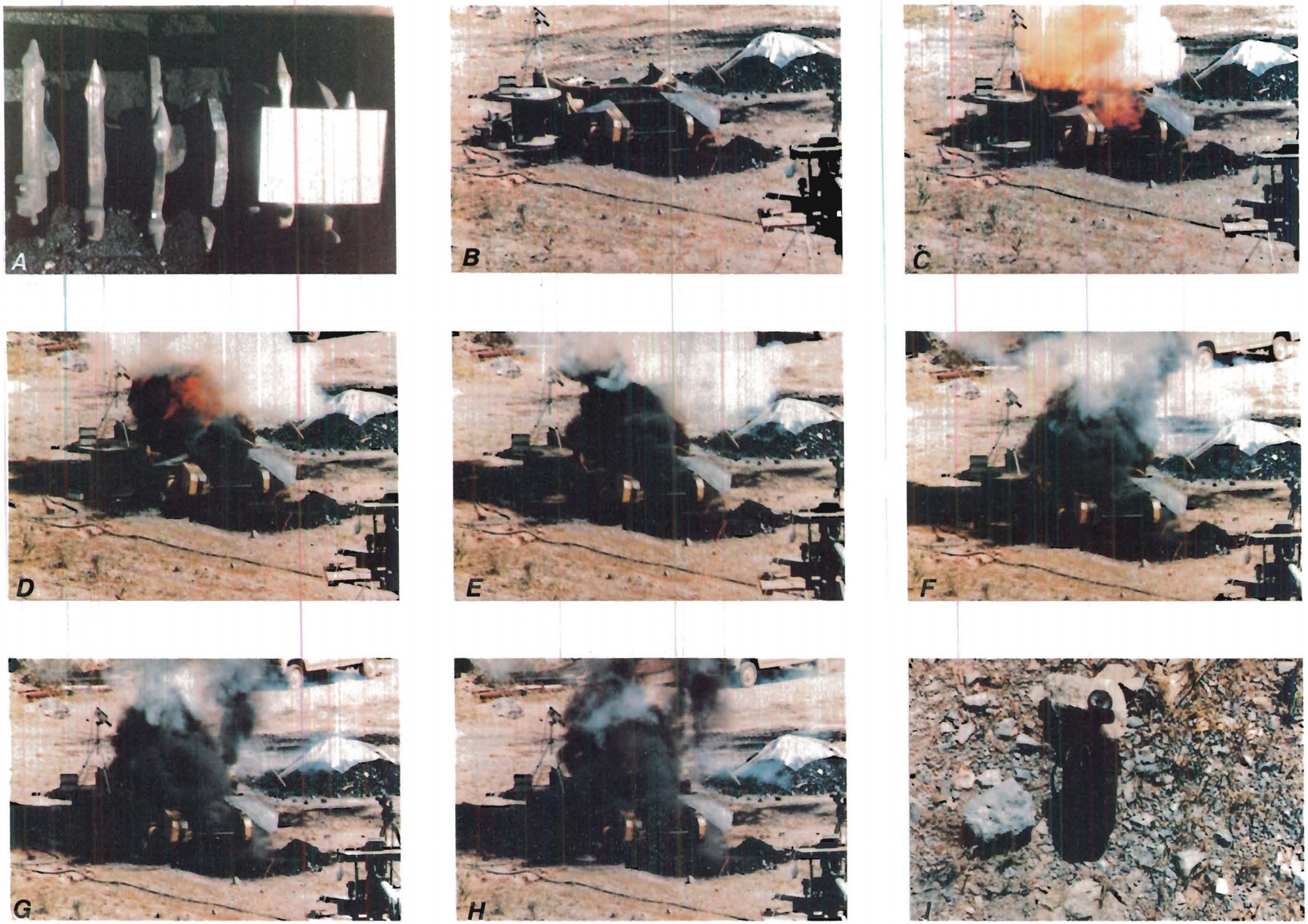

FIGURE 23. - Feeder-breaker impact test 64 with an OCENCO bottle which resulted in damage of degree 1e. Flame is clearly visible in panels *C* and *D* but is barely perceptible in panel *E*.

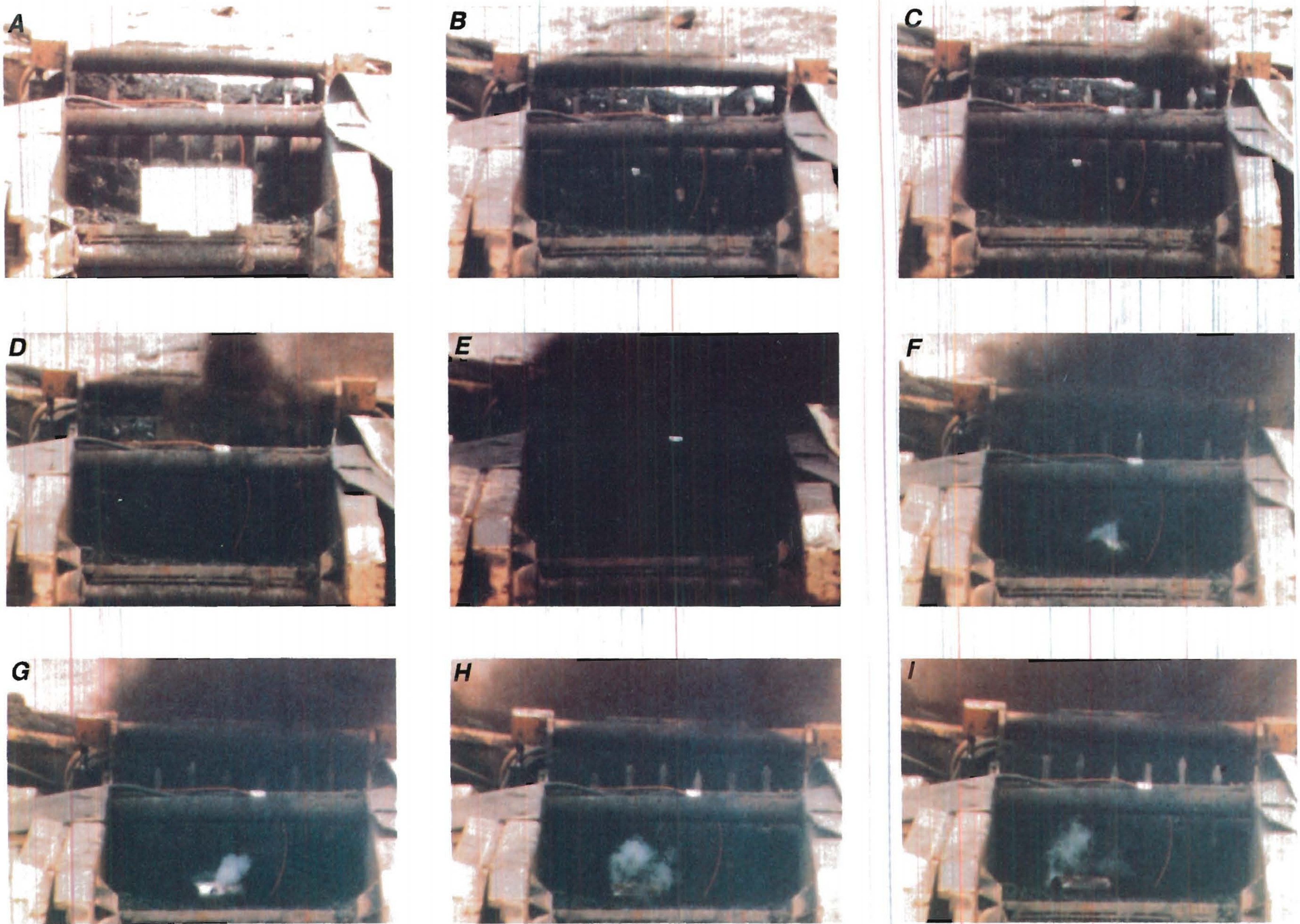

FIGURE 24. - Feeder-breaker impact test 57 with a PASS bottle which resulted in damage of degree 2. Black coal dust cloud associated with bottle puncture is seen in panel *C*, and white vapor cloud associated with cooling effect of oxygen release forms in panel *F*.

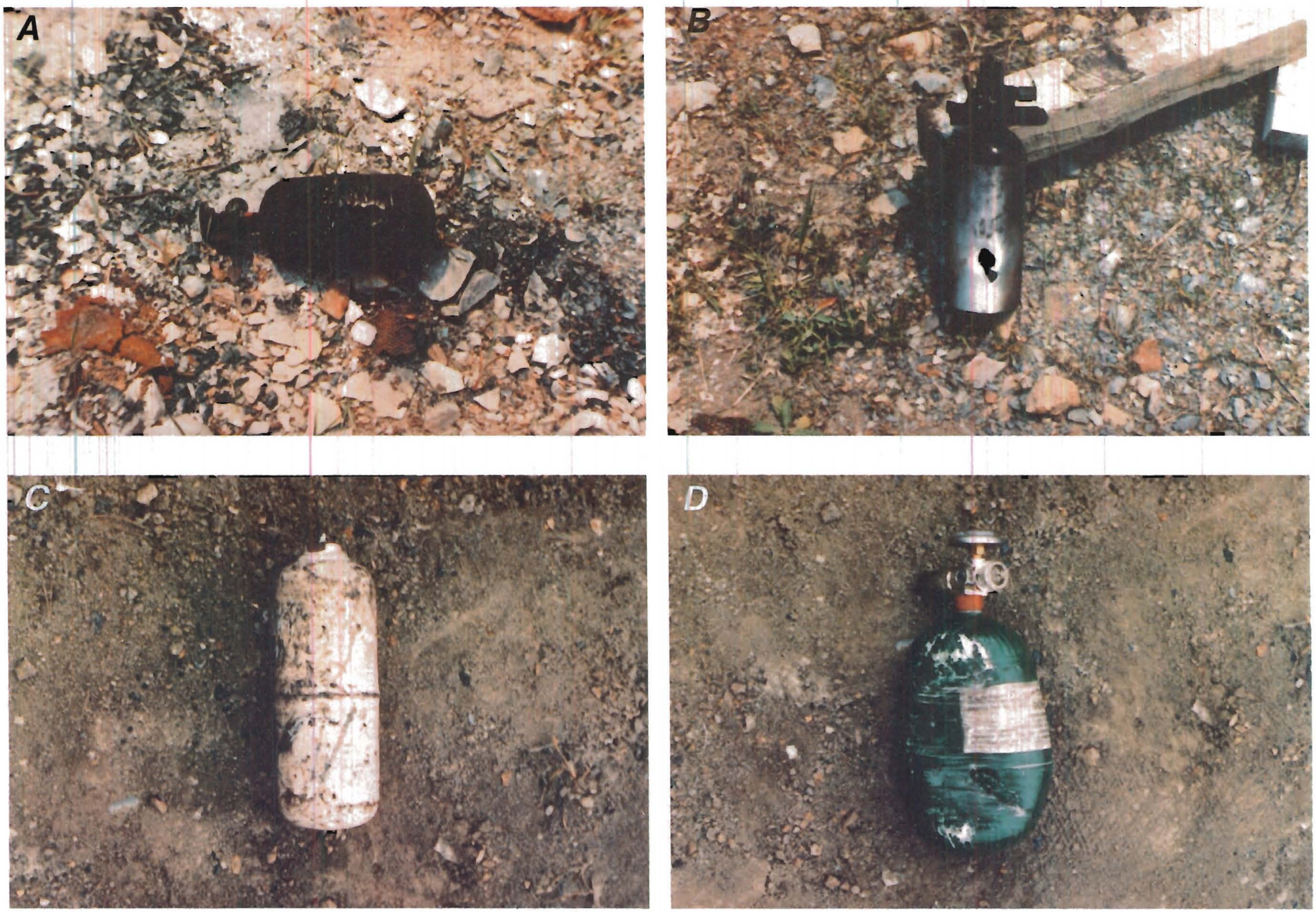

FIGURE 25. - Bottle damage resulting from feeder-breaker impacts. *A*, Flame-blackened OCENCO bottle from test 56, degree 1e; *B*, punctured PASS bottle from test 57, degree 2; *C*, CSE bottle with missing valve assembly, degree 3; *D*, dented but otherwise undamaged OCENCO bottle, degree 4.

in test 187 with a PASS unit. Combustion reactions (degree le damage) were observed in test 97 with the CSE unit and in all five tests with the OCENCO unit. No reaction was observed in test 187 with the PASS unit.

The combustion reactions associated with impact puncture of the bottles within SCSR units resembled to a large degree those observed with bottles alone. This is illustrated in figure 26, which shows selected frames from a high-speed motion picture sequence of test 97 which involved a CSE unit with added coal dust. For comparison purposes, scenes from test 187, which resulted in bottle puncture but no combustion reaction, are presented in figure 27.

As was the case with feeder-breaker impacts on bottles in the "fixed" position, impacts on fixed units represent very severe (and somewhat artificial) test conditions inasmuch as bottle puncture was observed in 7 out of 13 trials. When the units were freely positioned on a layer of coal beneath a pick to assure impact on the bottle and yet allow for natural movement, only 1 impact puncture was observed in a total of 16 trials. This occurred in test 147 with a PASS unit and did not result in a combustion reaction. Thus the chance of a puncture, given a direct hit on a bottle, would appear to be about 1 in 20, and the probability of an ignition, given a puncture, would be even lower.

It is of interest to compare the intensity of degree le events resulting from feeder-breaker impact on self-rescuers with and without added coal dust. This may be done by comparing figure 26 (test 97 with added coal dust on a CSE unit) with figure 28, which shows some scenes from test 186 which involved impact on an OCENCO unit without added coal dust and resulted in degree le damage. Qualitatively, there is little difference in the visual appearance of the two events, and it would appear that a significant quantity of the "natural" coal dust present in the bed of the feeder-breaker was involved in the deflagration shown in figure 28.

While the addition of coal dust to the units does not appear to significantly alter the nature of the combustion reactions that sometimes accompany bottle puncture, the addition of water sprays certainly does. This may be seen by comparing figure 20 with figure 29, which shows scenes from test 102 which involved an impact on an OCENCO unit while the water spray system was operating. In this case, there is a short-lived combustion reaction associated with bottle puncture but no subsequent burning of coal dust (particles). Thus the water spray appears to be effective in inhibiting the ignition of coal in the vicinity of the unit but not the impact-induced combustion of the wall material of the bottle or combustibles in the interior of the unit, which may have been involved to a minor degree in test 102. In view of our speculation concerning the nature of the impact-induced combustion reactions, this is not unreasonable.

Examples of the damage suffered by the complete SCSR units in the feeder-breaker impact trials are shown in figure 30. They further illustrate the severity of the destructive testing conducted in the experimental program.

FEEDER-BREAKER FEED-THROUGH TRIALS

The feeder-breaker impact experiments demonstrated that it was possible for a compressed oxygen bottle, or a bottle within a unit, to be punctured by the impact of a breaker pick. However, the probability of such an event was low if the bottles or units were free to move even when carefully positioned to assure a direct hit. Intuitively, one would expect the probability of bottle puncture to be even lower when the units were fed through the feeder-breaker in a "normal" way such as might occur in a situation where the unit was off-loaded onto a breaker conveyor. To prove this point, a number of feeder-breaker "feed-through" tests were conducted. For this purpose the Long-Airdox unit was loaded with approximately 5 tons of coal, and a self-rescuer was positioned on top of the pile some 4 to 5 ft upstream of the rotary breaker assembly. The chain conveyor and

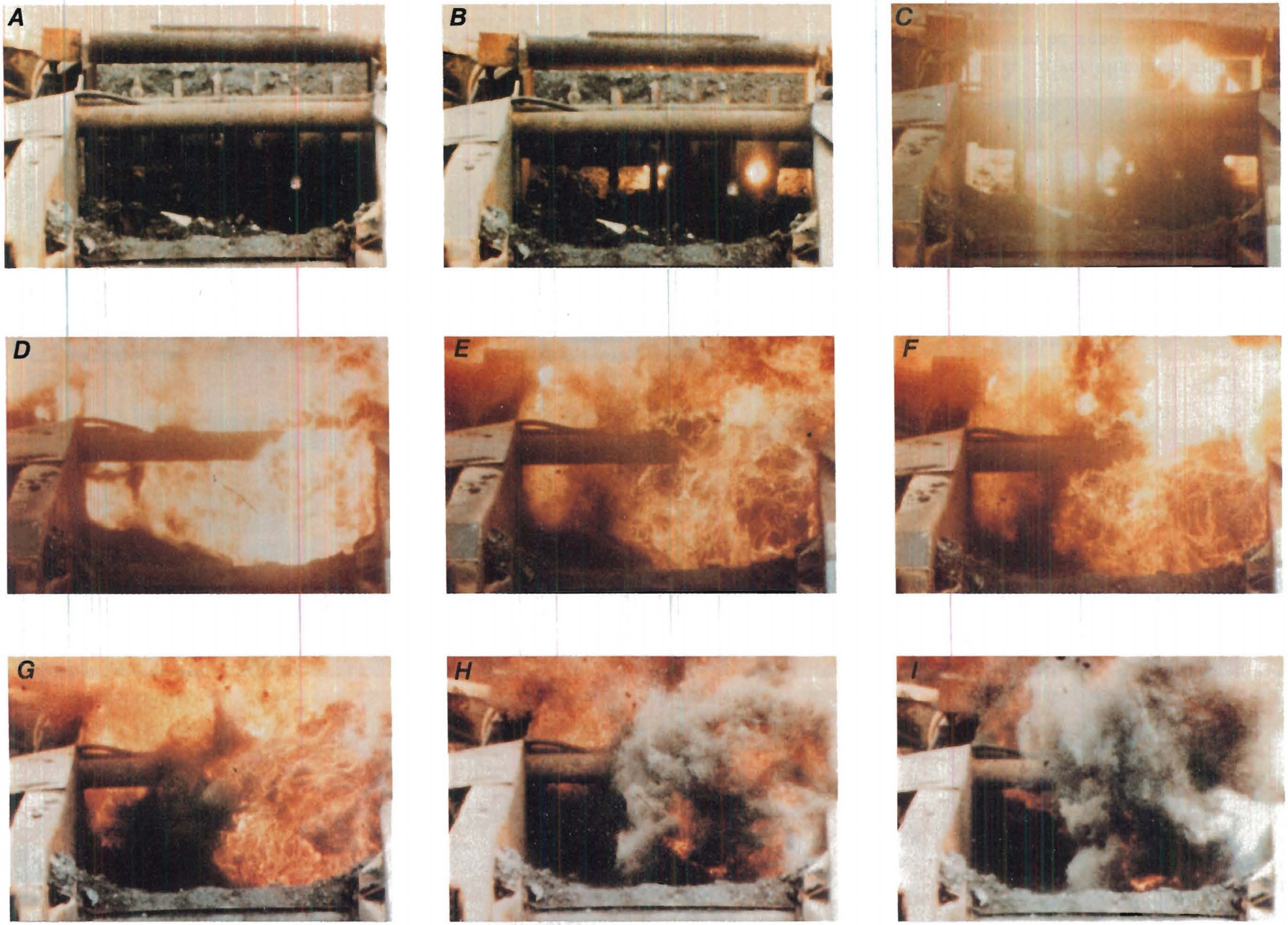

FIGURE 26. - Feeder-breaker impact test 97 with a CSE unit which resulted in damage of degree 1e. Flame from combustion reaction initiated in panel *B* completely engulfs interior of feeder-breaker.

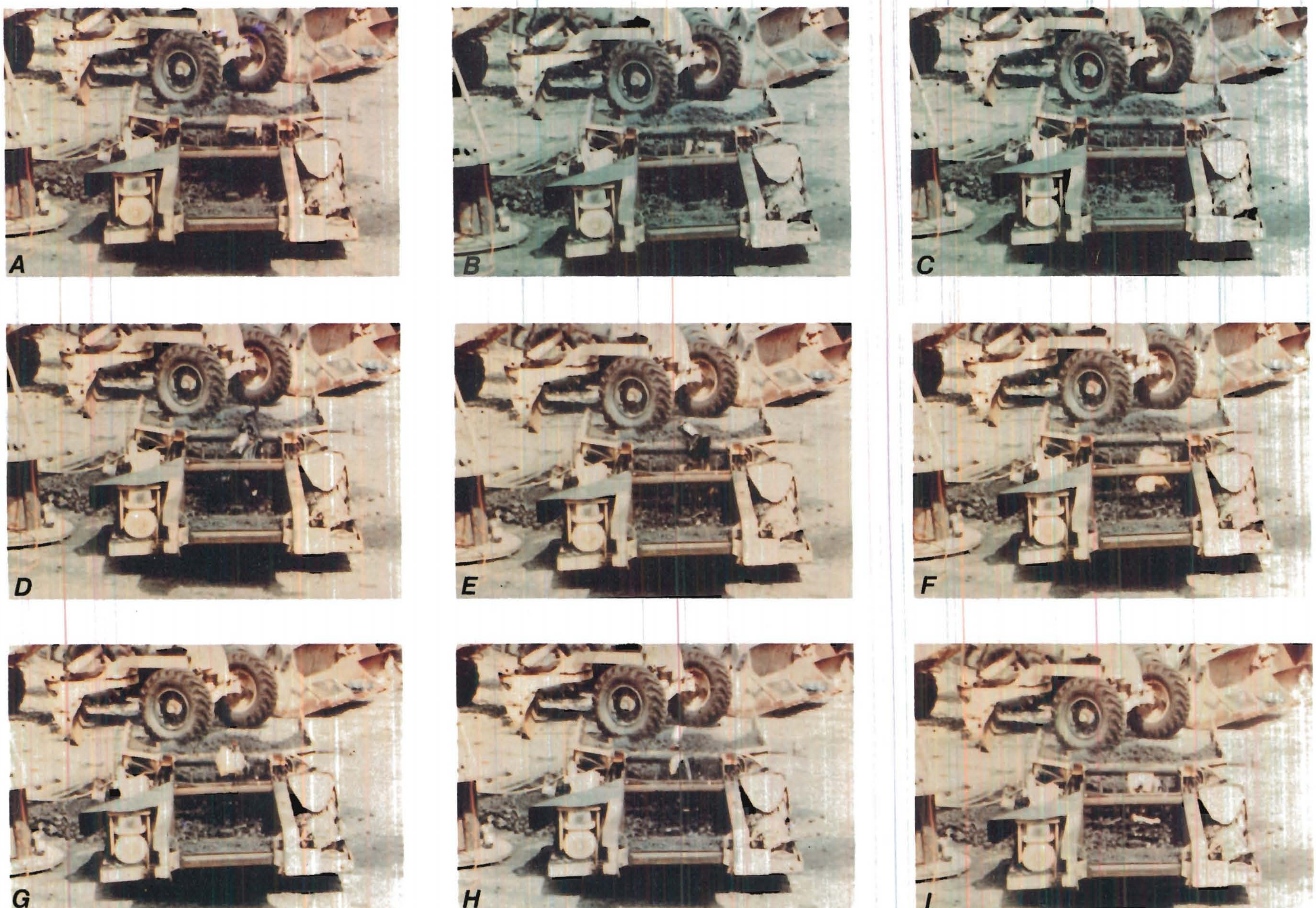

FIGURE 27. - Feeder-breaker impact test 187 with a PASS unit which resulted in damage of degree 2. Silver aluminum bottle being spun around hub of breaker assembly can be seen in panels *D*, *E*, and *H*; rotating yellow case can be seen in panels *A*, *B*, *F*, *G*, and *I*.

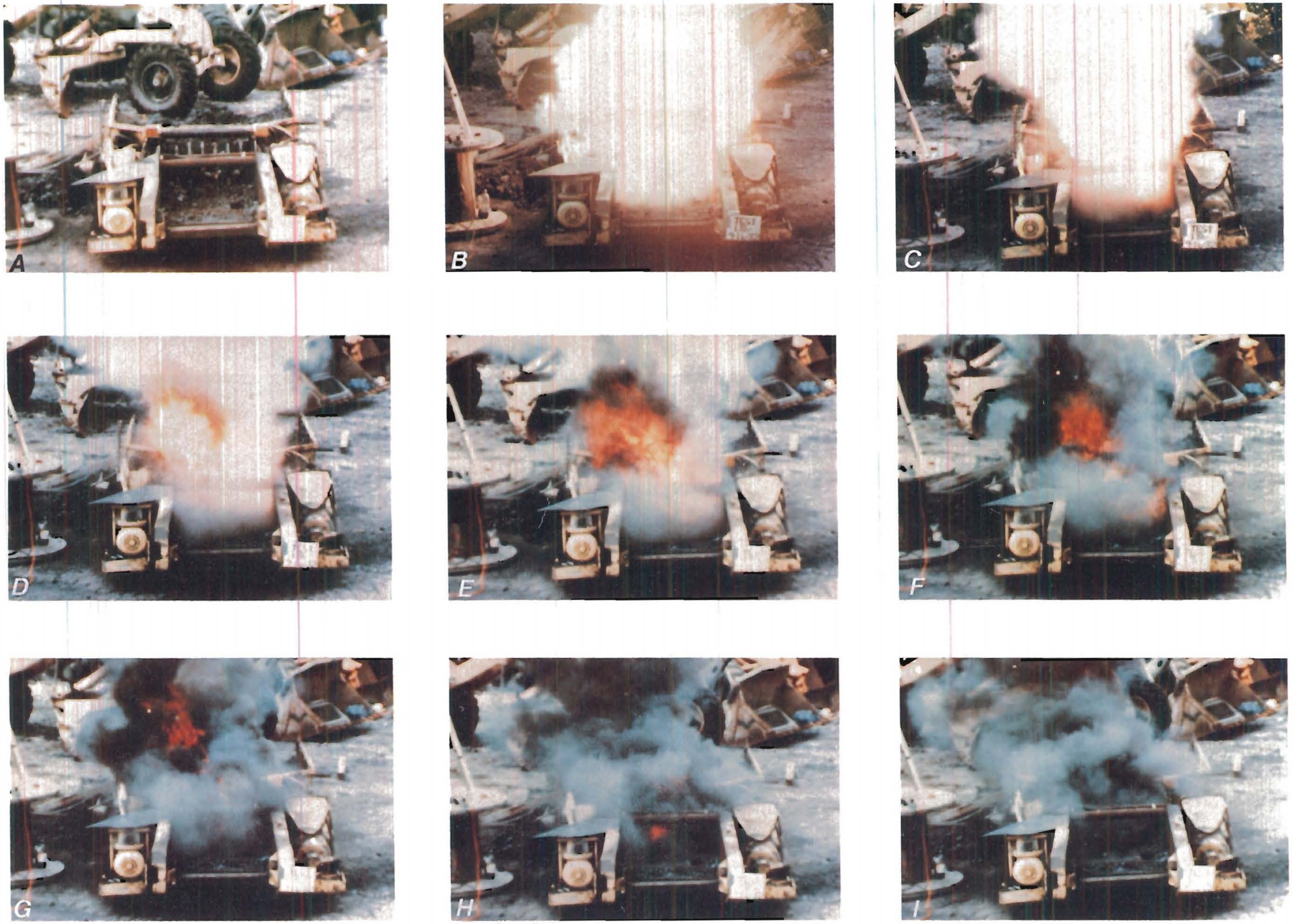

FIGURE 28. - Feeder-breaker impact test 186 with an OCENCO unit which resulted in damage of degree 1e. Intense white flame in panel *B* gradually fades to orangish-red in panel *H*.

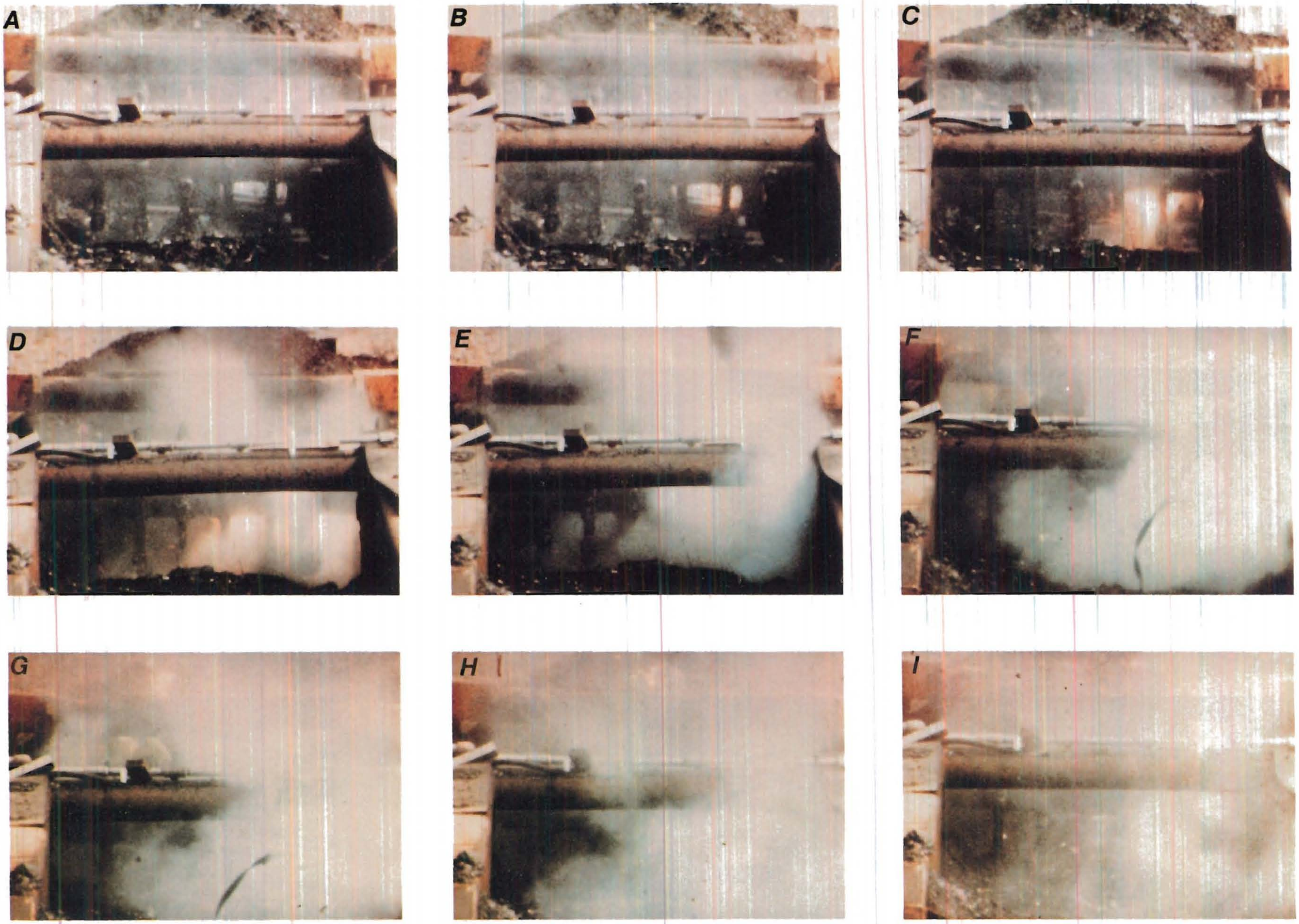

FIGURE 29. - Feeder-breaker impact test 102 with an OCENCO unit showing effect of water sprays. Orange-white flames can be distinguished from white steam cloud in panels *B*, *C*, and *D*.

FIGURE 30. - Damage to units resulting from feeder-breaker impact. *A*, Flame-blackened bottle and interior components from test 97 with a CSE unit, degree 1e; *B*, punctured PASS bottle and damaged components from test 147, degree 2; *C*, damaged OCENCO bottle and components from test 135, degree 3; *D*, intact CSE bottle and other damaged components from test 142, degree 4.

rotary head were then activated, and the self-rescuer was allowed to feed into the breaker assembly along with the moving pile of coal. Observations were made of the degree of damage suffered by the units in passing through the breaker assembly. The experimental arrangement for the feed-through tests is depicted in figure 31, which shows a CSE unit positioned for entry into the breaker assembly and the aftermath of the experiment.

In all, 27 runs were conducted which involved 8 CSE units, 7 OCENCO units, and 7 PASS units; the test results are summarized in table 8. It will be noted

TABLE 8. - Summary of feeder-breaker feed-through trials

Test	Test configuration			Damage[1]
	Cutter bar	Coal dust	Water spray	
CSE UNIT				
84	Fixed...	Yes....	No....	4
99	...do...	No.....	No....	4
132	...do...	No.....	No....	4
132-1	...do...	No.....	No....	3
118	Free....	No.....	No....	3
119	...do...	No.....	No....	4
120	...do...	No.....	No....	4
121	...do...	No.....	No....	4
122	...do...	No.....	No....	4
122-1	...do...	No.....	No....	3
OCENCO UNIT				
85	Fixed...	Yes....	No....	4
98	...do...	No.....	No....	4
104	...do...	No.....	Yes...	4
128	Free....	No.....	No....	4
128-1	...do...	No.....	No....	4
129	...do...	No.....	No....	4
129-1	...do...	No.....	No....	3
130	...do...	No.....	No....	4
130-1	...do...	No.....	No....	4
131	...do...	No.....	No....	4
PASS UNIT				
87	Free....	Yes....	No....	4
100	...do...	No.....	No....	4
123	...do...	No.....	No....	3
124	...do...	No.....	No....	4
125	...do...	No.....	No....	3
126	...do...	No.....	No....	3
127	...do...	No.....	No....	3

[1]Damage code:
3 - Valve or gauge damaged; oxygen leak.
4 - Superficial damage; no oxygen leak.

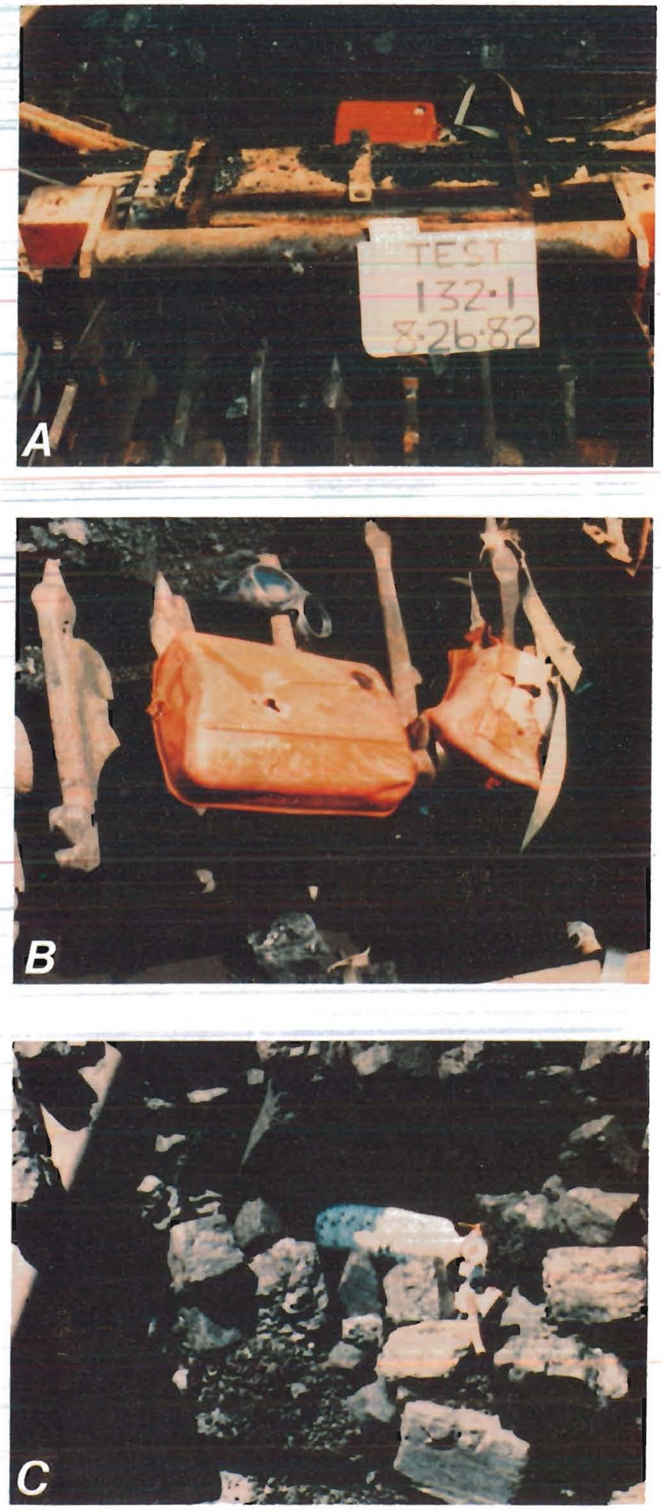

FIGURE 31. - Feeder-breaker feed-through test 132-1 with a CSE unit which resulted in damage of degree 3. Orange CSE unit can be seen entering the unit in panel *A*; subsequent damage to the case and bottle is shown in panels *B* and *C*, respectively.

that the cutter bar was fixed in some cases and free in others. In addition, pulverized coal was added in three of the tests (84, 85, and 87), and the water spray system was used in one test (104). On occasion, the same unit was used for two successive runs, e.g., test 132 and 132-1. This was done to conserve materials and only when the first test resulted in degree 4 damage.

All of the feed-through tests resulted in either degree 3 or 4 damage to the units. While there were no degree 1e or degree 2 events, the rigor of the test as well as the resultant damage was quite severe, as illustrated in figures 32 and 33. Figure 32 shows scenes from a high-speed motion picture of tests which resulted in degree 4 damage, and figure 33 shows the typical degree 3 and degree 4 damage inflicted on the three different units.

The results of the feed-through tests indicate that the probability of a compressed oxygen bottle in a self-rescuer being punctured while passing through a feeder-breaker is low, inasmuch as no punctures were observed in the 27 trials conducted. As expected, the probability is lower than that associated with the "free" impact studies with the feeder-breaker, which resulted in 1 puncture in 16 trials. How low is difficult to say, but the chance of a bottle being perforated in a feed-through encounter was estimated to be less than 1 in 100. Since judgments on the safety of these devices must assume that ignition can occur in this damage mode, it is probably not worth the enormous cost that it would take to verify this estimate.

Of the 8 degree 3 events observed in the feed-through experiments, 3 occurred in 10 trials with CSE units, 1 in 10 trials with OCENCO units, and 4 in 7 trials with PASS units. The relatively high frequency of degree 3 damage with the PASS unit is probably associated with the size of this unit, which would tend to enhance damage under these circumstances. Since there were no degree 1e or degree 2 events in the feed-through experiments, the presence of added coal dust in tests 84, 85, and 87 and of water sprays in test 104 is irrelevant.

EQUIPMENT RUNOVER TRIALS

While roof fall and encounters with coal cutting equipment represent realistic mine scenarios which could lead to the rupture or puncture of the compressed oxygen bottles contained in SCSR's, another danger is the possibility of being run over by heavy mining equipment. In fact, the chance of a misplaced unit being run over is probably a good deal higher than the chance of a unit being caught in a roof fall or in coal cutting equipment. For this reason a number of runover tests were conducted with compressed oxygen bottles and complete SCSR's using two heavy track-mounted vehicles and one heavy vehicle equipped with pneumatic tires.

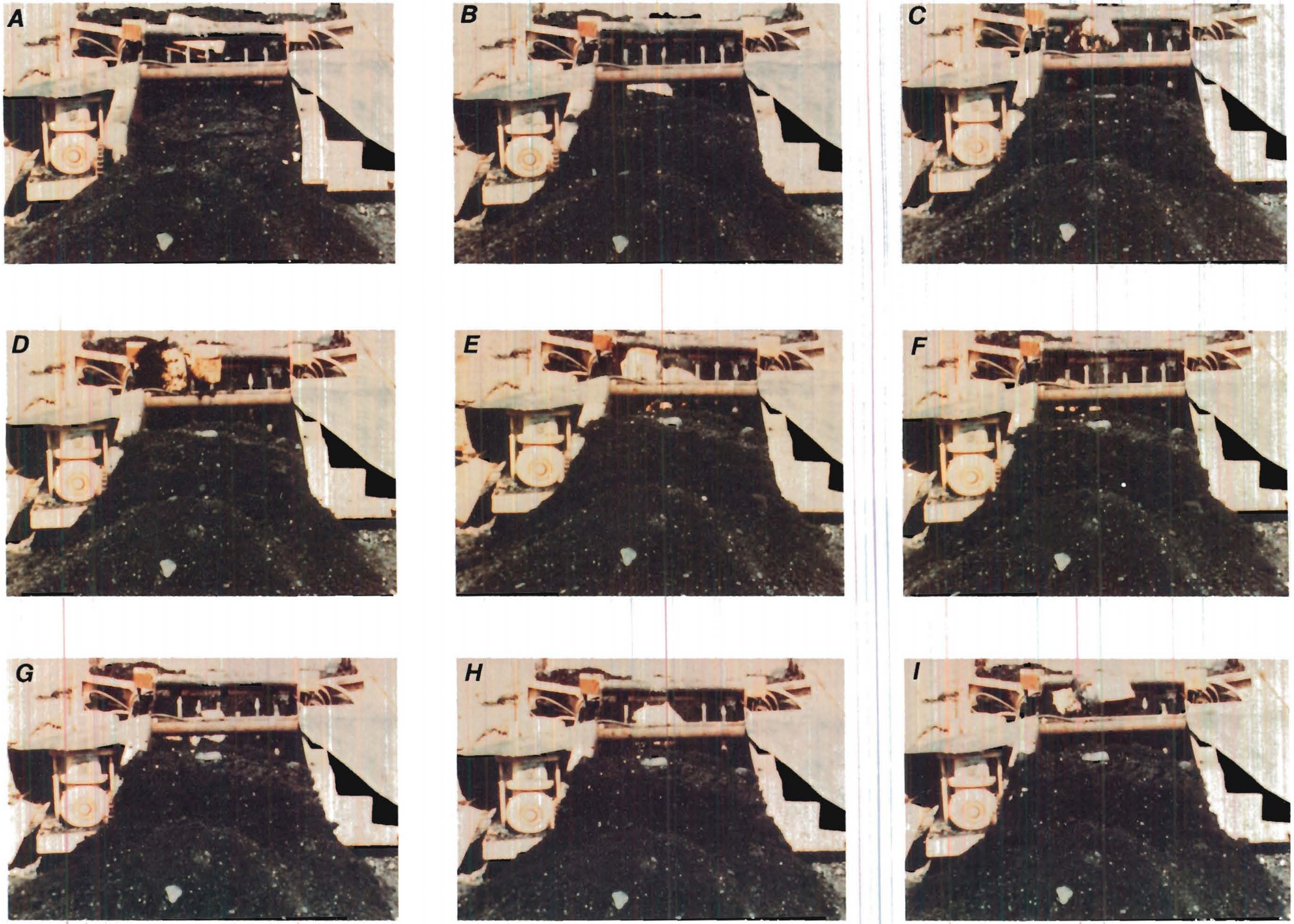

FIGURE 32. - Feeder-breaker feed-through test 124-1 with a PASS unit which resulted in damage of degree 4. Yellow unit can be seen entering feeder-breaker in panel *A* and spinning around hub of breaker assembly in panels *C*, *D*, *E*, and *I*.

FIGURE 33. - Damage resulting from feeder-breaker feed-through trials. *A*, Test 132-1 with a CSE unit, degree 3; *B*, test 121 with a CSE unit, degree 4; *C*, test 129-1 with an OCENCO unit, degree 3; *D*, test 131 with an OCENCO unit, degree 4; *E*, test 123 with a PASS unit, degree 3; *F*, test 124 with a PASS unit, degree 4.

FEEDER-BREAKER

The initial tests were performed with the Long-Airdox feeder-breaker that was used in the impact and feed-through trials. This is a crawler-mounted vehicle which weighs approximately 30,000 lb. For test purposes a bottle or unit was positioned directly in front of one of the tracks with the bottle oriented either parallel or perpendicular to the direction of travel. The test item was then liberally sprinkled with pulverized coal and runover when the feeder-breaker was turned on. Figure 34*A* shows a bottle in the parallel position prior to runover, and figure 34*B* shows a unit with its bottle perpendicular to the direction of travel; the results of trials with samples of the three types of bottles and units are summarized in table 9.

TABLE 9. - Summary of feeder-breaker runover trials

Test	Test item	Bottle orientation	Coal dust	Damage[1]
61	CSE bottle...	∥	Yes	3
73	CSE unit.....	⊥	Yes	3
63	OCENCO bottle	⊥	Yes	1e
72	OCENCO unit..	⊥	Yes	3
62	PASS bottle..	∥	Yes	3
71	PASS unit....	⊥	Yes	4

[1]Damage code:
- 1e - Bottle perforated; violent combustion reaction.
- 3 - Valve or gauge damaged; oxygen leak.
- 4 - Superficial damage; no oxygen leak.

In the six trials conducted with the feeder-breaker there were four instances of degree 3, one of degree 4, and one of degree 1e damage. Figure 35 shows scenes from a television tape of test 73, which resulted in degree 3 damage to a CSE unit. All tests resulting in degree 3 or 4 damage were equally unspectacular.

Degree 1e damage occurred in test 63 with an OCENCO bottle and is illustrated in figure 36, which shows selected frames from a television tape of the event. With one notable exception the behavior in this test was similar to that observed in the drop weight and feeder-breaker impact trials when similar bottles were punctured. Therefore, there is good reason to believe that the ignition mechanism is the same, i.e., mechanical puncture of the bottle accompanied by local heating leading to combustion of the wall material in the vicinity of the puncture. The exception lies with a coal dust cloud that was observed to form a short time before ignition occurred. This may be seen by examining panels *A*, *B*, *C*, and *D* of figure 36. The cloud is indicative of an oxygen leak associated with valve or gauge failure which took place a second or two before the bottle was punctured.

The remnants of the bottles and units from the feeder-breaker runover trials are shown in figure 37. The violence of the reaction in test 63 was sufficient to burst the bottle, as shown in figure 37*C*. This certainly could not have occurred if the ignition shown in figure 36 involved only coal dust ignited by a source outside the bottle such as friction--an alternative to the explanation given above.

CONTINUOUS MINER

For the runover tests with a continuous miner the Bureau was very fortunate in obtaining the use of a 100,000-lb remote-controlled prototype miner under development by the Lee-Norse Co., together with the test arena at the Lee-Norse Development Center in Belle Vernon, PA.

The prototype miner is shown in figure 38*A*; the remote control feature allowed for complete safety in conducting the tests as well as very delicate control over the speed and direction of the machine. As in the case of runover with the feeder-breaker, tests were conducted with compressed oxygen bottles alone, and with bottles within units, aligned perpendicular and parallel to the direction of machine travel (figs. 38*B* and 38*C*). In one test, a unit was positioned with its bottle oriented at 45° to the

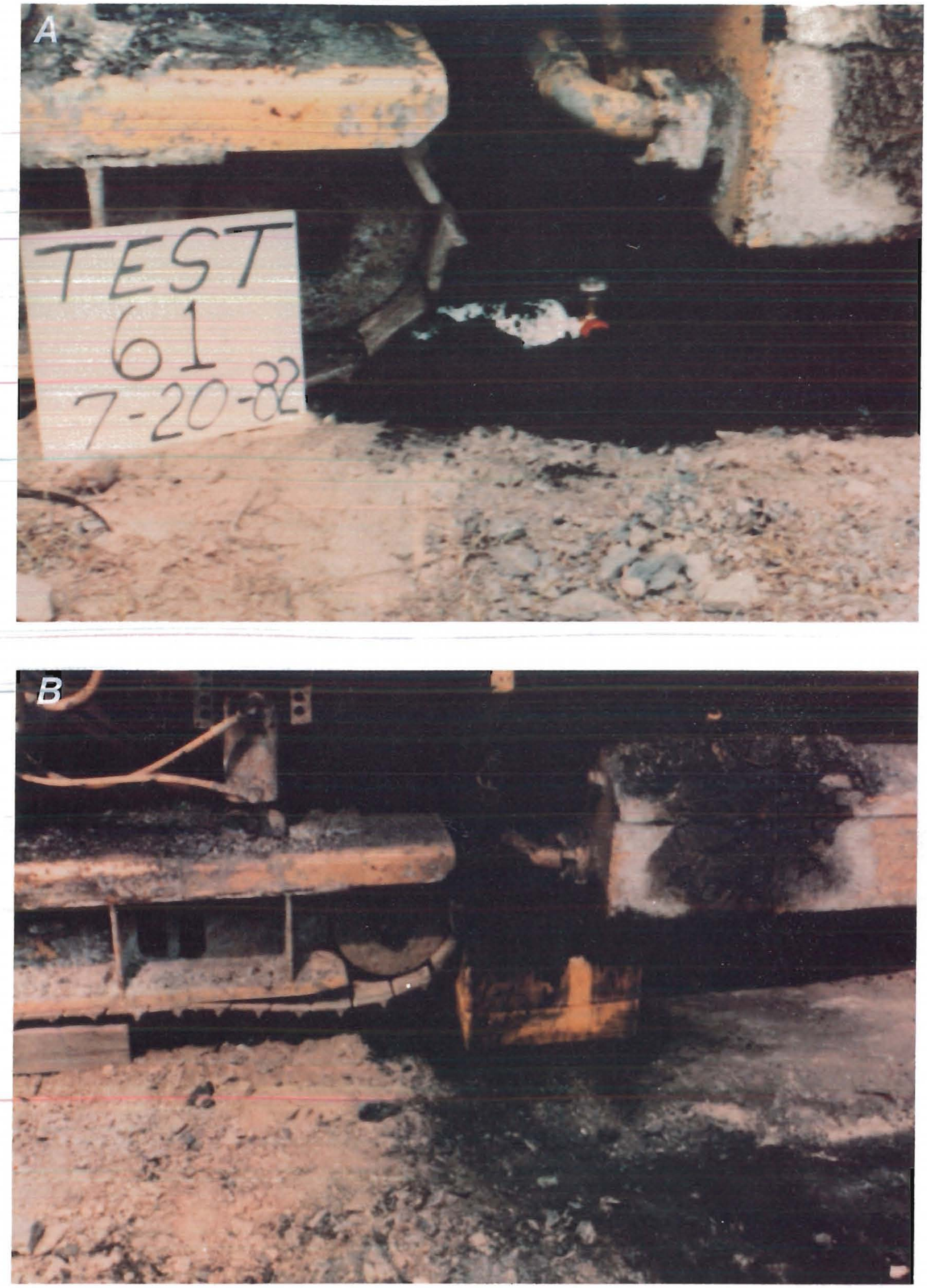

FIGURE 34. - Feeder-breaker runover trials. *A*, Bottle parallel to direction of travel; *B*, unit with its bottle perpendicular to direction of travel. Black substance around white CSE bottle in panel *A* and yellow PASS case in panel *B* is coal dust.

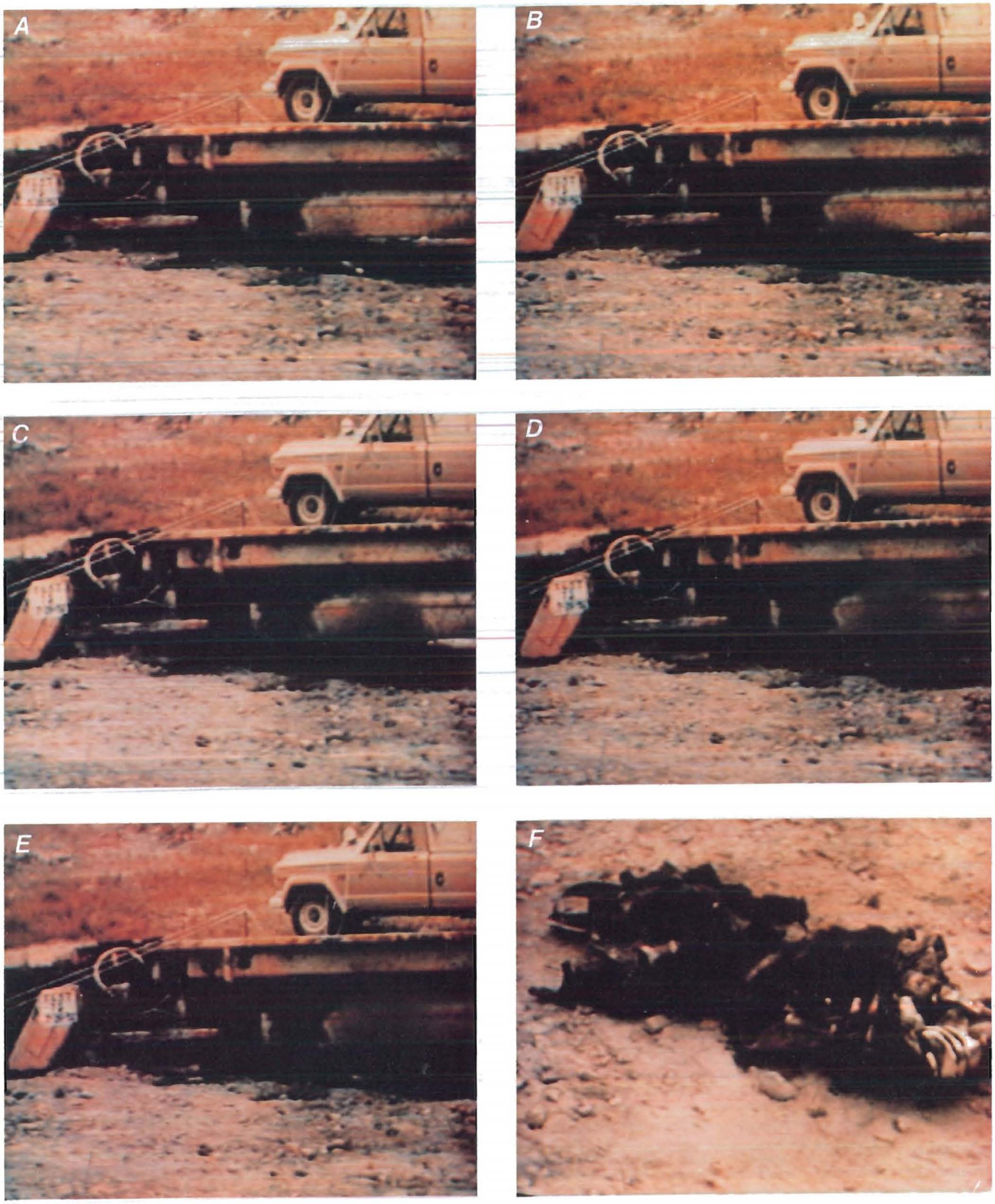

FIGURE 35. - Feeder-breaker runover test 73 with a CSE unit which resulted in damage of degree 3. Evidence of damage to unit in form of rising black coal dust cloud is first seen in panel *B*.

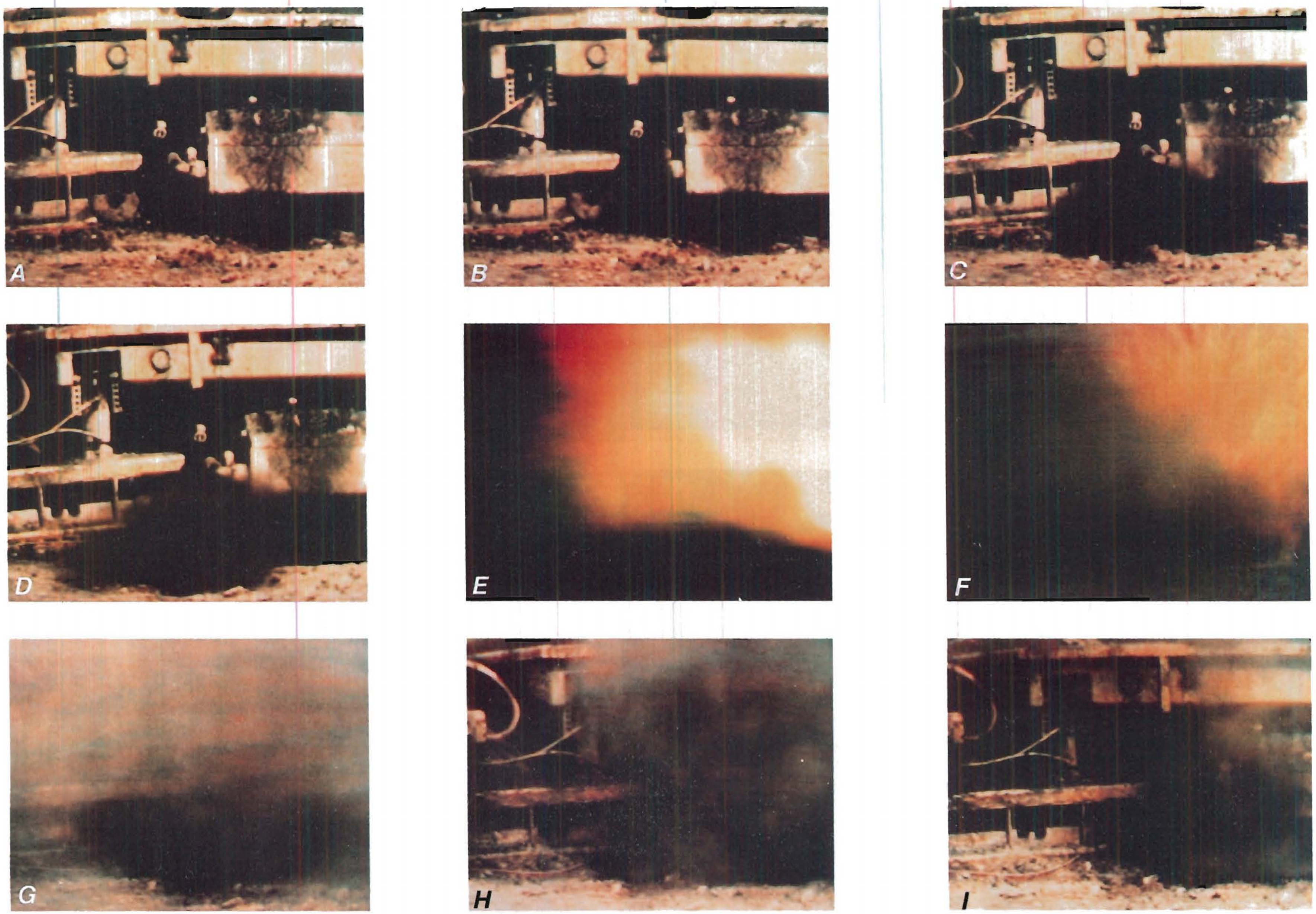

FIGURE 36. - Feeder-breaker runover test 63 with an OCENCO bottle which resulted in damage of degree 1e. Clear evidence of oxygen release was first noted in form of rising coal dust cloud shown in panel *C*; ignition took place somewhat later. Note that true flame color is lost in this TV rendition.

FIGURE 37. - Remnants of bottles and units from feeder-breaker runover trials. *A*, White CSE bottle from test 61, degree 3; *B*, CSE unit blackened with coal dust from test 73, degree 3; *C*, OCENCO bottle blown open in test 63, degree 1e; *D*, OCENCO unit blackened with coal dust from test 72, degree 3; *E*, damaged PASS bottle from test 62-1, degree 3; *F*, damaged PASS unit from test 71, degree 4.

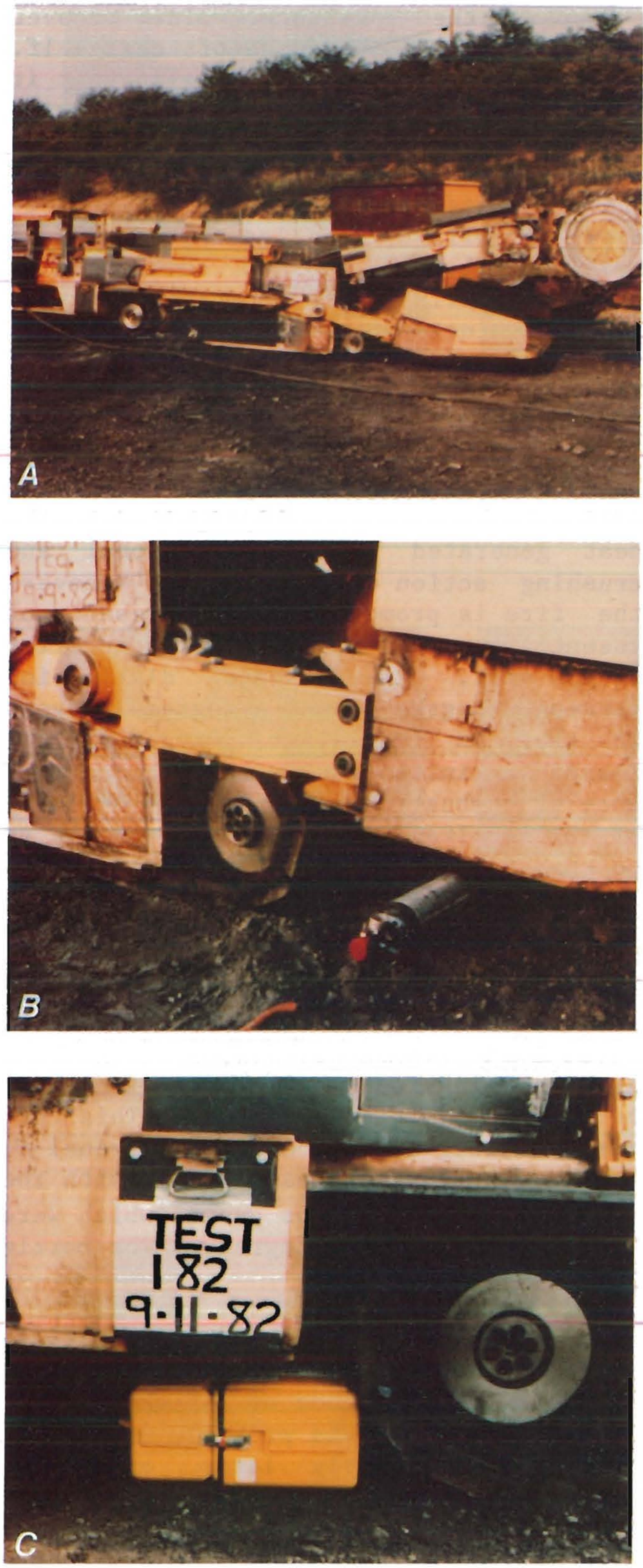

FIGURE 38. - *A*, Lee-Norse prototype miner; *B*, aluminum PASS bottle perpendicular to direction of travel; *C*, yellow PASS unit with bottle parallel to direction of travel.

direction of travel. In trials with the PASS unit, which did not conveniently fit under the front gathering pan, the machine was backed over the units (fig. 38*C*). In some of the tests, the bottles or units were in close proximity to the crawler track; in others the items were placed 4 or 5 ft ahead of the track to allow the machine to build up speed before the runover. Ordinarily the machine was passed over the test item once; however, in several of the tests the machine was trammed while passing over the item in attempts to inflict maximum damage. Pulverized coal was not used in any of the tests, but the dirt floor of the test arena contained a significant fraction of crushed coal residues left from previous machine testing at the Development Center.

The experimental results of the continuous miner runover trials are summarized in table 10, which gives the test configuration and resultant damage for each of the 26 tests conducted.

Runover by the continuous miner represented very severe test conditions as evidenced by the fact that no degree 4 events were observed in any of the trials. There were 16 degree 3 events--4 with bottles and 12 with units.

Selected frames from a television tape of a trial leading to degree 3 damage are shown in figure 39. These were taken of test 162, which involved a CSE bottle oriented perpendicular to the direction of vehicle travel. In this test the pressure gauge was sheared off, resulting in a rapid release of oxygen which caused the bottle to be propelled a short distance from the continuous miner.

There were four events leading to degree 2 damage. These involved an OCENCO bottle (test 163), two PASS bottles (tests 164 and 174), and one PASS unit (test 182). Selected views from a television tape of test 163 are presented in figure 40. In this test the valve assembly was damaged and one of the cleats of the crawler track punctured the bottle, resulting in the rapid release of oxygen but no flame, i.e., degree 2 damage.

TABLE 10 - Summary of continuous miner runover trials

Test	Test configuration: Run up	Tram	Bottle orientation	Damage[1]
		CSE BOTTLE		
158	No....	No...	⊥	3
162	No....	No...	⊥	3
176	No....	Yes..	∥	3
		CSE UNIT		
165	Yes...	No...	⊥	3
168	Yes...	No...	⊥	3
179	No....	No...	∥	3
180	No....	No...	∥	3
181	No....	Yes..	45°	3
		OCENCO BOTTLE		
157	No....	No...	⊥	1f
163	No....	No...	⊥	2
175	No....	No...	∥	1e
		OCENCO UNIT		
169	No....	No...	⊥	3
170	Yes...	No...	⊥	3
171	Yes...	No...	∥	3
172	Yes...	No...	∥	3
173	No....	Yes..	∥	3
177	No....	No...	∥	1e
178	No....	Yes..	∥	3
		PASS BOTTLE		
159	No....	No...	⊥	3
164	No....	No...	⊥	2
174	No....	No...	∥	2
		PASS UNIT		
166	No....	No...	⊥	1f
167	No....	No...	⊥	3
182	No....	Yes..	∥	2
183	No....	Yes..	∥	1f
184	No....	Yes..	∥	1f

[1]Damage code:
- 1e - Bottle perforated; violent combustion reaction.
- 1f - Bottle perforated; nonviolent combustion reaction.
- 2 - Bottle perforated; oxygen released.
- 3 - Valve or gauge damaged; oxygen leak.

Four of the continuous miner runover trials resulted in damage of degree 1f. This type of damage was unique in that it was observed only in runover trials with the continuous miner and was apparently caused by a somewhat different mechanism than that associated with degree 1e damage. It will be recalled that degree 1e events involve the violent combustion of the metal walls of the compressed oxygen bottles coincident with bottle puncture. A 1f event apparently involves an initial release of oxygen by valve or gauge failure or bottle puncture. This is followed, some time later, by a fire involving the combustible components of the SCSR, which are presumably ignited by the heat generated by the frictional and crushing action of the machine runover; the fire is promoted by the presence of essentially pure oxygen in the interior of the unit. The principal distinction between a degree 1e and a degree 1f event is that, in the latter, oxygen is released a finite time *before* the appearance of combustion and that the intensity of the resultant combustion is too low to be characterized as violent.

Selected frames from a television tape of test 183, which involved a PASS unit and resulted in degree 1f damage, are presented in figure 41. While it is not obvious in figure 41, oxygen began to leak, judging from the sound, a full 8 s before the ignition occurred. This corresponds roughly to the scene in panel *C*. The oxygen leak was associated with the failure of the valve or gauge, which were both damaged to some degree. The bottle was not punctured.

It will be noted from the results in table 10 that degree 1f damage was the most common mode of failure of the PASS units. This is probably associated with the relatively large amount of

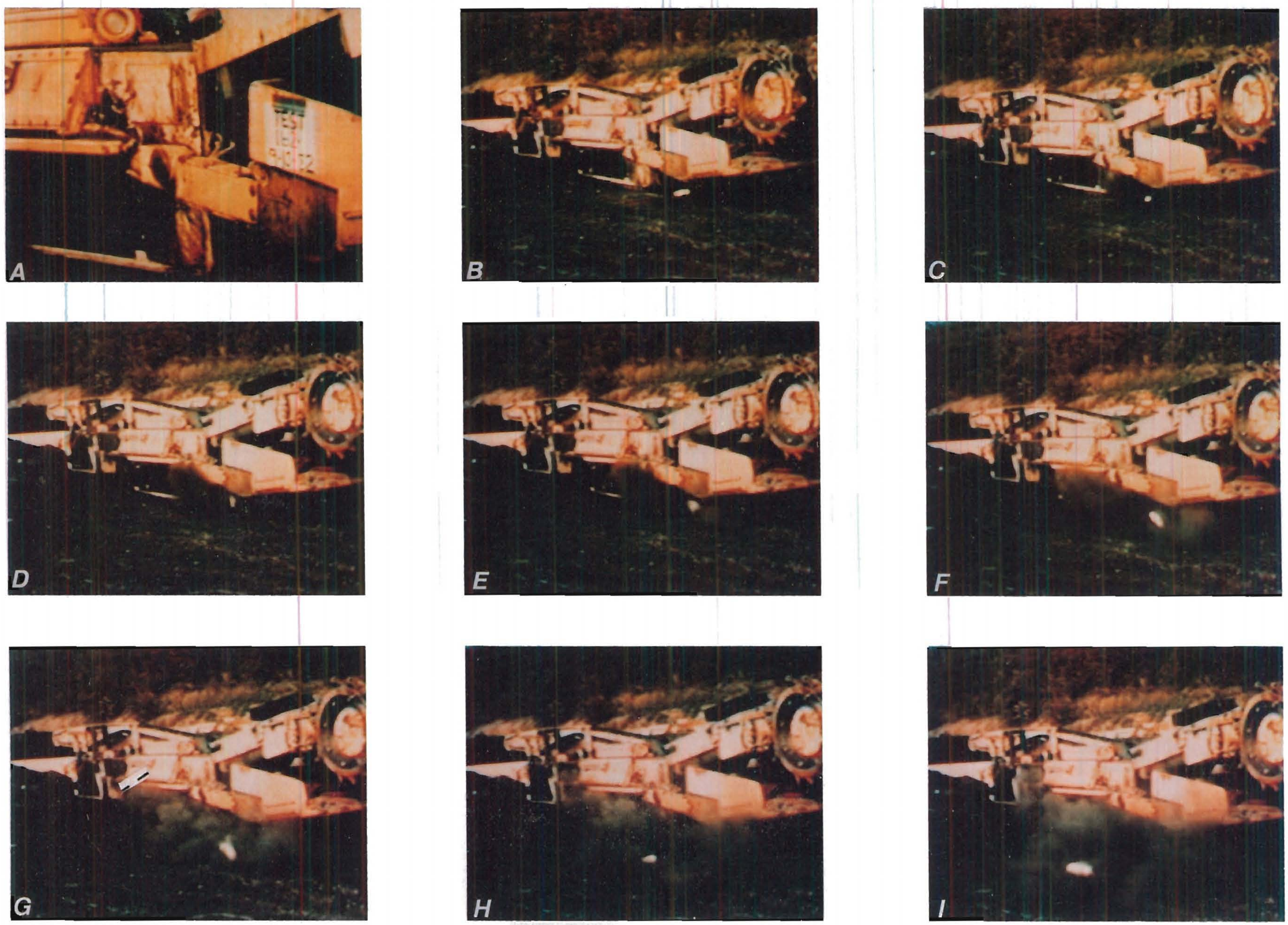

FIGURE 39. - Continuous miner runover test 162 with a CSE bottle which resulted in damage of degree 3. White CSE bottle can be seen being propelled from machine in panel *C*. It approaches the camera in panels *D-I*.

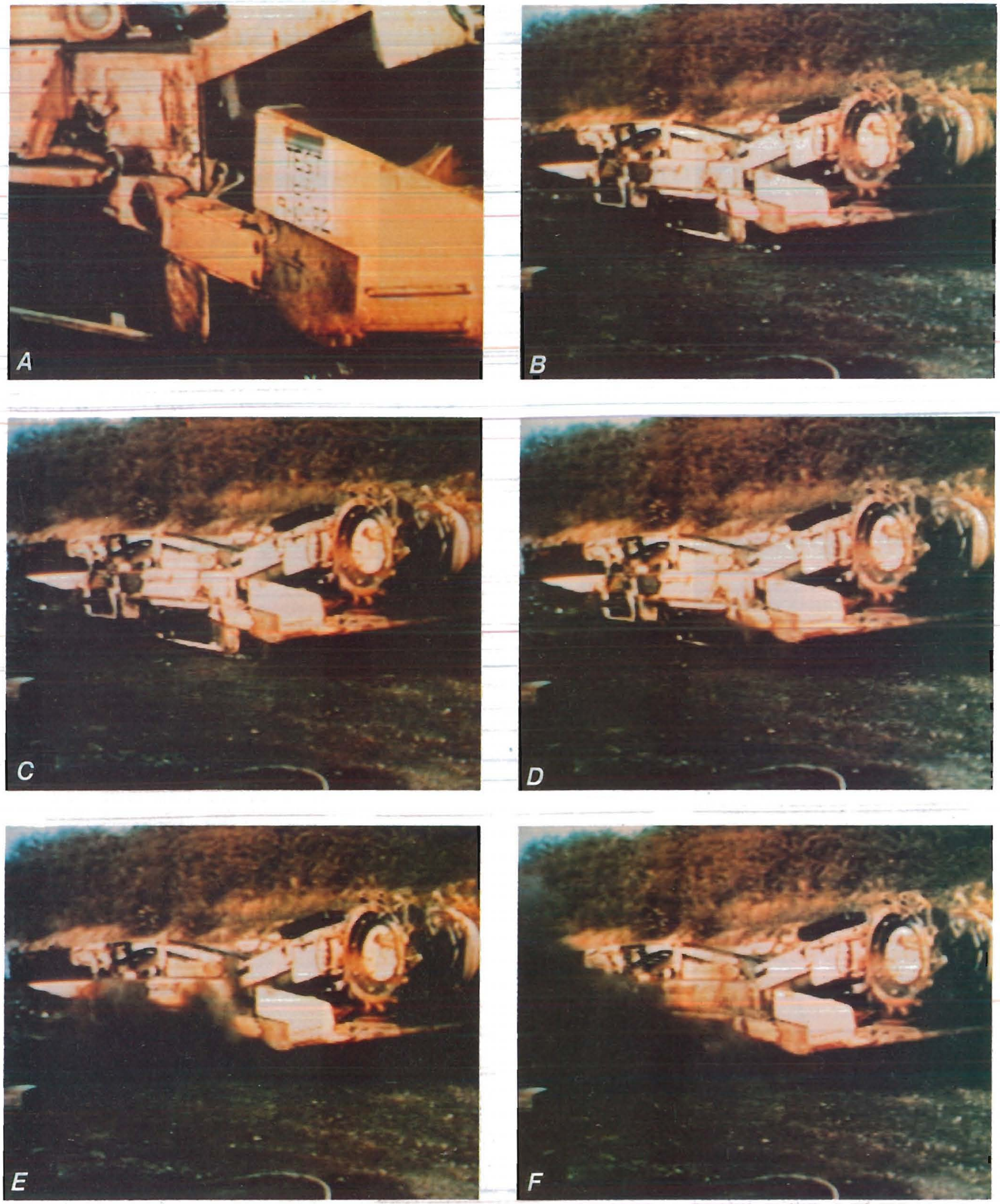

FIGURE 40. - Continuous miner runover test 163 with an OCENCO bottle which resulted in damage of degree 2. Black dust cloud associated with oxygen leak can be seen forming in panel *D*.

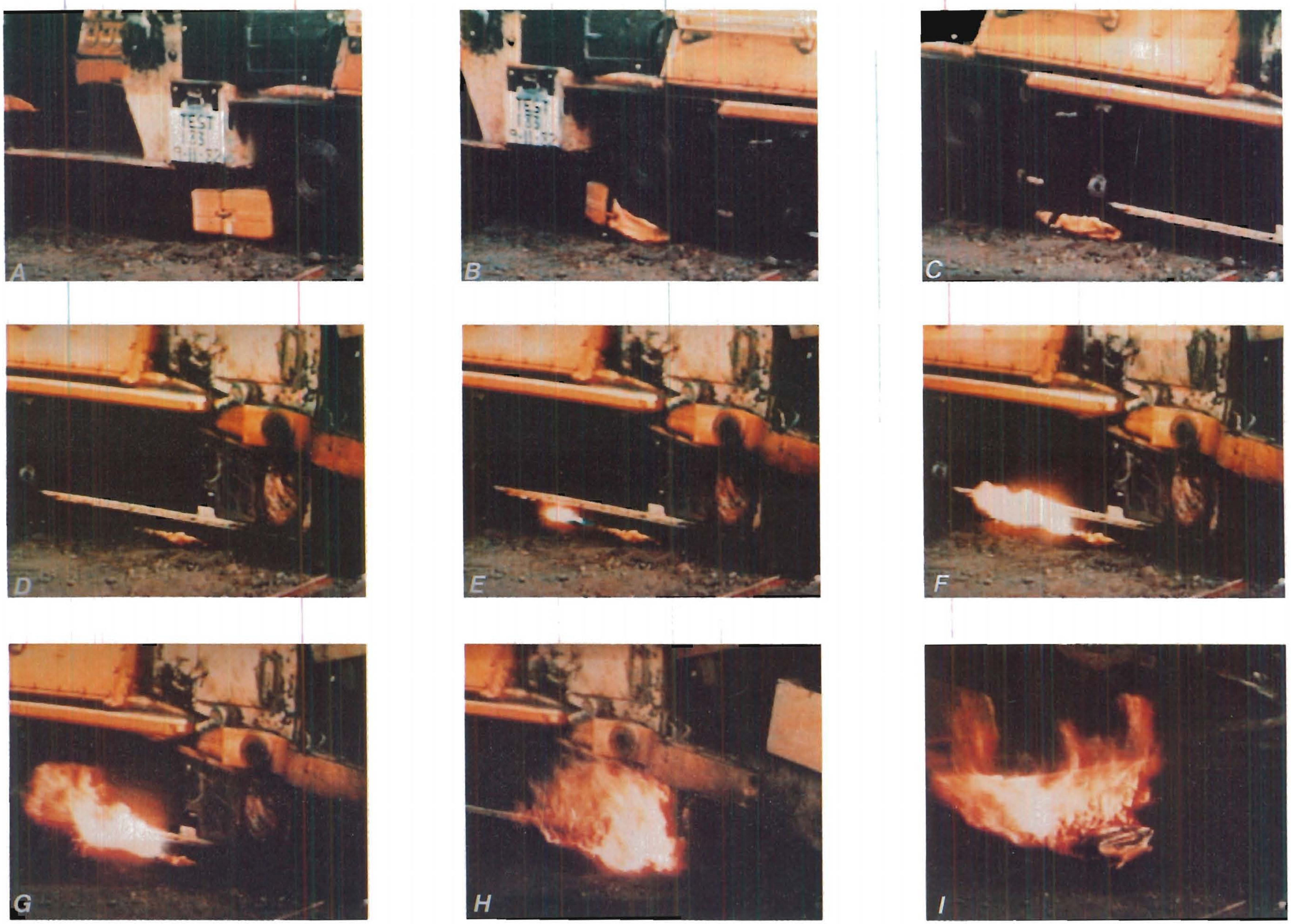

FIGURE 41. - Continuous miner runover test 183 with a PASS unit which resulted in damage of degree 1f. First signs of a luminous combustion reaction are seen in panel *E*; however, an oxygen leak was audible somewhat earlier.

combustible material available in the exterior plastic case. It will also be noted that test 157, which involved an OCENCO bottle, also resulted in degree 1f damage. In this case, the release of oxygen was observed to occur 3 s before ignition, which was nonviolent; thus the degree 1f label was assigned.

Two of the mining machine runover trials resulted in damage of degree 1e. This occurred in test 175 with an OCENCO bottle and in test 177 with an OCENCO unit. These results are in qualitative agreement with the results of other tests reported here, which indicate that the OCENCO bottle (unit) is more prone to degree 1e damage than the other two bottles or units. In view of the relatively thin wall of the OCENCO bottle, this was not unexpected. Scenes from a television tape of test 177 are presented in figure 42. In this test the bottle was punctured, resulting in an ignition accompanied by an audible report; hence the degree 1e label was assigned. The various degrees of damage inflicted on the bottles and units in the continuous miner runover trials are further illustrated in figure 43. The severity of the continuous miner runover trials is amply demonstrated in panels *C* and *D*.

RUBBER-TIRED VEHICLES

The last of the equipment runover trials involved a 30,000-lb front-end loader equipped with pneumatic rubber tires. This vehicle was selected because it represented a tire loading typical of equipment that might be found on mine property.

In these runover tests, samples of the three SCSR's were placed in front of one of the rear tires of the vehicle and repeatedly run over in the forward and reverse direction. The results of the tests are summarized in table 11 in terms of the observed degree of damage; scenes from test 189 with a CSE unit are shown in figure 44.

TABLE 11. - Summary of runover trials with rubber-tired vehicle

Test	Test item	Bottle orientation	Number of passes	Damage[1]
189	CSE unit...	∥	6	4
191	OCENCO unit	∥	5	4
190	PASS unit..	∥	5	3

[1]Damage code:
- 3 - Valve or gauge damaged; oxygen leak.
- 4 - Superficial damage; no oxygen leak.

The CSE and OCENCO units suffered only degree 4 damage; the PASS unit was assigned degree 3 damage owing to a slow oxygen leak which developed around the valve-gauge assembly. Pictures of three units taken after the trials were completed are shown in figure 45. On comparing figure 45 with figure 43 it can be seen that the rubber-tired vehicle does not compare with the continuous miner in terms of damage potential. On the other hand, the results of the runover trials with the rubber-tired vehicle demonstrate that all three SCSR's can sustain considerable abuse without posing any safety problems.

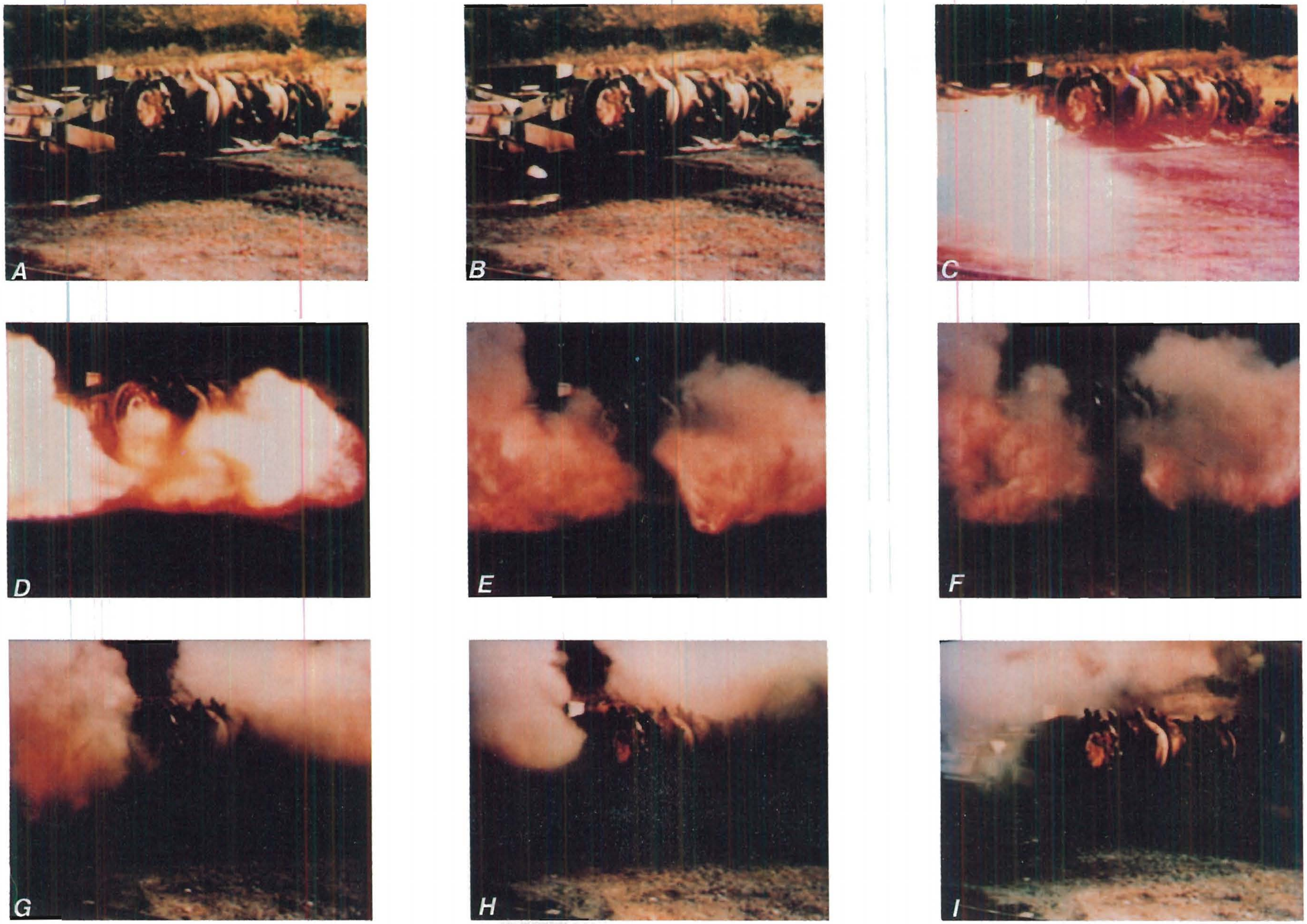

FIGURE 42. - Continuous miner runover test 177 with an OCENCO unit which resulted in damage of degree 1e. First sign of luminous combustion reaction appears in panel *B*. Color balance is poor in this TV rendition.

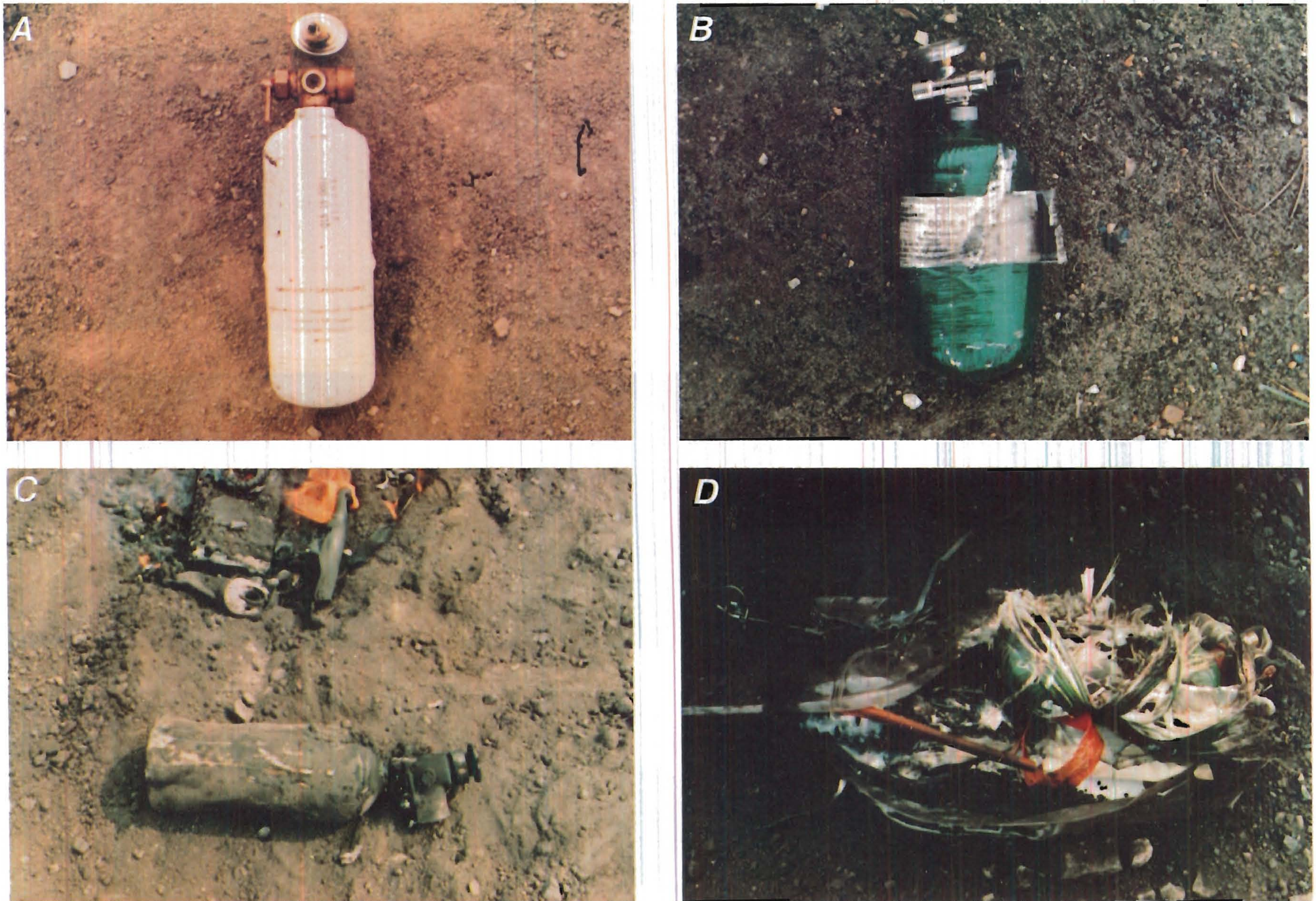

FIGURE 43. - Damage resulting from continuous miner runover trials. *A*, CSE bottle from test 162, degree 3; *B*, OCENCO bottle from test 163, degree 2; *C*, PASS unit from test 183, degree 1f (note orange flames on interior components); *D*, OCENCO unit from test 177, degree 1e (white entanglement is fiberglass overlay on bottle).

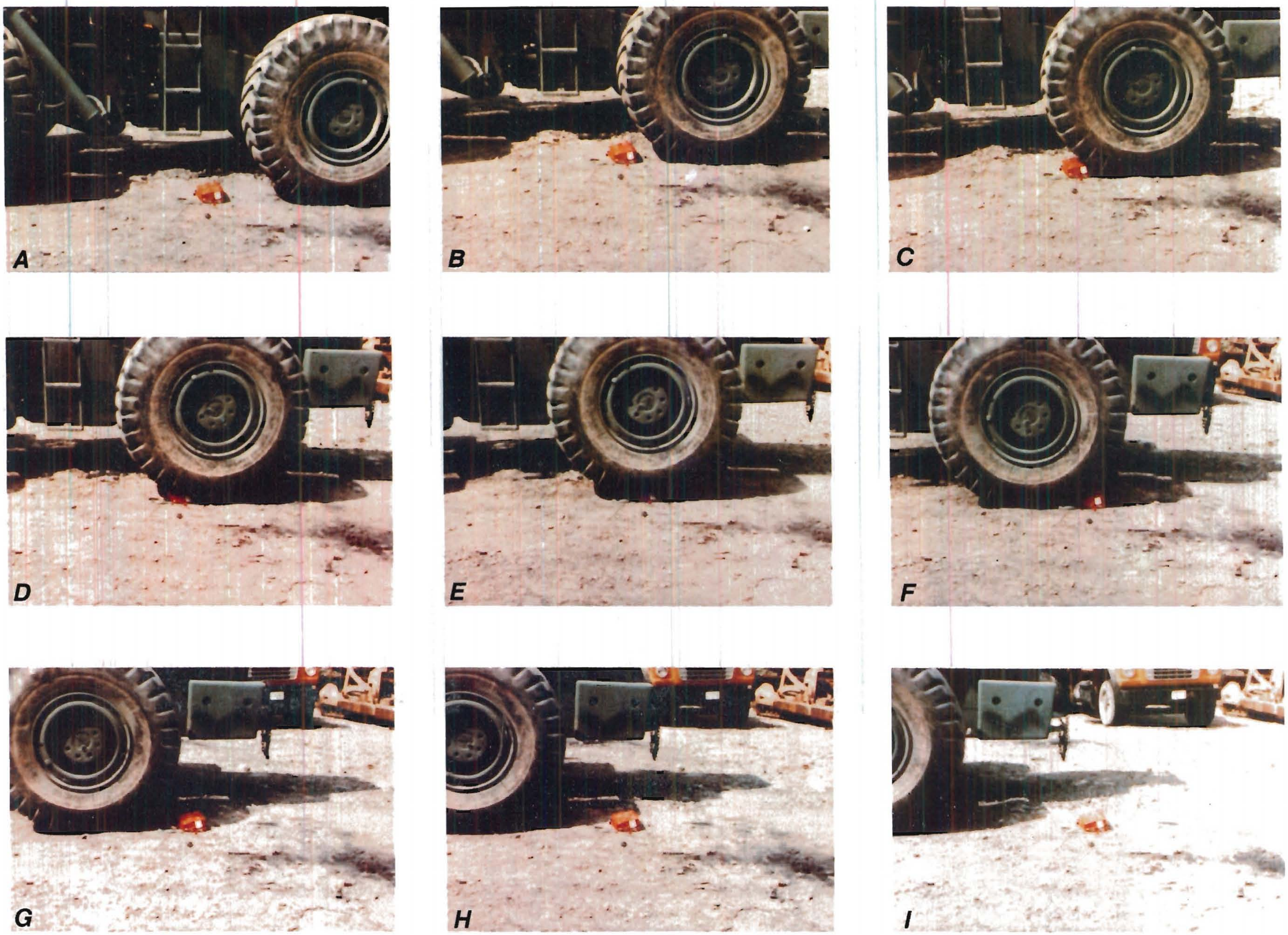

FIGURE 44. - Rubber-tired runover test 189 with an orange CSE unit which resulted in damage of degree 4.

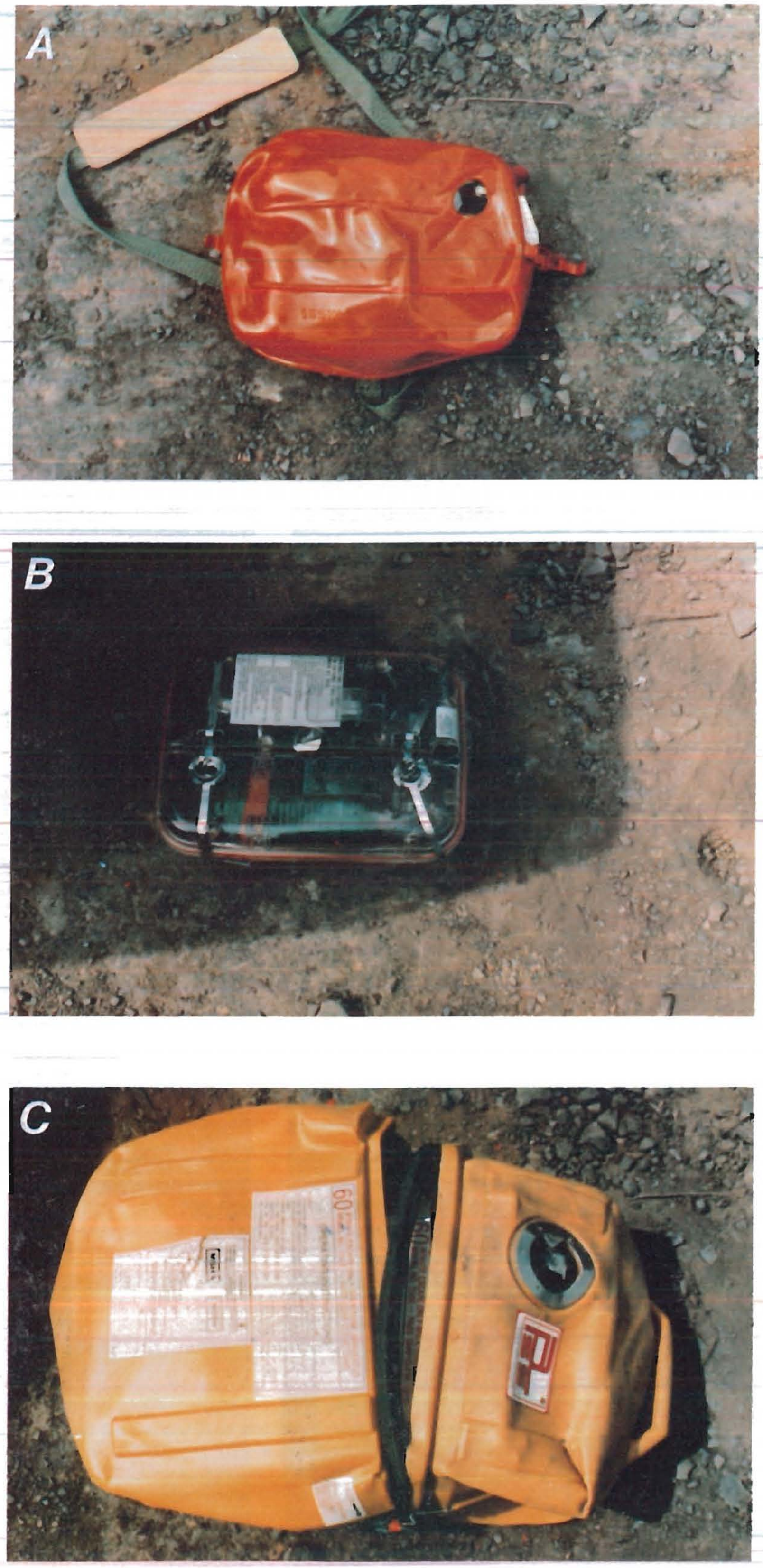

FIGURE 45. - SCSR's after having been repeatedly run over with a 30,000-lb rubber-tired vehicle. *A*, Orange CSE unit; *B*, transparent OCENCO unit; *C*, yellow PASS unit.

SUMMARY AND CONCLUSIONS

This section discusses the implications of the results of the destructive testing program on compressed oxygen self-rescuers in terms of the potential hazards these devices might pose in a coal mining environment.

The bonfire tests showed that there was no tendency for the compressed oxygen bottles to fragment and that the high-pressure oxygen was released in a controlled way through failure of either the pressure gauge or the frangible disc used to protect the bottle from pressure buildup. Thus there does not appear to be any unusual hazards associated with fire exposure.

Impact experiments with high-velocity bullets demonstrated that there was no tendency for the compressed oxygen bottles to fragment under mechanical stress. The experiments also permitted estimates of the impulse associated with the rapid release of oxygen. These estimates showed that the catastrophic failure of a *bottle alone* could lead to sufficiently high bottle velocities to pose a missile hazard. Since the bottles are always contained in units, this is not a plausible hazard in a coal mine environment. Extrapolation of the impulse measurements to the failure of a bottle within a unit showed that this represented a lesser missile hazard and was equally implausible because of the nondirectional escape of gas, which would detract from the momentum transferred to the unit. The failure of a bottle within a unit being worn was shown to be an insignificant event because of the low resultant velocity of the wearer. Parallel experiments where the bottles within units were purposely pressurized to the point of frangible disc failure showed no significant hazard and corroborated the main conclusions of the impulse measurements.

The bullet impact tests uncovered a potentially serious hazard associated with certain modes of oxygen bottle failure: Explosionlike combustion reactions were observed to occur when the compressed oxygen bottles were perforated by high-speed bullets. These reactions involved the combustion of a portion of the metal walls of the bottles and occurred with aluminum and steel bottles alike.

Drop weight impact experiments showed that these reactions could be induced at lower impact velocities when the bottles were perforated with sufficient energy and led to the conclusion that similar reactions might occur under conditions resembling those to be found in coal mining.

This conjecture was verified in drop weight trials designed to simulate mine roof fall and in impact experiments with a feeder-breaker. However, the probability of this actually happening was judged to be low inasmuch as the simulated roof fall trials assumed a direct hit by a sharp rock on a bottle contained within a unit; also, the bottles, or units, had to be held in a rigidly fixed position to promote an impact reaction in the feeder-breaker.

Similar reactions were observed in runover tests with track-mounted vehicles including the feeder-breaker and a continuous miner but not with a rubber-tired vehicle. Besides the explosivelike combustion reactions, ordinary fires were also observed to occur in several of the runover trials with the continuous miner.

There is no doubt that the combustion reactions that accompany the mechanical puncture or rupture of compressed oxygen bottles represent the most serious hazard posed by introducing compressed oxygen SCSR's into a coal mining environment.

The fact that these combustion reactions can ignite predispersed coal dust clouds was demonstrated both in the drop weight trials and in impact experiments with the feeder-breaker. Since the energy source strength for igniting coal dust is considerably higher than that required to ignite methane, it follows that the impact ignitions could easily ignite a methane-air mixture within the flammable limits. However, with normal ventilation, methane-air mixtures of this concentration would ordinarily be limited to the vicinity of the working face. While a methane face ignition resulting from bottle puncture is possible, the probability of such an event is very small in comparison to the probability of a frictional face ignition and since few frictional face ignitions are serious, the possibility of a face ignition due to bottle puncture is not viewed as a major problem at present. The main problem with the combustion reactions accompanying the puncture of the compressed oxygen bottles lies in their potential for dispersing and subsequently igniting a coal dust explosion. To grasp the magnitude of this problem, the energy available by this means must be compared with the energy of other sources known to be capable of causing a coal dust explosion.

In Nagy's "The Explosion Hazard in Mining" (6), values of 13 cu ft of methane or 5 lb of coal dust are listed in the section on the minimum quantity of methane or coal dust required to ignite a coal dust explosion. Nagy also points out that 4 lb of black powder fired from a steel cannon is another source capable of igniting a coal dust explosion in a quiescent coal dust environment. For convenience, these sources are listed in table 12 along with corresponding values of total combustion energy calculated from the heats of combustion for the three sources. They range from 1.3 $\times 10^6$ calories for 4 lb of black powder to 17.6 $\times 10^6$ calories for 5 lb of coal dust.

Proceeding with the comparison, the compressed oxygen SCSR'S contain approximately 130 L of oxygen. This amount of oxygen defines the total energy of an SCSR when viewed as a potential ignition source for a coal dust explosion. Assuming that all of the oxygen is consumed in burning the metal walls of the bottle, it can be deduced that 130 L of oxygen is capable of burning 207 g of aluminum with a total energy yield of 1.4 $\times 10^6$ calories, or 430 g of steel with a yield of 0.7 $\times 10^6$ calories. Although the weight loss measurements indicate that not all of the oxygen is consumed this way, any residual oxygen could contribute to the energy yield by burning coal particles in the vicinity of the punctured bottle. If the entire 130 L of oxygen was consumed by reaction with coal dust alone, the energy yield would be 0.5 $\times 10^6$ calories with 70.7 g of coal dust entering into the reaction. Thus the energy yield of a compressed oxygen SCSR when viewed as a potential ignition source for a coal dust explosion lies somewhere between 0.5 $\times 10^6$ and 1.4 $\times 10^6$ calories. As can be seen from table 12, these values fit neatly on the lower end of the scale of energies for sources known to be capable of igniting a coal dust explosion. From the safety point of view it must be concluded that under the right (or wrong) circumstances a compressed oxygen SCSR is capable of igniting a coal dust explosion. These circumstances include bottle puncture by a sufficiently energetic source in a dusty environment.

TABLE 12. - Comparison of ignition source energy

Source	Heat of combustion, calories per gram	Total energy, calories
130 L oxygen + 70.7 g coal dust............	7,769	0.5 $\times 10^6$
130 L oxygen + 207.0 g aluminum............	7,000	1.4 $\times 10^6$
4 lb black powder.....	738	1.3 $\times 10^6$
13 cu ft methane......	11,360	3.0 $\times 10^6$
5 lb coal dust........	7,769	17.6 $\times 10^6$

Fortunately, the probability of bottle puncture is very small in "normal" encounters with coal cutting equipment. The probability of bottle puncture (or rupture) was observed to be somewhat higher in the heavy equipment runover trials, but the chance of this happening in an environment conducive to the ignition of a dust explosion, i.e., one containing loosely consolidated dry coal dust, is small. The safety advantages associated with the deployment of these devices underground outweigh the potential hazards, and with proper attention to the details of their deployment, any concern for their safety would disappear.

This is not to say that there is no concern over the present deployment of SCSR's in an underground coal mining environment. There have been periodic reports of incidents leading to physical damage to SCSR's since their introduction to underground coal mining in June 1981. To obtain a clearer picture of the level of abuse sustained by SCSR's since their introduction, a brief mine survey was conducted in September 1982 to uncover such incidents. The results indicated that 66 units out of 17,961 units surveyed had been damaged to the extent that they had to be replaced. Fourteen of the incidents involved heavy equipment runover, 14 involved exposure to excessive heat, and 38 were associated with rough handling; there was no instance of bottle puncture. A more alarming picture emerged from a private survey performed by one of the manufacturers of compressed oxygen SCSR's. This survey involved 225 units at a single mine where the units were carried on mantrips and had seen an average of 5.5 months of service. There were 10 instances of minor damage and 17 cases of major damage which required replacement. From any point of view, whether it be safety, economic, or just common sense, this is an unacceptably high failure rate and is indicative of a poorly designed and/or executed deployment plan. If the coal mining industry and its workers are to benefit from this new safety technology, ways must be found to assure that the SCSR's are maintained in a safe operating condition. This would eliminate any further concern over their potential fire and explosion hazards in coal mines.

RECOMMENDATIONS

On September 27, 1982, the bulk of the work in this report was presented to the officials of the Mine Safety and Health Administration. On September 30, 1982, a Labor Department news release was issued that acknowledged the Bureau's test work and outlined MSHA's position regarding the safety of self-contained self-rescuers. In the news release which is appended to this report, Joseph A. Lamonica of MSHA stated "...that because, under conditions of extreme abuse, the units can present a potential ignition or explosion hazard, SCSR's used in underground coal mines should be either properly worn by the miner, stored in heavy containers, or otherwise protected from situations in which the units might be accidently ruptured or destroyed, such as runover by mobile mine equipment." The Bureau of Mines fully concurs with this statement and recommends that current deployment plans for SCSR's be reviewed to assure that they meet the stated requirements and that periodic SCSR damage surveys be made to determine the effectiveness of the deployment plans in preventing serious damage to SCSR's.

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