SANDIA REPORT

SAND88–0145 • UC–71
Unlimited Release
Printed May 1988

High-Velocity Impact Testing of an Accident Resistant Container Using a Large Centrifuge

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Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550
for the United States Department of Energy
under Contract DE-AC04-76DP00789

SF2900Q(8-81)

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

NTIS price codes
Printed copy: A02
Microfiche copy: A01

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Distribution
Category UC-71

High-Velocity Impact Testing of an Accident Resistant Container Using a Large Centrifuge

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Abstract

An impact test technique using the 35-ft centrifuge located in Area III at Sandia National Laboratories in Albuquerque, New Mexico is described. An Accident Resistant Container was thrown into a hard target at impact velocities of up to 425 ft/s using the tangential velocity of the centrifuge. The dynamics of motion in a curvilinear path, design considerations and limitations, hardware, target setup, release mechanism, and instrumentation are discussed.

Acknowledgment

We would like to thank the people in the following Sandia divisions, without whose support the test series would not have been possible:

1552	Parachute System Division
2853	Project Design Definition Division V and Contract Drafting
3153	Motion Picture-Video Services
7556-1	Photometrics

Contents

Figures

Nomenclature

V	general velocity(ft/s)
V_r	velocity component in radial direction (ft/s)
V_θ	velocity component in angular direction (ft/s)
r	radius measured from center of centrifuge rotation to ARC unit (ft)
θ	angular displacement of centrifuge (radians)
a	general acceleration (ft/s^2)
ω	angular velocity of centrifuge (radians/s)
a_g	gravitational acceleration (32.2 ft/s^2)
CG	location of center of gravity of test unit
G	a/a_g (dimensionless)

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Introduction

The Area III 35-ft centrifuge at Sandia-Albuquerque has the capability to achieve a rotational velocity up to 15.2 rad/s, which corresponds to a maximum tip tangential velocity of 558 ft/s (380 mph). This velocity regime (0 to 380 mph) is convenient for releasing test items from the moving arm into a hard target. Test costs are relatively inexpensive when compared to other methods of impact testing, and a multitude of tests can be performed in a short period of time once the experiment is set up.

The impact idea is not new for the 35-ft centrifuge. In the early 1970s the centrifuge was used to release Accident Resistant Containers (ARCs) into various hard targets at velocities of 275 ft/s (180 mph).[1]

A renewed interest in ARC designs with more stringent survivability constraints created a need for more ARC impact testing. The Trident II Warhead Division 5153 at Sandia National Laboratories designed a new Accident Resistant Container which required impact testing up to 425 ft/s (290 mph) into a hard target to verify its structural and functional adequacy.[2]

It is the purpose of this paper to describe the new test parameters and techniques of ARC impact centrifuge testing, which are substantially different from previous ARC testing. New fixturing and different release circuitry and mechanisms have improved the test technique. The report will also show once again that impact testing using the 35-ft centrifuge is a feasible alternative to other impact test techniques.

Dynamics of Motion in a Curvilinear Path

In analyzing the ARC experimental setup, it is important to understand the governing equations of motion as applied to ARC centrifuge testing.

The general velocity equation in vector notation and polar coordinates (Figure 1) for a moving particle in a curvilinear path is as follows:

$$V = \dot{r}\, r_1 + r\dot{\theta}\theta_1 \quad (1)$$

where

$V_r = \dot{r}$

$V_\theta = r\dot{\theta}$

$V_{TOT} = (V_r^2 + V_\theta^2)^{1/2}$.

Since r is constant before the unit is released, then

$V_r = 0$

$V_\theta = r\dot{\theta}$.

Hence,

$$V = r\dot{\theta}\,\theta_1 \ . \quad (2)$$

In the postrelease condition, it is assumed that

$$V_{initial} = V_{tangential} = r\dot{\theta} \ ,$$

and therefore,

$$V_{impact} \cong r\dot{\theta} \ . \quad (3)$$

It may be further noted that $\dot{\theta}$ is rotational velocity ω, and therefore impact velocity is given by

$$V = r\omega \ . \quad (4)$$

Taking the derivative of the general velocity equation (1) above gives the acceleration components (Figure 2) in Eq (5):

$$a = (\ddot{r} - r\dot{\theta}^2)\, r_1 + (r\ddot{\theta} + 2\dot{r}\dot{\theta})\theta_1 \ . \quad (5)$$

Note that

r_1
- $\ddot{r}$ = Acceleration along radius in the absence of change of θ .
- $-r\dot{\theta}^2$ = Normal component of acceleration if r were constant as in circular motion (centrifugal accel) ($\dot{\theta}$ is due to fact that system is rotating) .

θ_1
- $r\ddot{\theta}$ = Tangential acceleration which particle would have if r were constant, but in only a part of acceleration due to change in magnitude of V_θ when r is variable ($\ddot{\theta}$ is zero at constant rpm)
- $2\dot{r}\dot{\theta}$ = Comes from two effects:
  - a) change in magnitude of V_θ due to change in r
  - b) change in direction of V_r .

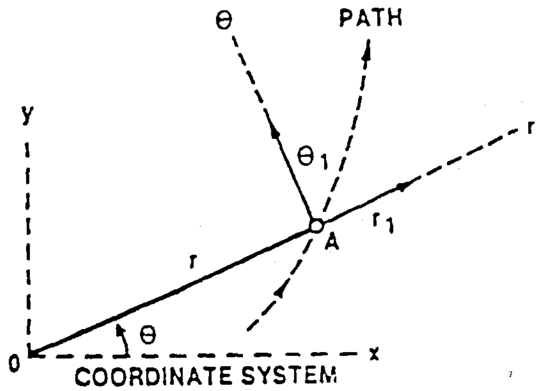
Since r is constant, both the first and second derivatives of r are zero. Also note that at constant rpm, the second derivative of θ is zero also. Therefore, the general acceleration equation simplifies to:

$$a = r\,(\dot{\theta}^2)\ . \qquad \textbf{(6)}$$

Substituting ω for $\dot{\theta}$ in Eq (6) gives

$$a = r\,(\omega^2)\ . \qquad \textbf{(7)}$$

These two simple velocity and acceleration equations, (4) and (7), are used as the basic design parameters for setting up the ARC experiment on the centrifuge.



r_1 = RADIAL (NORMAL) UNIT VECTOR
θ_1 = ANGULAR UNIT VECTOR
A = MOVING PARTICLE

Figure 1. Coordinate System

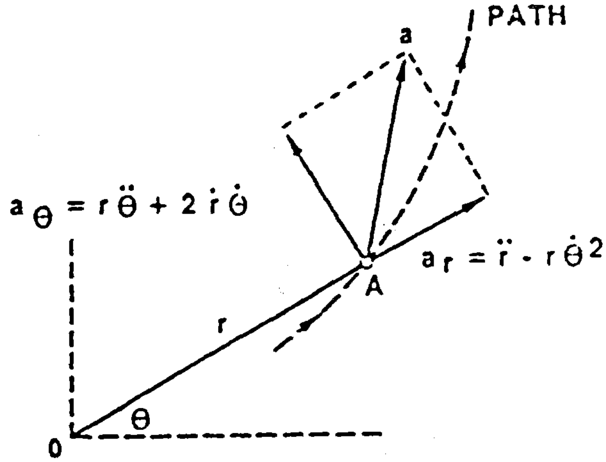


Figure 2. Acceleration Components

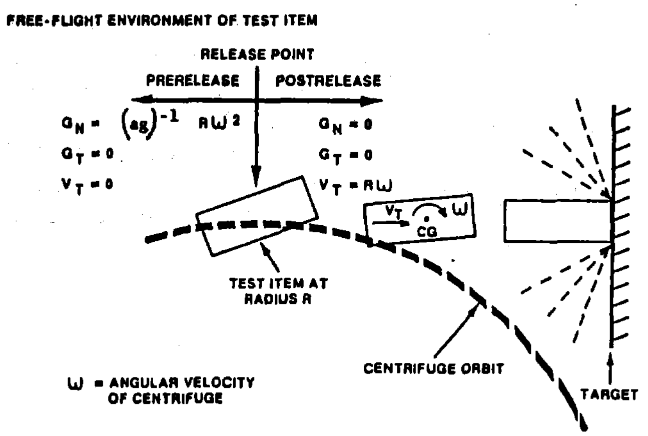
Design Considerations

The hydraulically driven 35-ft centrifuge has the following design capabilities and limitations:

• Maximum Speed (faired)	15.2 rad/s (145 rpm)
• Maximum Speed (unfaired)	8.4 rad/s (80 rpm)
• Payload Limit	10,000 lb
• Dynamic Load Limit	450,000 G-lb
• Maximum Normal Acceleration (1800-lb payload @ 35 ft)	245 G's
• Overall Length of Rotating Arm	56 ft
• Radius (center of rotation to payload bay)	35.5 ft
• Radius (center of rotation to counter weight end)	20.5 ft

The ARC experiment had a design impact velocity of 425 ft/s, which corresponded to a centrifuge rotational velocity of 108 rpm. At a 37-ft test radius, the entire payload would see up to 148 G's before release of the test item. At 148 G's, the dynamic load limitation on the machine limited the entire payload weight to 3000 lb.

With the above design constraints, a fixture was designed such that the container could impact the target axially, longitudinally, and at a 45° angle of attack. The fixture also allowed the unit to rotate about its CG, so that a normal impact would occur on the hard target (Figure 3).[1]



Source: J. V. Otts, ***Impact Testing With the 35-Foot Centrifuge***, SC-DR-72 0795. Albuquerque, NM: Sandia Laboratories, December 1972.

Figure 3. Free-Flight Environment of the Test Item

Hardware

ARC Unit

The 85-lb quarter-scale ARC unit was a 12.770-in.-diameter cylinder that was 26.996-in. long. There were three Endevco accelerometers (model 7270A) mounted within the main warhead cavity of the container, with one instrumentation cable coming out the side of the canister (Figure 4). Ten feet of instrumentation cable were wound in "accordion" style so that the cable would not break until after impact.

Centrifuge Fixture

The centrifuge variable angle fixture (Figure 5), designed specifically for the quarter-scale ARC, has the capability to withstand a 220-G load with a 100-lb container mounted to it. (Reference 3, Figure 6, and

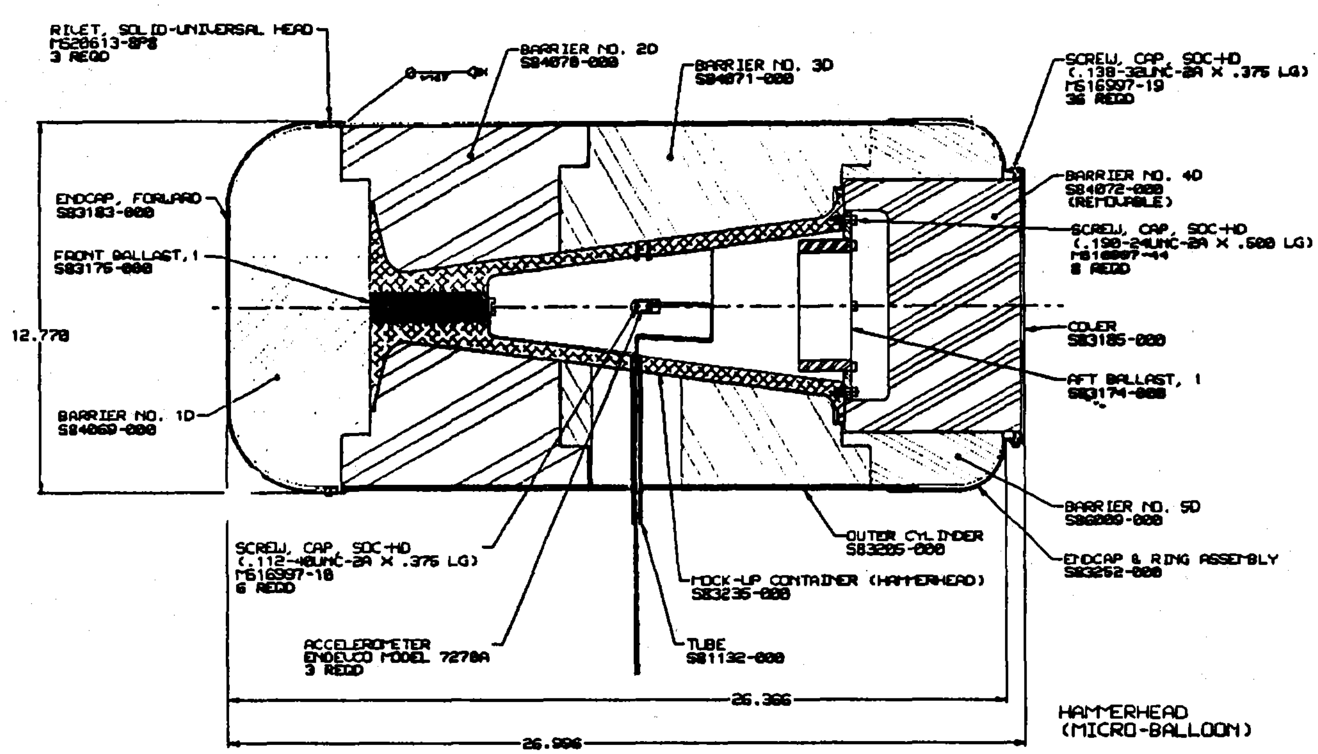


Figure 4. Quarter-Scale ARC

Sandia Drawings S73948, S73950, S73951, S73955, S73956, S73960, S73961, S73962, S73963, and S73965.) The customer requested that the 60-mil-thick outer canister of the unit not be crushed under the G load, and hence a large circular cradle with sufficient cross-sectional area to distribute the load was designed. Note, too, that a specially fabricated 4-in.-wide Kevlar strap was used to mount the canister to the cradle. The cradle was designed such that a 3-in.-axial elongation could be preloaded into the Kevlar strap so that it would not stretch under the G field. Also, a Holex cable was slipped onto a 3-in.-long, 0.5-in.-diameter piece of Kevlar rope that was connected to the main Kevlar strap for release purposes. (See details of Holex cable cutter and release mechanism in later paragraphs.)

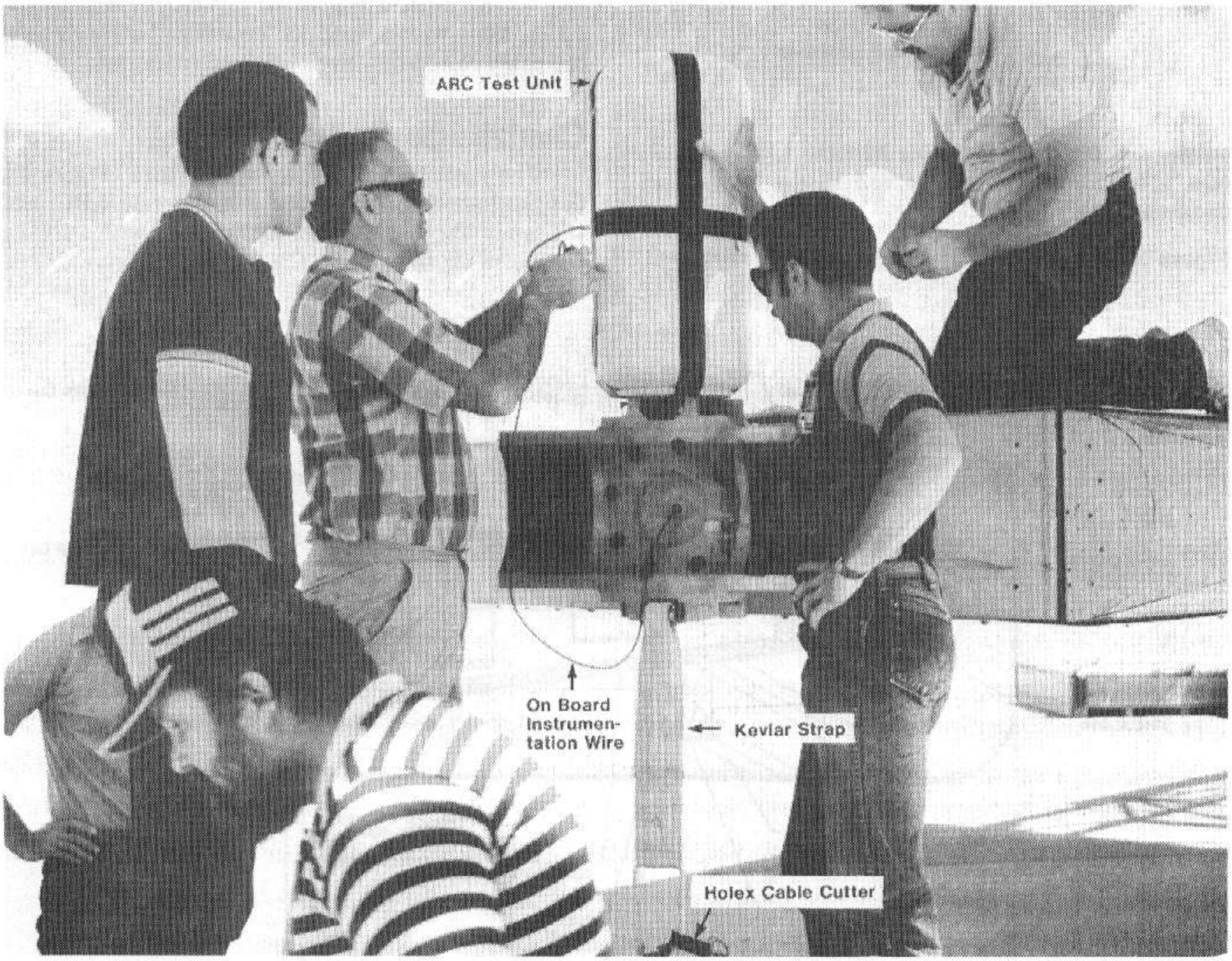


Figure 5. Centrifuge Fixture

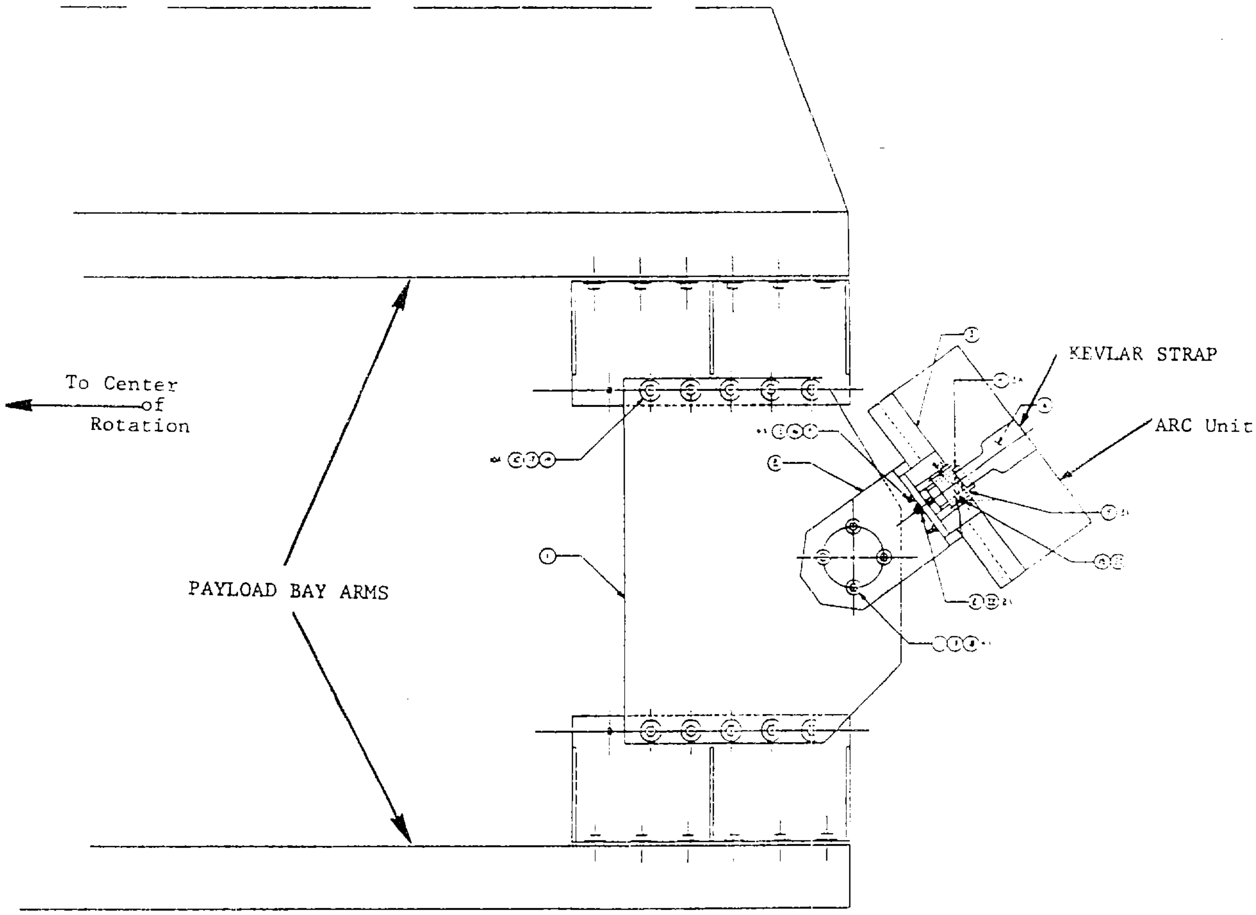


Figure 6. Plan View of Centrifuge Variable Angle Fixture

Target Area

The amount of mass required to prevent the impact target from moving was determined from an impulse-momentum relationship. Hence, an impact target (Figure 7) consisting of a reinforced concrete block 5×2×12 ft (~18,000 lb) faced with a steel plate 4×8×2-in. (~2600 lb) was designed to absorb the impact loads of the ARC. Of course, the CG of the impact mass was difficult to hit with the container, and bracing of the block was required to keep the block from rotating during every shot.

A major concern in the target area was the rebound of the ARC into the path of the rotating centrifuge arm. It was possible that the ARC could be "batted" out of the 48-ft-diameter bullpen that surrounds the centrifuge. Hence, three catcher sandboxes (12×12×1 ft) were placed on the ground in front of the impact area to absorb some of the rebound energy of the container.

High-speed cameras were mounted for orthogonal views of the angle of attack of the unit. A 2000-frames/second (fps) camera was mounted on the overhead bridge crane structure, and a second 2000-fps camera was mounted on top of the bullpen wall. An overall camera set at 400-fps monitored the entire impact area. A real-time videotape of the event was recorded for each shot, and a videotape of impact testing is available.

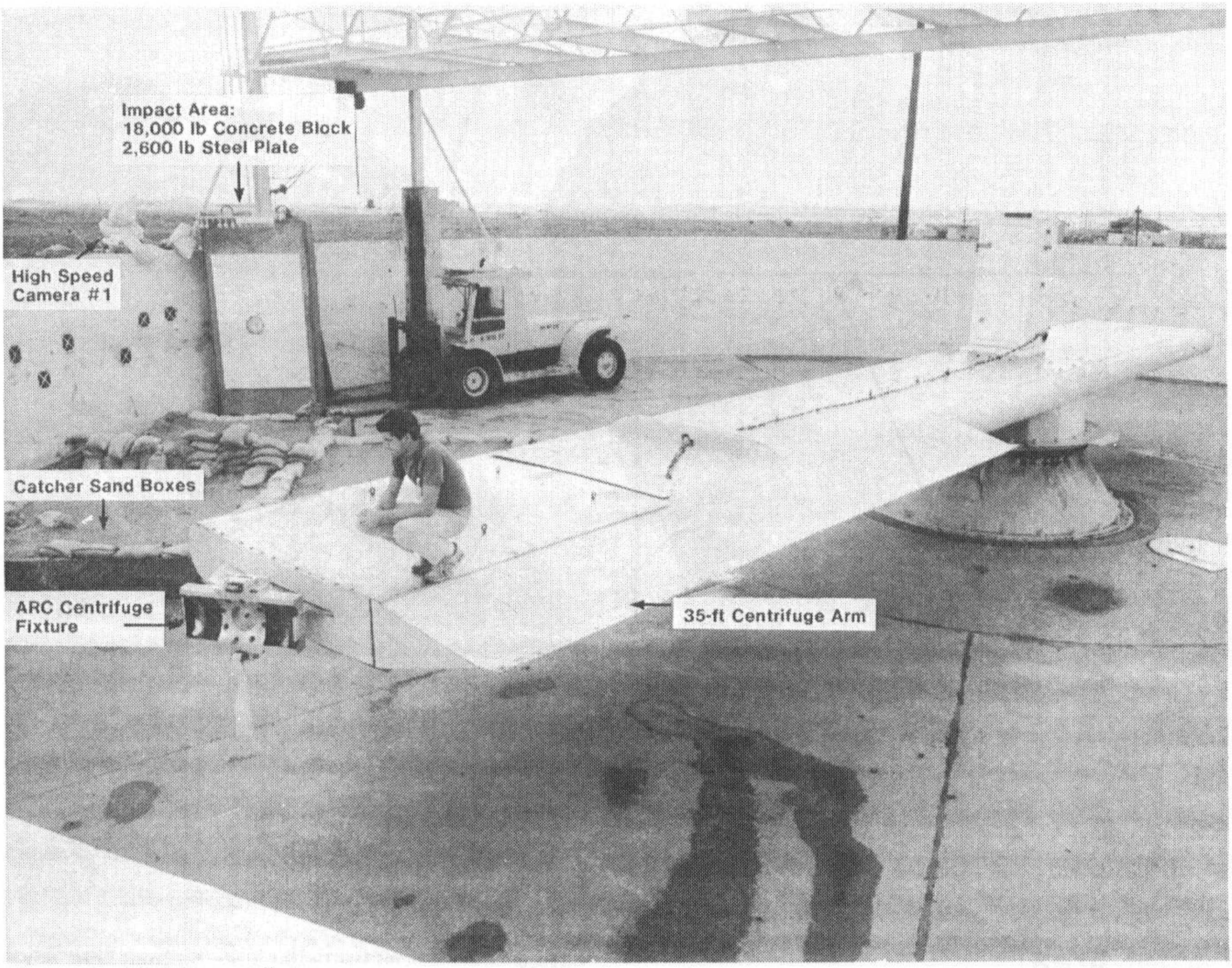


Figure 7. ARC Target Setup

Release Mechanism

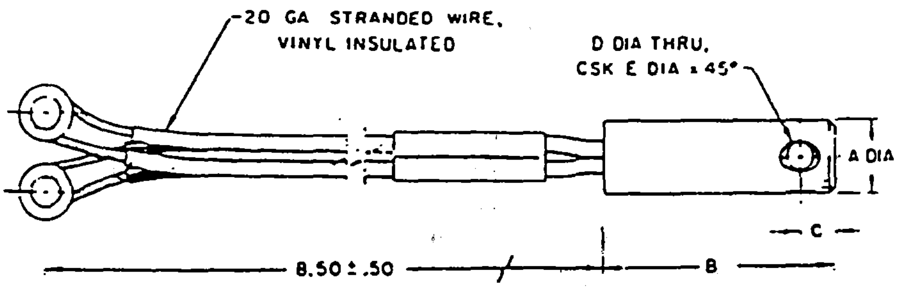
During previous impact testing programs in the 1970s, a photodiode was mounted to the base of the centrifuge structure to reference the position of the arm to a desired release point of the test object. A signal from the photodiode was fed to the control room in Building 6526 and to the firing circuit mounted in the doghouse on the centrifuge arm. The photodiode signal would energize a light-emitting diode at the firing panel, in Building 6526, each time the centrifuge arm passed the release point. Once the centrifuge system was at the correct speed, the firing relays were energized and the photodiode would fire the cable cutter the next time it passed the release point.

A Holex cable cutter was used to release the ARC unit in both previous tests in the 1970s and in the current tests (Figure 8). The explosive guillotine cutter used in current tests (model 2803) is designed to operate with a 0.5-A no-fire and a 1.5-A all-fire condition. To fire the Holex cable cutter, a 28-V, 5-A power supply was used to supply the current to the cutter, and an SCR (2N688) was used to control the switching of the firing current (Figure 9). To maintain a safe operating condition, the facility operator must be familiar with the SOP #06801 8705 which pertains to the wiring and handling of the Holex cable cutters. There is also a step-by-step checklist called IMPK-CHK (see Appendix) that must be used to fire the release system at the centrifuge.

TECHNICAL DATA SHEET
HOLEX SERIES 2800 GUILLOTINES

DESCRIPTION

The HOLEX 2800 Series Guillotines are small, propellant actuated cutting devices . The unit is electrically initiated and a propellant charge drives a piston with a wedge-shaped knife through the cable, hose or bolt located in the guillotine opening. The severance of the cable, tube or bolt is clean and practically silent. The unit does not give off shrapnel in operation, and may be fired without a cable or tube in the opening without danger of fragmentation. The HOLEX Model 2800 Guillotines are classified as "Class C" Explosives and may be shipped by either Air Express or Air Freight as well as by surface transportation. The 2800 Series Guillotines are a simple, reliable, efficient and safe unit for accomplishing rapid severance of mechanical units. Tho significant characteristics of these units are given below.



APPLICATION DATA

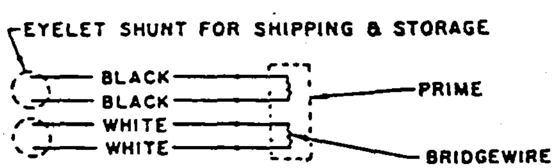
The 2800 series guillotines have been extensively tested for operation over a temperature range of −60°F to +200°F and are designed to meet most current military environmental specifications.

These guillotines will cut the following specific cables:

MODEL 2800—3/32 DIA 7x 7 CRES CABLE PER MIL-C-5424
MODEL 2801—3/16 DIA 7x19 CRES CABLE PER MIL-C-5424
MODEL 2802—3/8 DIA 7x19 CRES CABLE PER MIL-C-5424
MODEL 2803—7/16 DIA 7x19 CRES CABLE PER MIL-C-5424
½ DIA 6x19 GALV STL COMMERCIAL CABLE

For applications involving other sizes and materials please contact HOLEX incorporated.

HOLEX PART NO.	DIA A ±.005	DIM. B ±.035	DIM. C ±.025	DRILL D DIA	CSK E DIA	UNIT WT (OZ)
2800	.375	1.490	.200	#30 (.1285)	.188	7/8
2801	.500	2.01	.250	1/4 (.2500)	11/32	1
2802	.875	3.120	.870	7/16 (.4375)	5/8	3-1/2
2803	1.125	3.500	.800	9/16 (.5625)	7/8	6



SCHEMATIC

FIRING CHARACTERISTICTS (EACH BRIDGEWIRE)

NO-FIRE CURRENT	0.5 AMP MAX
ALL-FIRE CURRENT	1.5 AMPS MIN
BRIDGEWIRE RESISTANCE (THRU LEADWIRES)	0.66 ± .08 OHM
LEADWIRE-TO-CASE NO-FIRE	1000 V AC RMS MAX
LEADWIRE-TO-CASE RESISTANCE	2 MEGOHMS MIN AT 500 V DC
RECOMMENDED ALL-FIRE CURRENT	5 AMPS PER BRIDGE

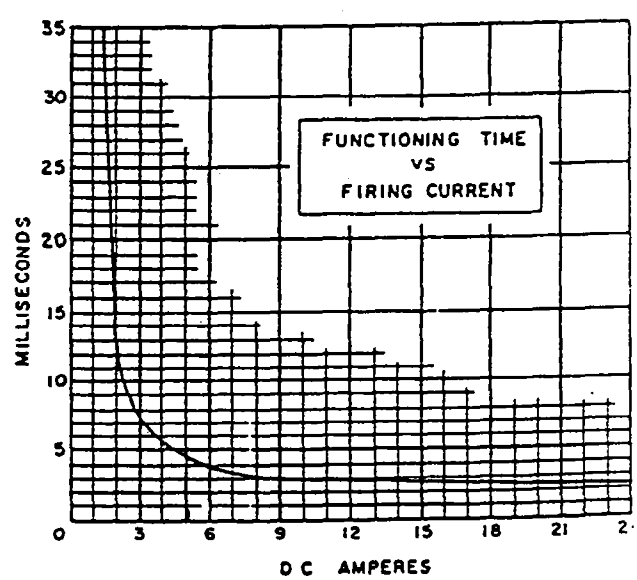


Figure 8. Holex Cable Cutter Data Sheet

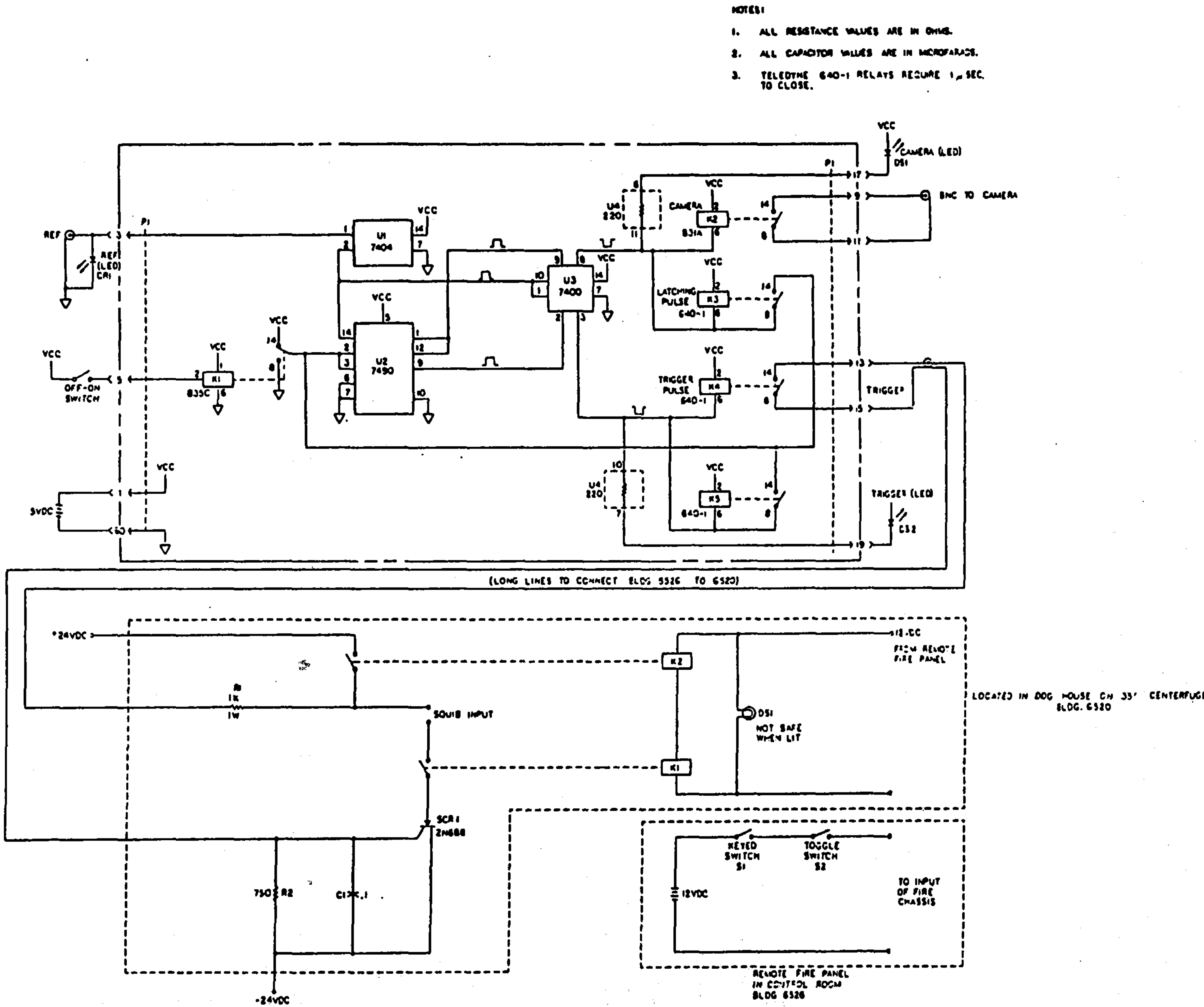


Figure 9. Impact Release Mechanism Schematic

It should be noted that the previous ARC test parameters (1970s) were slow enough (~1 revolution per second, rps) to allow the operator to energize a toggle switch between revolutions. However, the new ARC system was turning at nearly 2 rps, and the high-speed cameras had to be started 1 revolution before impact to allow the cameras to come up to speed before filming the impact shot. Hence, a different method of release was designed.

To release the ARC unit at a specific location, a precise method of determining the position of the arm was needed. To do this the incremental shaft encoder on the centrifuge was used. This optical encoder, model number H25E-SS-6000 made by BEI Electronics, puts out 6000 counts per revolution (± 1 count) plus one reference pulse per revolution. Note that the encoder is normally used to determine the rotational velocity of the centrifuge while operating. The encoder is adjustable, however, on the shaft of the centrifuge and therefore the reference pulse can be changed to match the release point of the ARC unit. The exact release point of the ARC unit, plus the delay time of the Holex cable cutter, was determined and the reference point of the encoder was adjusted to match this point. The reference pulse was then fed to a timing counter that was used to start the high-speed cameras and to activate the firing circuit for the Holex cable cutter. The timing counter was activated by the facility operator when the centrifuge was at the speed requested by the test consultants. Once the timing counter was activated, it caused the high-speed cameras to start the first time the centrifuge arm passed the release point, and activated the firing circuit for the Holex cable cutter the second time the centrifuge arm passed the release point.

To compute the delay time in the timing system, a Nicolet high-speed digital scope, model 2090, was used. The reference pulse, at the encoder, was fed to one channel of the scope, and a break wire that was cut by the Holex cable cutter was fed to the second channel. The system was activated by the reference pulse, which was recorded on the first channel, and the Holex cable cutter fired which in turn cut the break wire, giving a second pulse that was recorded on the second channel. The difference in the two pulses on the scope represented the actual delay time in the complete circuit, including the long lead lines and the propagation time of the explosive charge in the Holex cable cutter. This time delay turned out to be approximately 5.5 ± 0.5 ms. Because of the monetary expense involved in using an actual Holex cable cutter for circuit time delay determination, only 5 trial runs were made. The release time was very repeatable, but inherent noise problems caused by the long lead lines and the old slip rings were of a large enough voltage amplitude to cause the SCR to go into conduction accidently. This in turn caused a spontaneous firing of the Holex cable cutter. There were three such incidents in the ARC test series. It was felt that this problem could be solved in the future by optically coupling the timing circuit and the firing circuit.

To test the position of the release point, an audible detector was connected to the reference pulse signal and a plumb bob was connected to the CG of the test item. By using this system, the exact release point was located by rotating the centrifuge (by hand) to the release point until the audible detector sounded. After this point was located, a distance equal to the time delay was added in and the new release point was shifted by this amount.

Conclusion

Impact testing at the centrifuge in Area III provides a convenient method of testing the structural and functional adequacy of a consultant's design of a test item. This process, although not a new one, has been refined to allow higher tangential velocities and more accurate release points. It is a relatively inexpensive impact test method with a quick turnaround time.

A major advantage to impact testing on the centrifuge, as opposed to other impact test environments, is that it allows the test consultants to do an instrumentation precheck, once at the required velocity, before actually releasing the test unit. This would allow the consultant to abort the test without destroying the test item. The test item must, however, meet the size, weight, and velocity constraints mentioned within this report.

A total of 16 actual test units were impacted into the target. Some of the 16 were instrumented with accelerometers located at the center of the warhead container, and others were thrown without accelerometers to verify the structural design of the unit. All information from these transducers is given in Reference 2.

The high-speed camera coverage that is available through Sandia's photometric division allows a detailed viewing of the events that occurred during impact of the test item into the target area. It was noted in the films, however, that the Holex cable cutter fired randomly in approximately 2 out of every 10 container releases. This is due primarily to the inherent noise problems caused by the long lead lines and old slip rings on the 35-ft centrifuge.

References

[1]J. V. Otts, *Impact Testing with the 35-Foot Centrifuge*, SC-DR-72 0795 (Albuquerque, NM: Sandia Laboratories, December 1972).

[2]R. K. Thomas, N. G. Rackley, and R. E. Howell, *Feasibility Study of an Accident Resistant Container for Fleet Ballistic Missile Reentry Bodies, and the Impact of the Risk of Air Transport*, SAND87-2845 (Albuquerque, NM: Sandia National Laboratories, to be published).

[3]J. R. Garcia, Letter to T. B. Lane, "ARC Centrifuge Fixture Design Capabilities and Limitations" (Albuquerque, NM: Sandia National Laboratories, June 1987).

APPENDIX

IMPK-CHK:

CHECKLIST FOR IMPACT FIRING AT THE 35-FT CENTRIFUGE

BEFORE WIRING THE HOLEX CABLE CUTTER:

_____ 1. "IMPACT FIRE TIMING PANEL"—POWER OFF

_____ 2. "IMPACT REMOTE FIRE PANEL"—KEY SWITCH IS OFF & ARM-SAFE SWITCH IS IN "SAFE" POSITION

_____ 3. 28-V POWER SUPPLY IN DOGHOUSE IS OFF

_____ 4. WIRE CABLE CUTTER ACCORDING TO S0P #06801 8705

BEFORE TEST

_____ 5. TURN 28-V POWER SUPPLY ON
(Note: This supplies power to the firing circuit in the doghouse)

_____ 6. "IMPACT FIRE TIMING PANEL"—POWER ON AND PUSH RED RESET BUTTON
(Note: Energizing the "IMPACT FIRE TIMING PANEL" will energize the 12-Vdc power supply. See schematic impact release mechanism)

_____ 7. BRING CENTRIFUGE UP TO REQUIRED RPM.

_____ 8. START 10-SECOND COUNTDOWN

_____ 9. AT COUNT 10—"IMPACT REMOTE FIRE PANEL"—TURN KEY SWITCH ON

_____ 10. AT COUNT 1—"IMPACT REMOTE FIRE PANEL"—ARM-SAFE SWITCH TO "ARM"
(Note: When Key switch and toggle switches are both energized the 12-Vdc is applied to the remote firing circuit.)

_____ 11. AT COUNT 0—ENERGIZE TOGGLE SWITCH ON TIMING BOX
(1ST REV. CAMERAS ARE TURNED ON)
(2ND REV. CUTTER IS FIRED)

AFTER RELEASE

_____ 12. "IMPACT FIRE TIMING PANEL"—POWER OFF

_____ 13. "IMPACT REMOTE FIRE PANEL"—KEY SWITCH IS OFF & ARM-SAFE SWITCH IS IN "SAFE" POSITION

_____ 14. 28-V POWER SUPPLY IN DOGHOUSE IS OFF

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