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2.6 NORMAL CONDITIONS OF TRANSPORT

Tests which demonstrate normal conditions of transport are specified in 10 CFR, Ch. 1 Section 71.71. One critical component of the F-294 package is the C-188 sealed source capsule, which is part of the containment system of F-294. This capsule is illustrated in Chapter 4, Appendix 4.4.2. It is designed, tested and certified to meet the requirements of both the IAEA SS 6 - Special Form Requirements (Ref. [9]) and the ANSI Standard N542 (Ref. [10]). Certification of performance to these standards is also included in Chapter 4, Appendix 4.4.2.

2.6.1 HEAT

A detailed thermal evaluation of the normal conditions of transport as they apply to the F-294 Package is reported in Chapter 3, Section 3.4. For 360 kCi of cobalt-60 in the cavity of F-294, the maximum steady state temperature within the cavity is determined to be 824°F (440°C) (C-188 source temperature). This temperature will be the same for both the F-294/F-313 and F-294/F-457 configurations.

2.6.1.1 Summary of Pressure and Temperatures

2.6.1.1.1 Summary of temperatures in the F-294 package

For 374,428 Ci of cobalt-60 loading (5.766 kW), the temperature distribution of the F-294 package is given in Table 2.6-T1 and Figure 2.6-F1. The temperatures stated in the Table 2.6-T1, column 2, include the following three (3) temperature correction factors:

1. Ambient temperature factor: (38°C - 20°C) = 18°C
2. Total measurement errors: ± 3°C for temperature range up to 300°C and ± 4 °C for temperature range up to 450° C.
3. Solar heat factor impact on the cask temperatures: (1)

2.6.1.1.2 Summary of pressures in the F-294 package

The determination of the pressure build-up inside the cavity of the F-294 container and the C-188 sealed source is presented as follows:

Maximum Internal Pressure

#1. Cavity of F-294

The calculations for the pressure build-up in F-294 cavity are presented in Chapter 3, section 3.4.4. We shall recapture the results here. Given that the maximum activity within the cavity is the same regardless of the source carrier used, temperatures of the F-294 container will be the same for both the F-313 and F-457 source carriers.

The cavity of F-294 in normal conditions of transport is at 16 psig and average environment temperature of 606°F.

#2. C-188 Assembly.

The calculations for the pressure build up in C-188 assembly are presented in Chapter 3, section 3.4.4. We shall recapture the results here:

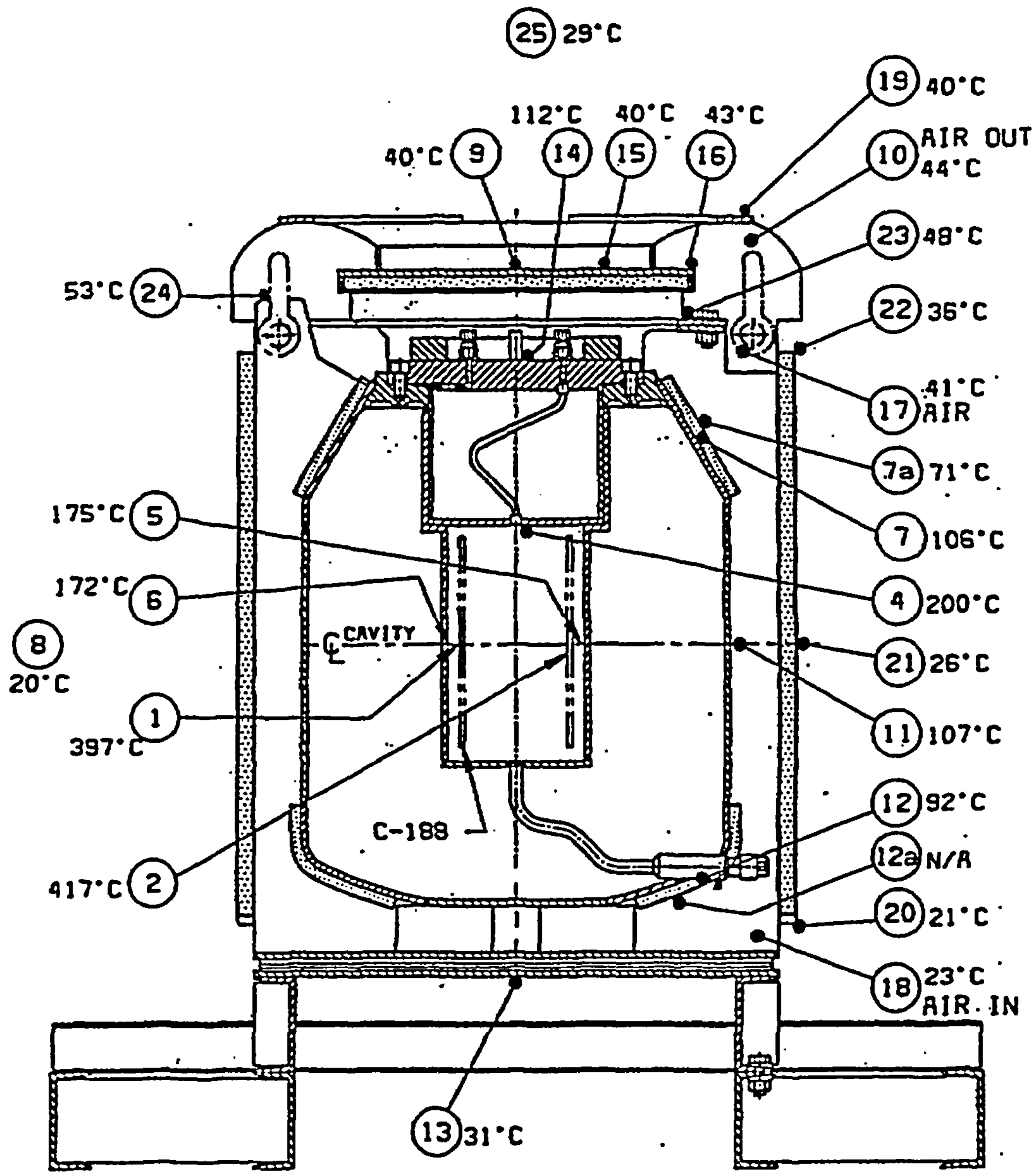
During normal conditions of transport of C-188's in F-294, the C-188 has internal pressure of 22 psig and temperature of 824°F (440°C).

Table 2.6-T1
F-294 Steady State Temperature Distribution Prior to Drop Test of the F-294 (F-313 Source Carrier Configuration)

Cobalt Loading	Test	Test	FEM	Node
External surface of package:				
Ambient	38°C	20°C	38°C	400
Bottom of ext. cyl. fireshield	43°C	21°C	45°C	373
Middle of ext. cyl. fireshield	48°C	26°C	44°C	251
Top of ext. cyl. fireshield	58°C	36°C	49°C	315
Bottom of fin (air), entrance to chimney	45°C	23°C	N/A	-
Top of crush shield (air), exit from chimney	66°C	44°C	N/A	-
Top of the lift lug	75°C	53°C	70°C	709
Top crush shield/fireshield, upper surface, centre	62°C	40°C	51°C	85
Top crush shield/fireshield, upper surface, midway centre/edge	62°C	40°C	51°C	88
Top crush shield/fireshield, upper surface, edge	65°C	43°C	52°C	295
Crush shield, fin bottom	49°C	48°C	N/A	-
Main shield plug (top surface)	134°C	112°C	149°C	40
Container fin (root)	129°C	107°C	117°C	185
Container fin (tip)	N/A	N/A	100°C	702
Container wall, conical surface (primary shell),	N/A	N/A	81°C	717
Container wall, conical surface (secondary shell)	N/A	N/A	131°C	118
Container wall, mid-level	129°C	107°C	117°C	185
Container wall, bottom (primary shell)	N/A	N/A	96°C	215
Container wall, bottom (secondary shell)	N/A	N/A	83°C	732
Section through the shielding of the container: mid-level				
Outer wall (external - mid level)	129°C	107°C	117°C	185
Outer wall (internal - mid level)	N/A	N/A	118°C	173
Lead shielding (outside radius)	N/A	N/A	152°C	673
Lead shielding, average	N/A	N/A	N/A	-
Lead shielding (inside radius)	N/A	N/A	181°C	141
Cavity wall (outside radius)	N/A	N/A	181°C	141
Cavity wall (inside radius)	197°C	175°C	181°C	146
Cavity bottom	N/A	N/A	172°C	136
C-188: One ring Only: S/N 59532	440°C	417°C	N/A	-
C-188: One ring Only: S/N 59475	438°C	415°C	N/A	-
Bottom of the main shield plug	222°C	200°C	215°C	17

Notes: [1] Corrected for ambient, measurement errors and solar heat, see Chapter 3, Appendix 3.6.2 for details.
[2] Measured test data,, see Chapter 3, Appendix 3.6.2 for details (374,428 Ci.; 5.766 kW)
[3] Finite Element Model (FEM) heat transfer model, see Chapter 3, Appendix 3.6.4 for details.

Figure 2.6-F1
Measured Steady State Temperature for F-294 Container (374,428 Ci load: 5.766 kW) Before the F-294 Drop Test (with F-313 Source Carrier)



T/C #3 - C-188 TEMPERATURE (415°C), NOT SHOWN IN THIS PLANE

2.6.1.2 Differential Thermal Expansion

The temperatures to determine the thermal expansions are taken from Chapter 3, Appendix 3.6.4. Given that the maximum activity within the cavity is the same regardless of the source carrier used temperatures of the F-294 container will be the same for both the F-313 and F-457 source carriers.

Axial - Stainless Steel Expansion

1. Container external stainless steel wall of primary shell: 253.4°F (123°C) at top (Node 105), 280.4°F (138°C) at bottom (Node 600).
   $\Delta L = L_0 * \alpha_{SS} * \Delta T$
   $= 43 \text{ in.} * [10 * 10^{-6}] \text{ in/in/°F} * [280.4 - 253.4] \text{ °F}$
   $= 0.012 \text{ in.}$
2. Container internal stainless steel lower cavity wall:
   345°F (174°C) at top (Node 93), 336.2°F (169°C) at bottom (Node 138).
   $\Delta L = L_0 * \alpha_{SS} * \Delta T$
   $= 19.75 \text{ in.} * [10 * 10^{-6}] \text{ in/in/°F} * [345.2 - 336.2] \text{ °F}$
   $= 0.002 \text{ in.}$
3. Container internal stainless steel upper cavity wall:
   285.8°F (141°C) at top (Node 98), 332.6°F (167°C) at bottom (Node 7).
   $\Delta L = L_0 * \alpha_{SS} * \Delta T$
   $= 11 \text{ in.} * [10 * 10^{-6}] \text{ in/in/°F} * [332.6 - 285.8] \text{ °F}$
   $= 0.006 \text{ in.}$
4. Plug Cylinder:
   320°F (160°C) at top (Node 16), 387°F (197°C) at bottom (Node 4).
   $\Delta L = L_0 * \alpha_{SS} * \Delta T$
   $= 11 \text{ in.} * [10 * 10^{-6}] \text{ in/in/°F} * [387 - 320] \text{ °F}$
   $= 0.008 \text{ in.}$

The plug has clear, free room to expand axially up to 0.040 in.

Diametrical - Stainless Steel Expansion

1. Cavity wall
   $\Delta D = D_{mean} * \alpha * \Delta T$
   $= 12.0 * 10 * 10^{-6} * [358.9 \text{ (Node 146)} - 357.8 \text{ (Node 141)}] \text{ °F}$
   $= 0.0001 \text{ in.}$
2. External wall
   $\Delta D = D_{mean} * \alpha * \Delta T$
   $= 35.5 * 10 * 10^{-6} * [244.4 \text{ (Node (173)} - 242.6 \text{ (Node 185)}] \text{ °F}$
   $= 0.0006 \text{ in.}$

The container has clear free room to expand; therefore thermal stresses shall not arise.

2.6.1.3 Stress Calculations

1. C-188 Sealed source:

C-188 Sealed Source: Due to build up of internal pressure, C-188 encapsulation stresses are calculated and presented in Chapter 4, Appendix 4.4.4.

Due to internal pressure of 22 psig in the C-188 during Normal Conditions of Transport of the F-294,

- the hoop stress in the tube away from joint = 157 psi
- the hoop stress in the tube at the joint = 235 psi
- the bending stress in the end cap = 4 psi.

Based on yield stress of 16,500 psi for ss316L at 824°F, C-188 has a Factor of Safety of 70.2 and Margin of Safety of 69.2 Therefore the containment, i.e., the outer assembly of C-188 sealed source, shall maintain its structural integrity.

2. Main Closure Plug Bolted Joint:

Due to build-up of internal pressure, the main closure plug bolted joint is examined in detail in Chapter 2, Appendix 2.10.4 and Chapter 4, Appendix 4.4.3. The internal pressure in the cavity is 16 psig; see Figure 2.6.1-F2. The bolted joint shall be maintained during the normal conditions of transport.

The internal pressure load, W_{OP} is calculated as follows:

$$\begin{aligned} W_{OP} &= \Delta P * \text{Area} \\ &= \Delta P * [\pi * G^2/4] \\ &= 16. * \pi * 15.91^2/4\ [\text{psi} * \text{in}^2] \\ &= 3{,}200\ \text{lb.} \end{aligned}$$

where

W_{OP} = internal pressure load in pounds
ΔP = 16 psi (internal pressure - outside the F-294 container at atmospheric pressure)
G = gasket reaction diameter = 15.91 in.

The gasket seating load, F_{SG}, is calculated as follows:

$$F_{SG} = \pi * b * G * y$$

where

F_{SG} = gasket seating load in pounds
b = effective gasket seating width
G = gasket diameter
y = gasket seating stress = 200 psi
(Ref. [17] i.e., ASME VIII Div. I: Table UA-49-1)

Basic gasket seating width, b_O = actual width of gasket/2
= (16.38 – 15.44) x 0.5/2
= 0.235 in.

When $b_O \le 1/4$ in., the effective gasket seating width, $b = b_O = 0.235$ in.
When $b_O \le 1/4$ in., diameter at location of gasket reaction, G

G = Mean diameter of gasket contact face
= (16.38 + 15.44) x 0.5
= 15.91 in.

Gasket seating load, F_{SG}

$F_{SG} = \pi * b * G * y$
$= \pi * 0.235 * 15.91 * 200$
$= 2{,}400$ lb.

Therefore, gasket seating and internal pressure load acting on the plug,

$W_{\text{bolt load required}} = FSG + WOP$
$= 2{,}400 + 3{,}200$
$= 5{,}600$

Design check: what is the total bolt load available on basis of 2/3 * yield stress of the bolt material?

16 cap screws (1-8-UNC: UNBRAKO 1960) 1-in. are specified as closure plug bolts.

For UNBRAKO 1960 cap screw material, UTS = 180,000 psi; YS = 155,000 psi.

Bolt data - 1-in. nominal diameter
stress area per bolt = 0.551 in^2
root diameter = 0.838 in
UNC = coarse thread
8 threads per inch (8 tpi).

$W_{\text{bolt load available}}$ = no. of bolts x bolt area x allowable stress
$= 16 \times 0.551 \times [2/3 \times YS]$
$= 16 \times 0.551 \times 0.667 \times 155{,}000$
$= 911{,}000$ lb.

As $W_{\text{bolt load available}}$ (911,000 lb.) > $W_{\text{bolt load required}}$ (5,600 lb.), the closure plug bolting design is more than adequate to resist the forces on the closure plug due to internal pressure.

Safety factor (SF) $= W_{\text{bolt load available}} / W_{\text{required closure plug, NCOT}}$
$= 911{,}000$ lb./5,600
$= 162$

Margin of Safety = SF – 1 = 162 – 1 = 161

As the margin of safety (MS) is greater than zero, the bolted joint as specified shall be maintained during normal conditions of transport of the F-294 package.

Consequently, the bolted joint shall be maintained during the normal conditions of transport.

3. Cavity wall due to build -up of internal pressure:

The hoop stress in the lower cavity tube, without taking lead restraint into account, is as follows:

$\sigma_{hoop} = p\, d / 2t$

where

p = 16 psig internal pressure
d = mean diameter of lower cavity tube = 12.0 in.
t = 0.500 in.
$\sigma_{hoop} = 16 \times 12/2 \times 0.5 = 192$ psi.

For ss304L at 400°F, yield stress = 20,000 psi.

Safety Factor (SF) = allowable stress/applied stress
= $0.667 \times YS/\sigma_{hoop}$
= $0.667 \times 20{,}000/192$
= 69.4

Margin of Safety (MS) = SF – 1 = 69.4 – 1 = 68.4

4. Lower Cavity End Cap:

The bending stress in the lower cavity end cap, without taking restraint of lead into account, is as follows:

$\sigma_b = cp/[t/d]^2$

where

c = constant based on joint geometry
= 0.2 based on ASME VIII, Division 1, Figure UG = 34 (i)

p = internal pressure = 16 psig

t = thickness of end cap = 0.75 in.

d = internal diameter of the tube = 11.5 in.

$\sigma_b = 0.2 \times 16/[0.75/11.5]^2 = 752$ psi.

For Hastelloy C-276, YS, yield stress at 400 °F = 37,000 psi

Safety Factor (SF) = allowable stress/applied stress
= $0.667 \times YS / \sigma_b$
= $0.667 \times 37{,}000/752$
= 32.8

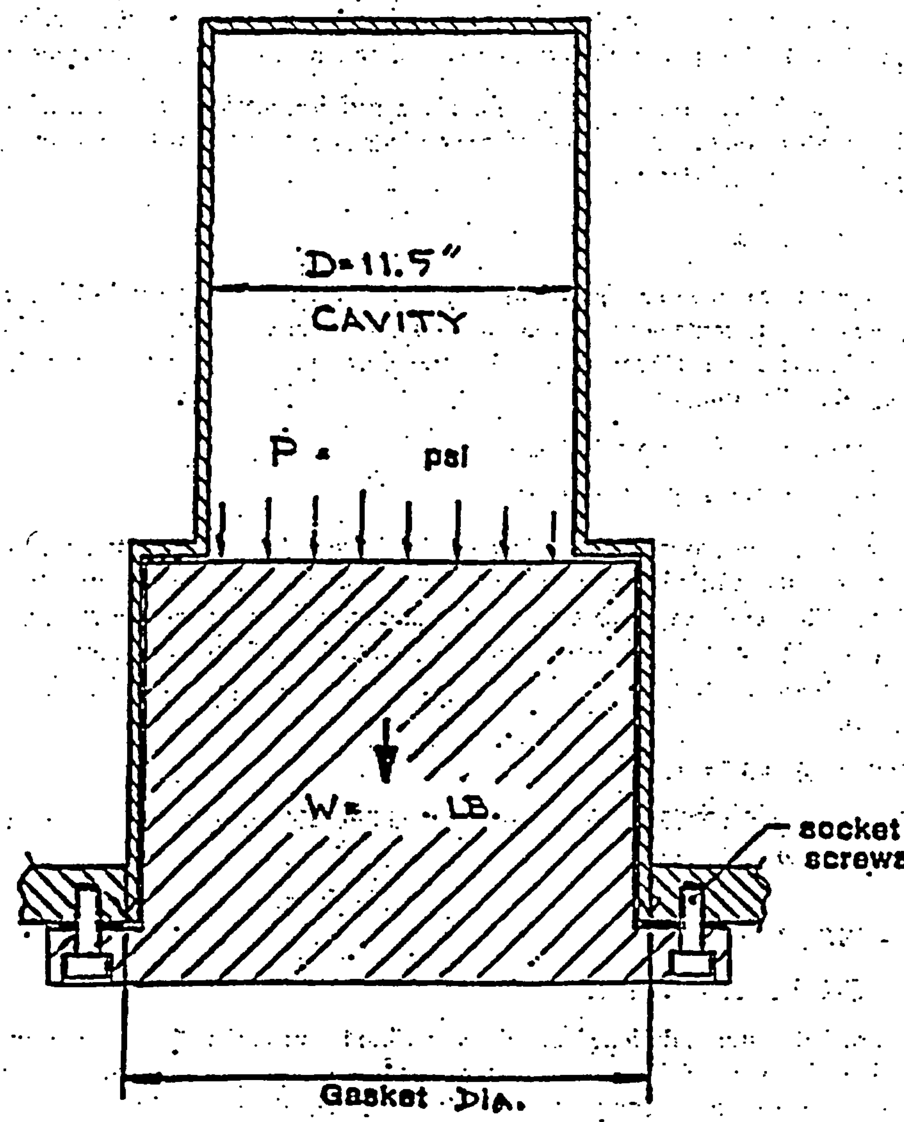
Margin of Safety (MS) = SF – 1 = 32.8 – 1 = 31.8

Therefore, the lower cavity assembly under build-up of pressure of 16 psig has sufficient margin of safety such that the structural integrity of the cavity assembly shall not be compromised.

5. Thermal stresses

Based on the estimates of thermal expansions given in section 2.6.1.2, there are no significant thermal stresses as the components have sufficient room to expand freely.

Figure 2.6.1-F2
Internal Cavity Pressure on the Closure Plug



2.6.2 COLD

A steady-state ambient temperature of −40°F (−40°C) would not adversely affect the ability of the package to contain its radioactive contents or shield the environment. There are no liquids present within the package to freeze under these conditions nor are the materials used in the construction of the package (see Table 2.3-T1) subject to brittle fracture as discussed in section 2.1.2 of this report.

Because of the high thermal conductivity of the lead, stainless steel and carbon steel, the primary materials used in the construction of the container of this package, no steep thermal gradients exist in the container to cause significant thermal stresses.

2.6.3 PRESSURE

An external pressure equal to 3.5 psia would have no effect on the package. In Chapter 2, Appendix 2.10.5, it is presented that the container shall withstand 44 atmospheres (650 psi) without taking credit of lead shielding and fin restraint. Therefore the F-294 container shall have no difficulty withstanding the external pressure equal to 3.5 psia.

Safety Factor (SF) = 650 / (3.5 + 14) = 37

Margin of Safety (MS) = SF − 1 = 37 − 1 = 36

The package is designed to transport radioactive C-188 sealed sources. These sealed source have been designed, tested and certified to meet the Class 5 external pressure test requirements of the ANSI N542 Standard (see Chapter 4, Appendix 4.4.2). This test requires that the capsule be subjected to external pressure ranging from 3.5 psia to 10150 psia without any loss of integrity. Hence, the source capsule is designed to withstand external pressures ranging from 0.25 atmospheres (3.5 psia) to 690 atmospheres (10,150 psia).

Safety Factor = 690/0.5 = 1,380.

Hence, in summary, the F-294 package would be unaffected by an external pressure equal to 0.5 standard atmospheric pressure.

2.6.4 VIBRATION

2.6.4.1 C-188 Sealed Source

The C-188 sealed source is designed, tested and certified to meet the Class 4 vibration test requirements of ANSI N542 Standard. This test requires the capsules to be subjected to vibrations ranging from 25 to 80 Hz at 1.5 mm peak to peak amplitude and 80 to 2000 Hz at 20 g for 90 minutes. According to RDT Standard No. F-8-9T (Ref. [23]), the highest frequency of vibration encountered during normal transport by road is 500 Hz. As the 2000 Hz level of the ANSI N542 vibration test is higher than the vibration frequency of 500 Hz encountered in road transport, this test, along with clean track operational record, provides a reasonable assurance that the C-188 sealed source is unaffected by the vibrations due to normal conditions of transport.

2.6.4.2 Packaging

The fasteners used on the F-294 package are listed as per Table 2.6-T2; the applied nominal torque on each of the fasteners is also given in Table 2.6-T2. The variation on the nominal torque is ± 10%. The assessment of the effect of vibrations due to normal conditions of transport is carried out analytically and on the basis of the field experience of the similar F-231 package. The areas that are considered susceptible to the effects of the vibrations are as follows.

1. closure plug screw
2. fasteners for fireshield, crush shield and skid.

2.6.4.2.1 *Demonstration by Analysis*

a) It is assumed that the closure plug screws would loosen only if the plug "NEOPRENE" gasket assembly attained resonance, meaning the applied frequency is equal to the natural frequency (ω_n).

ω_n = $[k/m]^{0.5}$ rad/sec

where

k = spring constant of the "NEOPRENE" gasket
= Total applied bolt load, F_{total}/deformation of gasket, δ
= 396,000 lb./ 0.010 in.
= $9.6 * 10^6$ lb./in.

The applied bolting torque, T = 100 ft.-lb. = 1,200 in.-lb.

Now $T = C * D_{nom.} * F_{bolt}$

where

C = constant = 0.2
$D_{nom.}$ = Nominal diameter of the screw = 1 inch.
F_{bolt} = Force per screw, lb.

Therefore

F_{bolt} = $T/[C * D_{nom.}]$
= 1,200/[0.2 * 1]
= 6,000 lb. per fastener

For 16 fasteners,

Total force, $F_{total} = 16 * F_{bolt} = 16 * 6{,}000 = 96{,}000$ lb.

Assume that the "NEOPRENE" gasket is deformed (compressed) by $\delta = 0.010$ in.

m = mass of the closure plug
= 1165 lb.

Therefore

ω_n = $[(9.6 * 10^6)/(1{,}070 \text{ lb.}/385 \text{ in/sec}^2)]^{0.5}$
= 1,858 rad/sec
= 1,858/2π Hz
= 295.7 Hz.

According to the "DRAFT" RDT Standard No. F-8-9T (Ref. [23]), the highest frequency of vibration encountered during normal transport by road (on bed of truck) is 500 Hz. Based on range of 3σ distribution, 500 Hz represents the highest, 1 Hz represents the lowest in the range of vibration distribution. For the F-294, the closure plug bolted joint is estimated to be of frequency 295 Hz. This is considered adequate to maintain the joint tight to withstand the vibrations based on experience of similar packages to F-294 (see section 2.6.4.2.2 below).

b) The main fireshield, the crush shield and the skid are fastened with bolts plus standard spring lockwashers. The applied torque on the 1 in. nom. diameter fasteners is 200 ft.-lb. This method is considered adequate to prevent the bolts from loosening.

2.6.4.2.2 *Demonstration by Field experience of Similar F-231 Package*

In the last 5-year period, MDS Nordion's F-231 package has been shipped from the Ontario Hydro Nuclear Power Reactors, Bruce NGS or Pickering NGS sites to MDS Nordion, Ottawa site, by road transport only. The following data provides the history. There has been no recorded evidence of loose bolts or screws on arrival at destination. The F-231 closure uses 10 fasteners (eight [8] 3/4 socket head and two [2] 3/4 hex head) and 1,800 in.-lb. of torque per fastener to seat the neoprene gasket. Table 2.6-T3 compares the F-294 plug/container closure bolted joint to the F-231 plug/container closure bolted joint. The natural frequency of F-294 closure bolted joint, $\omega_{n,F\text{-}294}$= 295 Hz is similar to the natural frequency of F-231 closure bolted joint of $\omega_{n,F\text{-}231}$ = 395 Hz.

Therefore, F-294 fasteners on the closure plug are not expected to loosen when subjected to the vibrations in the normal conditions of transport by road.

Table 2.6-T2
Fasteners on the F-294 Package

Item*	Type/Spec	Function	Applied Torque Ft.-Lb.
Item 12 Qty = 16	1-8-2.0 UNC, Soc. HD. Screw, Unbrako 1960, Low Alloy Steel	Main Closure Plug To Container Inner Shell Assembly	100
Item 4 Qty = 8	1-8x2.25, hex. HD., bolt, A-354, Gr. BD (Or SAE Gr. 8)	Crush Shield Retaining Bolts	200
Item 4 Qty = 8	1-8x3.25, HEX. HD., bolt, A-354, Gr. BD (Or SAE Gr. 8)	Crush Shield Retaining Bolts	200
Item 21 Qty = 8	1-8x2.25, Hex. HD., Bolt, A-354, Gr. BD (Or SAE Gr. 8)	Fixed Skid To Shipping Skid	200
Item 28 Qty = 16	1-8x1.75, Hex. HD., Bolt, A354, Gr. BD (Or SAE Gr. 8)	Cylindrical Fireshield To Fixed Skid	200
Item 11, Qty = 2	1/2 In. Cajon Pipe Cap (With Nickel Gasket)	Ventline Blind Cap	20
Item 18, Qty = 1	Cap, Ss3041, A-276 (With Neoprene Gasket)	Drainline Blind Cap	50

* Item Numbers as per Engineering Information Drawing inserted in Chapter 1, Appendix 1.4.2.

Table 2.6-T3
Comparison between F-294 and F-231 Plug/Container Closure

Item	Description	F-294	F-231
1	Plug Weight	1,070 lb.	750 lb.
2	Fasteners	1 - 8	3/4-10
3	Fasteners, Qty.	16	10
4	Applied Torque	100 ft.-lb.	150 ft.-lb.
5	Applied Load per Bolt	6,000 lb.	12,000 lb.
6	Gasket	"Neoprene"	"Neoprene"
7	Gasket Compression	0.010 in.	0.010 in.
8	Stiffness of Bolted Joint	9.6×10^6 lb./in.	$12. \times 10^6$ lb./in.
9	Natural frequency of Bolted Joint	295 Hz.	395 Hz.

2.6.5 WATER SPRAY

The water spray test would not adversely affect the package integrity as the F-294 package is designed for underwater loading and unloading.

If the water spray produces temperatures lower than the temperature at which the container was sealed, a negative pressure will be produced in the cavity of the F-294 container. The container closure plug and the container body are quite capable of withstanding full vacuum i.e., 14.7 psi external pressure. See Chapter 2, Appendix 2.10.5. The container, without credit of lead and the fins, is capable of withstanding external pressure of 650 psi (44 atmospheres.)

Therefore the F-294 can withstand the water spray test during normal transport without any loss of integrity.

2.6.6 FREE DROP

2.6.6.1 Method of Compliance

A full scale F-294 test packaging (with an F-313 source carrier) has been used to demonstrate compliance with the Normal conditions of transport tests. The test was managed by the test plan document (Ref. [48]) and the Quality plan document (Ref. [49]). At Chalk River Laboratory (CRL) of Atomic Energy of Canada Limited (AECL), Chalk River, Ontario, Canada, on February 25th 1998, a full-scale F-294 test packaging was subjected to a drop test program consisting of eight (8) drop tests. The eight (8) drop tests comprised the combination of normal and accident conditions of transport tests. Eight (8) drop tests were carried out on a single full-scale F-294 test packaging in the specified sequence:

Test #1:	Normal Free Drop Test: top end drop orientation
Test #2:	30-ft Free Drop Test: side oblique drop orientation
Test #3C:	Puncture Test: impact on the zone near lift lug fin #4
Test #4:	Puncture Test: impact on the cylindrical fireshield
Test #5:	Puncture Test: impact on the fixed skid lower plate
Test #6:	30-ft Free Drop Test: top end drop orientation
Test #7:	Puncture Test: impact on the crush shield upper plate
Test #8:	Puncture test: impact on the cylindrical fireshield (nameplate zone)

A single, full-scale F-294 test packaging was subjected to the normal 3-ft free drop test in one top end drop orientation (i.e., inverted). The weight of the F-294 test packaging of 21,482 lb. is marginally greater than the design maximum weight of the F-294 transport package of 21,000 lb. The cask or the closure plug or the crush shield or the fireshield or the removable shipping skid components and the F-294 fasteners were not replaced in between the drop tests; they were untouched throughout the drop testing program. This over-testing and extra test weight ensured a significant degree of cumulative damage and gave an added measure of conservatism to the test results.

The radioactive contents were simulated using eight (8) dummy, inactive, full-scale C-188 capsules evenly spaced around a full-scale F-313 source carrier. The eight (8) dummy C-188s and the F-313 source carrier were in the cavity of the F-294 test packaging throughout the drop testing. The F-457 source carrier loaded with 80 C-188 capsules weighs only 23 lb. more than the fully loaded F-313 source carrier. It is expected that the F-294 with the F-457 source carrier will behave similarly to the F-294 with the F-313 source carrier since the weight of the F-297/F-457 configuration is still less than the test packaging. The differences between F-294 test packaging and F-294 transport package are addressed in Chapter 2, Appendix 2.10.13.

2.6.6.2 Test Objectives

The purpose of the test, in addition to conditioning the package for the Hypothetical Accident conditions tests, was to generate the maximum load on the key structural components and the design features. These (components and the design features) are:

1. Retention of the closure plug (i.e., bolted joint).
2. Retention of the crush shield (i.e., fasteners attaching the crush shield to the container).
3. Retention of the cylindrical fireshield (i.e., fasteners attaching the cylindrical fireshield to the container).
4. The lead shielding in the closure plug and the container (i.e., lead slump).

2.6.6.3 Test Method

The mechanical test program, normal and accident conditions, was carried out in single integrated drop test program. Within the single integrated drop test program, the breakdown of the order of normal and/or accident transport tests was as follows:

1) Normal drop test in top end orientation, followed by
2) Combination of:
   - 30-ft free drop test in side oblique orientation, followed by
   - puncture test to detach the crush shield, followed by
   - additional puncture tests in other zones (side of cylindrical fireshield, bottom of fixed skid), followed by
3) Combination of:
   - 30-ft drop test in top end orientation, followed by
   - puncture test on upper plate of crush shield, followed by
4) Any unplanned tests.

As a result of the above logic, the following drop testing program emerged:

Test #1:	Normal Free Drop Test: top end drop orientation
Test #2:	30-ft free Drop Test: side oblique drop orientation
Test #3C:	Puncture Test: impact on the zone near lift lug fin #4
Test #4:	Puncture Test: impact on the cylindrical fireshield
Test #5:	Puncture Test: impact on the fixed skid lower plate
Test #6:	30-ft Free Drop Test: top end drop orientation
Test #7:	Puncture test: impact on the crush shield upper plate
Test #8:	Puncture test: impact on the cylindrical fireshield (nameplate zone)

At the conclusion of each test, the test packaging fasteners were not replaced. The cask was left untouched throughout the program, with the exception of accelerometer instrumentation, which meant that the damage was cumulative to give the results an added degree of conservatism.

2.6.6.4 Test Temperature

All free drop testing, performed on February 25, 1998 at Chalk River, Ontario, Canada, was conducted at ambient temperature between 5°C and 10°C. The stainless steel material, which surrounds the lead shielding of the F-294 container, suffers no loss of ductility at low temperatures.

2.6.6.5 Target

The drop test facility is located at AECL-Research Co., Chalk River, Ontario, Canada. It consists of an impact pad and a hoisting tower (Ref. CRL Drawing E -4511-2001). The base pad is fabricated from reinforced concrete (of size approximately 10 ft. x 10 ft. x 10 ft.) resting on a solid bedrock. The upper surface of the pad is covered with a 8-ft. x 6-ft x 4-inch thick alloy steel plate (Specification ASTM A-203 Grade E: YS = 56.7 ksi) and secured with the reinforced concrete (CRL drawing E-4511-2002). The top steel plate has a provision for mounting a target pin for puncture tests. The overall view of the drop test facility is shown in Figure 2.6.6-F1.

2.6.6.6 Package Contents

The radioactive contents were simulated using eight (8) dummy, in-active full-scale C-188 capsules evenly spaced around a full-scale F-313 source carrier. The eight (8) dummy C-188s and the F-313 source carrier were in the cavity of the F-294 test packaging all throughout the drop testing. The C-188 dummy capsules have a radial clearance of 0.015-inch and longitudinal clearance of 0.9-inch to ensure free movement of the capsules within the F-313 carrier. The F-313 source carrier was restrained longitudinally but was free to move radially. See Appendix 2.10.13.

2.6.6.7 Internal Heating

The assessment of the performance of F-294 under Normal and Hypothetical Accident condition tests is based on the response on a full-scale model. In service F-294 will operate at a range of temperatures imposed by the radioactive contents and the ambient conditions. Steady state temperature tests of the F-294, before and after the drop test program, have been conducted (see Appendix 2.10.12 for details).

For the purpose of the structural assessment of the cask, temperature has been taken as the temperature at the female flange top of the closure plug bolted joint, which is the key component as it holds the closure plug and provides the retention of the radioactive contents within the cavity of the F-294 container. The temperature at this point, under extremes of contents and ambient temperature, is shown below in Table 2.6.6-T1. The yield stress at the specified temperature for the material of the component is shown in Table 2.6.6-T2.

For the Normal conditions test, the temperature of the test packaging was ambient. However, the temperature range is such that in high heat content/high ambient conditions the material strength is marginally reduced. This is addressed in Chapter 4, Appendix 4.4.3 and sufficient margin of safety exists to demonstrate that the issue of higher temperature and reduced strength of the material is addressed.

Table 2.6.6-T1
Top Closure Plug Temperatures

Package Contents (Ci)	Heat Load (watts)	Ambient Temperature (°F)	Top of Closure Plug Temperature (°F)
0	0	–20	–20
0	0	100	100
374,428	5,766	–20	153
374,428	5,766	100	273

Table 2.6.6-T2
Component Material Yield Stress at Specified Temperature

Component	Female Flange
Material specification	SS304L, ASTM A-240
Yield Stress at 273°F	19,300 psi
Yield Stress at 153°F	23,100 psi

2.6.6.8 Pressure Buildup

The pressures and stresses generated by the internal heat load are calculated in section 2.6.1.

2.6.6.9 Normal Free Drop Test Orientations and Justification

2.6.6.9.1 Drop test height

Since the F-294 package weight of 21,000 lb. is between the range of 11,000 lb. (lowerbound) and 22,000 lb. (upperbound), 10 CFR Part 71 ss 71.71 (c)-(7) requires a free drop test through a distance of three (3) feet (0.9 metres). Therefore, the drop test distance is three feet.

2.6.6.9.2 Top end drop orientation

In this orientation, maximum loads shall act on the fasteners of the closure plug and the crush shield. The package center of gravity over the point of impact ensures that no energy is dissipated by being converted into rotational movement.

2.6.6.10 Pass/fail Criteria and Justification

1) Pass/fail criteria: closure plug and crush shield remain attached.
   Justification: essentially for ability to withstand accident condition tests and also shielding function.
2) Package surface dose rates increase by no more than 20%.
   Justification: regulatory requirement.

2.6.6.11 Test Results

In this section the key test results are recaptured from Appendix 2.10.12. See Appendix 2.10.12 for details of the test results.

1) 3-ft. free drop Test #1: top end drop orientation (i.e., inverted). See Figures 2.6.6-F2 (Dwg. F629401-005) and Figure 2.6.6-F3 (photo 9802-23308-5) as record of F-294 test packaging before the drop tests and Figures 2.6.6-F4 (photo 9802-23308-7) and Figure 2.6.6-F5 (photo 9802-23308-10) as record of the F-294 test packaging after the drop test. The closure plug, the crush shield and the cylindrical fireshield were all retained and remained securely attached. The principal damaged zones were centered around the crush shield. However, there was no breach of the primary container shell. The test observations are:
   1. Slight "ripple" on load spreader plate of crush shield.
   2. Mesh slightly bent inwards between two fins on crush shield.
   3. Up to 0.5 in. of deformation on the crush shield.
   4. No other visible change.

2.6.6.12 Shielding

There was no shielding test (radiation survey) conducted right after the Normal 3-ft. free drop test on the test packaging as this would have interrupted the balance of the accident drop testing program. However, radiation surveys were done before and after the eight drop test program. These results are given in Table 2.7.1-T1.

After the normal 3-ft free drop test, as the crush shield moved by about 0.5 inch and the radioactive sources can move up to 1.0 in. the cavity of F-294, the source-to-dose distance has been reduced by 1.5 in. compared to the source-to-dose distance before the drop test. The effect of this reduction in source-to-dose distance is presented in Chapter 5. The results are recaptured here.

Before the drop test: Top of the crush shield (beyond top of the plug): contact reading = 2.2 mrem/h (375,360 Ci as of 1998-Jan-07)

On contact: Top of the crush shield (beyond top of the plug): calculated dose = 1.7 mrem/h

After the NCOT test assessment: Top of the plug: contact calculated dose rate: 1.9 mrem/h

Therefore, the increase in radiation dose after the normal drop test compared to the radiation dose before the normal free drop test = (1.9 mrem/h)/(1.7 mrem/h) = 1.12 = 12%.

This complies with 10CFR 71, Para 71.43 (f).

2.6.7 Penetration

There was no penetration test performed on the F-294. Calculations are presented in Appendix 2.10.7. As both top and bottom carbon steel plates are 0.5 in. thick, they will resist puncture when the F-294 package is subject to the penetration test. As the cylindrical fireshield shell is 0.25 in. thick, it will resist puncture when the F-294 package is subject to the penetration test. Therefore the F-294 can withstand the penetration test during normal transport without any loss of integrity.

2.6.8 Conclusions

Full-scale F-294 test packaging, due to inherent conservatism and its performance, has demonstrated the ability of the F-294 transport package to maintain its structural integrity and shielding effectiveness under the regulatory Normal condition of transport test requirements.

Figure 2.6.6-F1
Overview of CRL Drop Test Facility

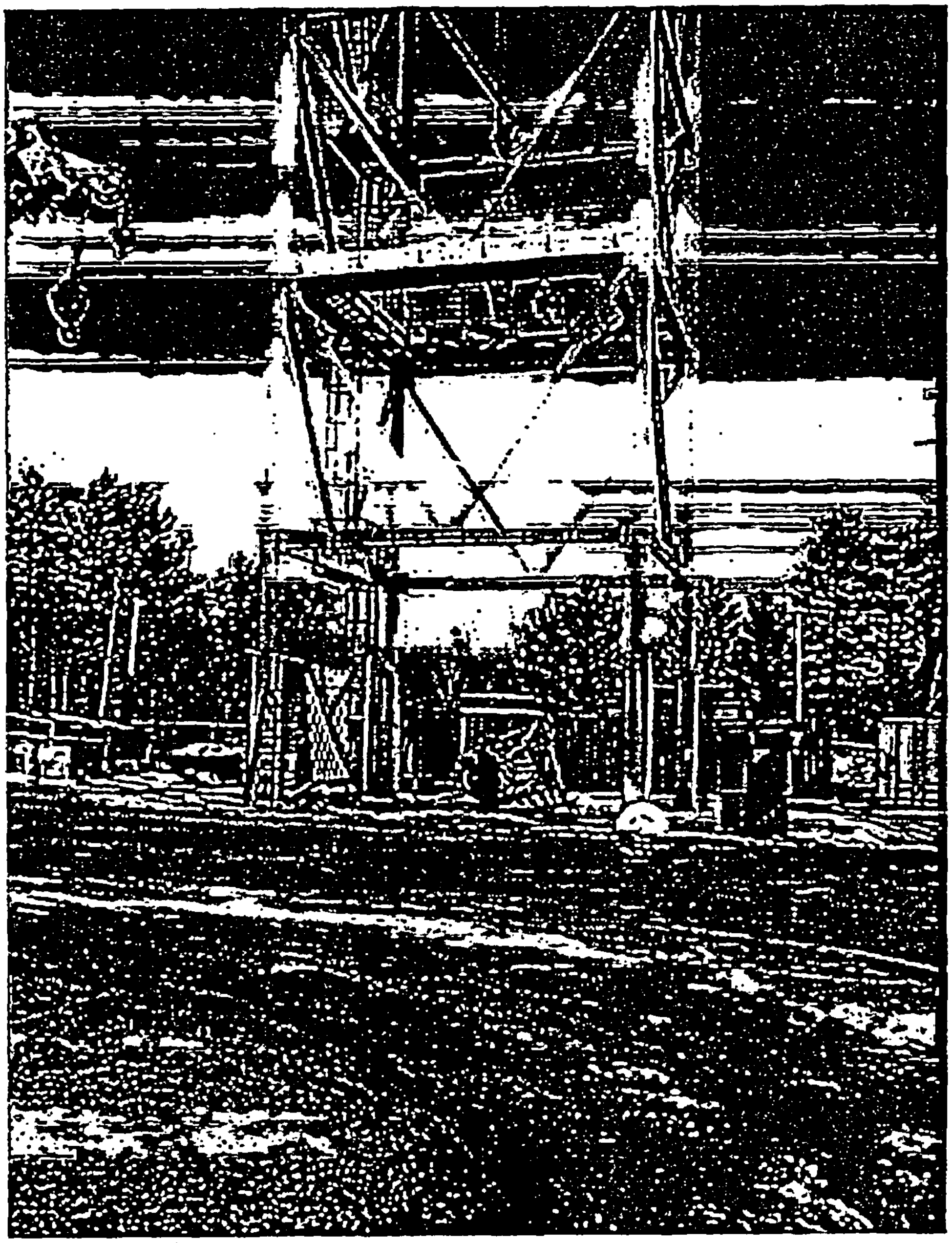


Figure 2.6.6-F2
3-Ft. Free Drop Test #1 in Top End (inverted) Orientation

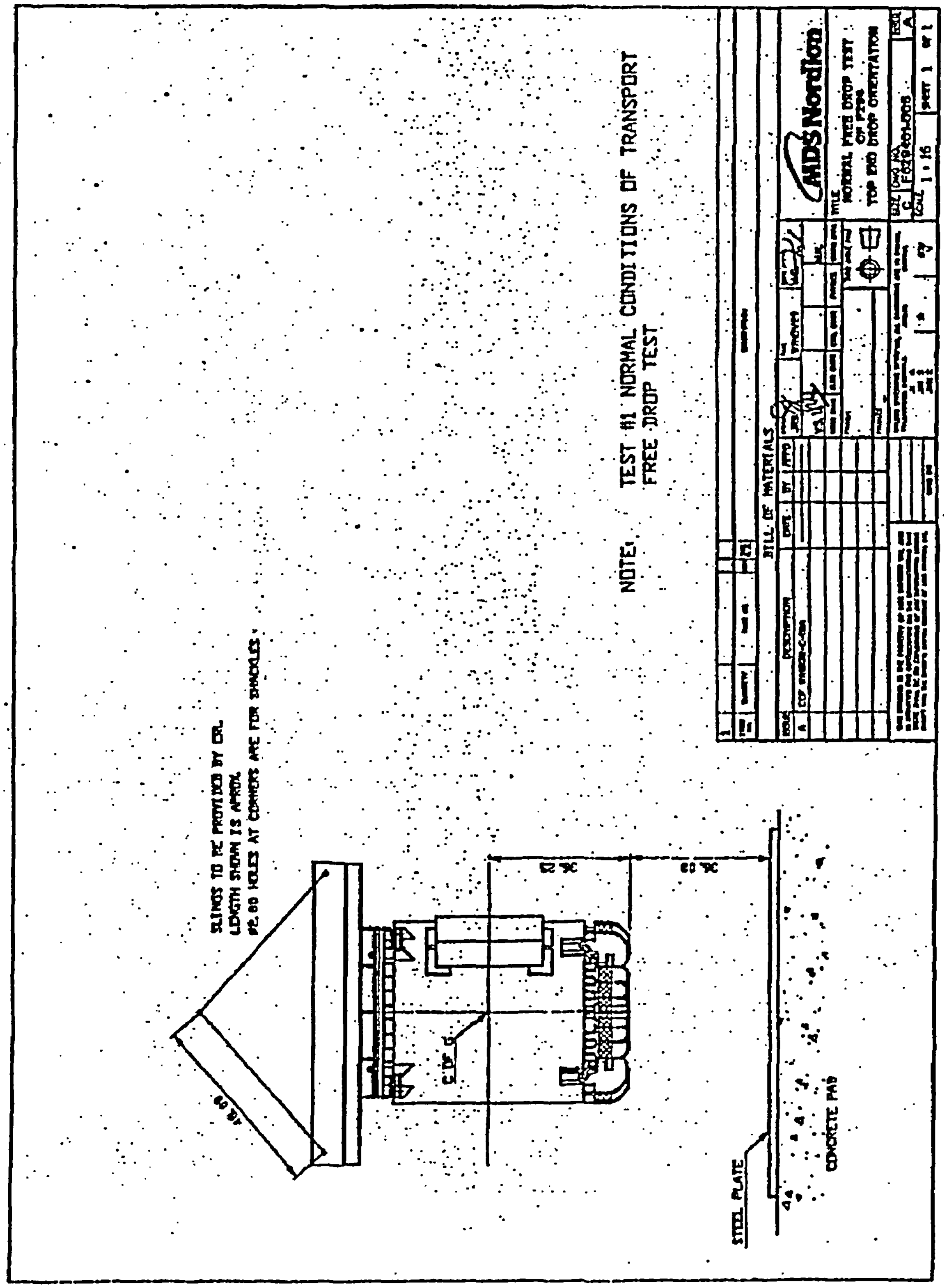


Figure 2.6.6-F3
Photograph 9802-23308-5

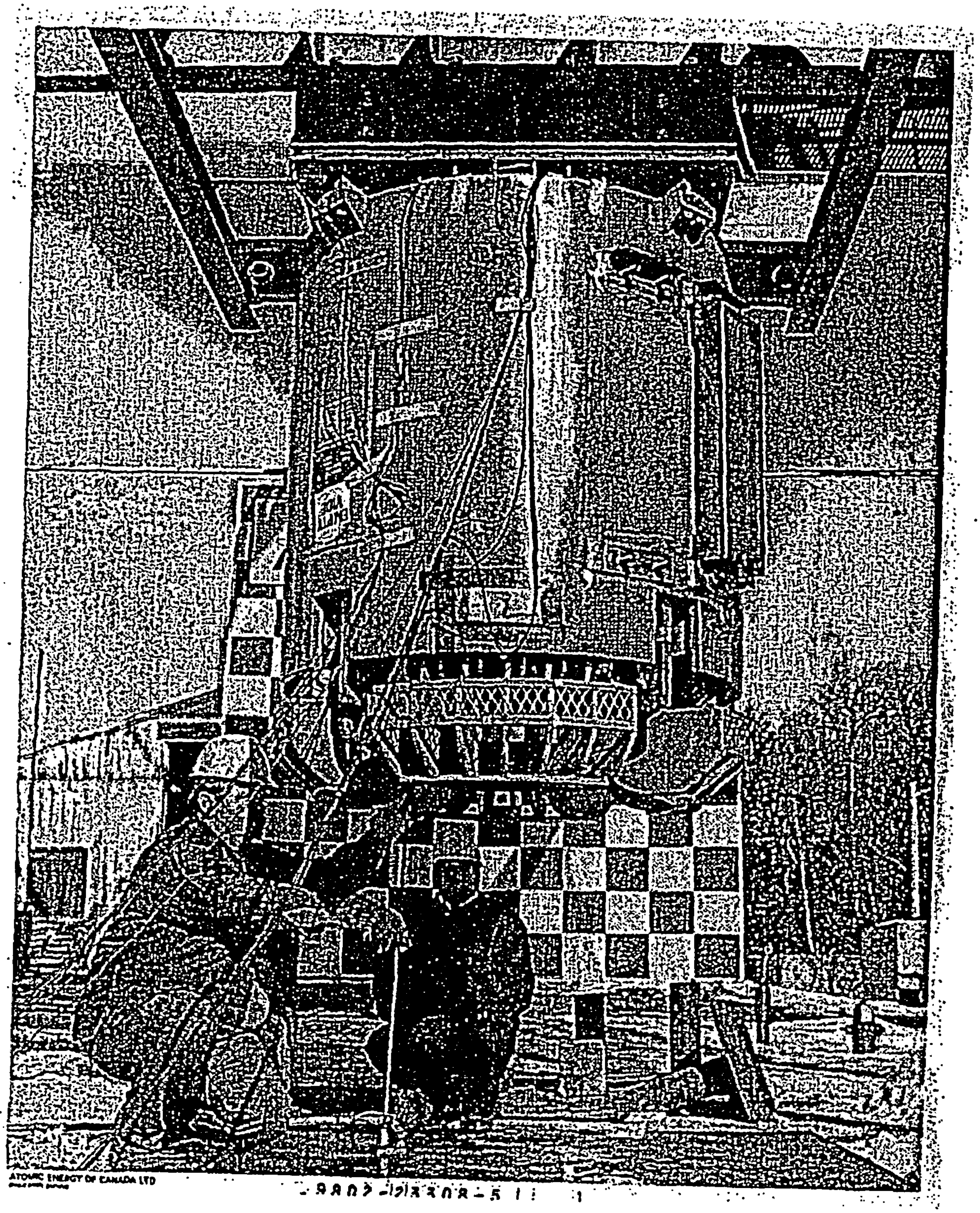


Figure 2.6.6-F4
Photograph 9802-23308-7

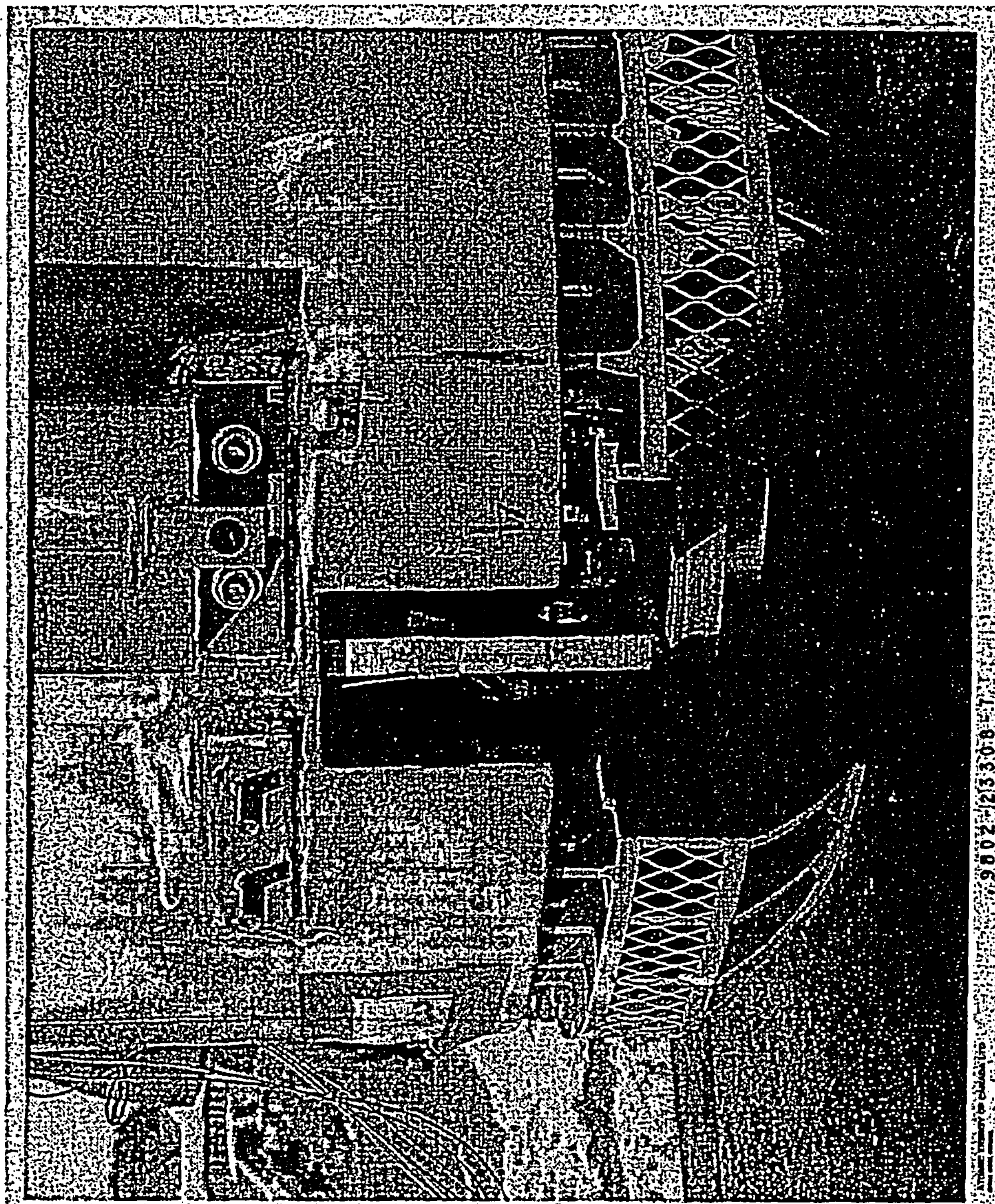
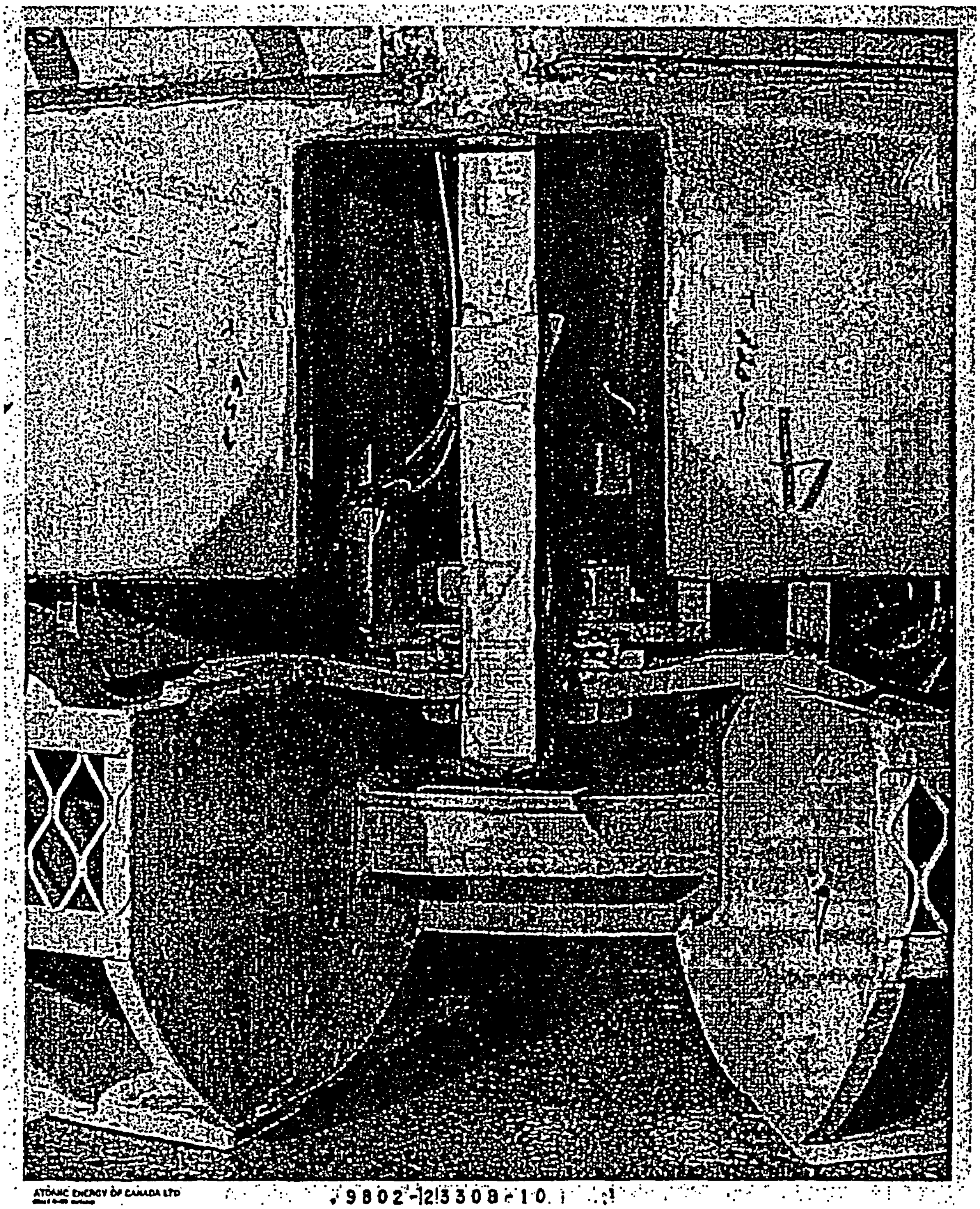


Figure 2.6.6-F5
Photograph 9802-23308-10



2.7 HYPOTHETICAL ACCIDENT CONDITIONS

The performance of the F-294 Transport Package, when subjected to the hypothetical accident conditions as specified in Section 71.73 of 10 CFR Part 71, is presented in this section by analysis and full scale prototype testing and is shown to meet the standards specified.

2.7.1 FREE DROP

There are several drop orientations of the F-294 to be considered in determining the one most likely to result in the greatest cumulative damage when the package is subjected to the subsequent Puncture, Thermal and Water Immersion tests.

The F-294 package can be dropped in any of the six designated free drop orientations shown in Figure 2.7.1-F1. The drop orientations are identified as

Orientation #1.1	—	End Drop - Top
Orientation #1.2	—	End Drop - Bottom
Orientation #2	—	Side Drop
Orientation #3.1	—	Corner Drop - Top
Orientation #3.2	—	Corner Drop - Bottom
Orientation #4	—	Oblique Drop

To cushion the impact during the 30-ft drop test, the F-294 package has a top crush shield. The crush shield assembly sits flush on the container top fins and is bolted at sixteen (16) locations to the container top fins. In addition to the above energy absorbing elements, the F-294 container has:

- the external cooling fins on the container
- the fixed skid
- the shipping skid

all of which serve as energy absorbing devices during the 30-ft drop test. Depending on the drop orientation, not all of the energy absorbing devices come into play.

Using Davis (Ref. [18]) data of fin impact limiters, the analytical assessment of the F-294 package subject to the 30-ft drop test is given in detail in Appendix 2.10.9. Based on the output of the Appendix 2.10.9, an assessment is presented in Appendix 2.10.11 to determine the most damaging 30-ft drop test orientation(s) for the F-294 transport package.

In Appendix 2.10.12, the details of eight (8) drop tests carried out on a full-scale F-294 test packaging are presented, inclusive of pre-drop and post-drop tests. The eight (8) drop tests that were carried out, in the specified sequence, are listed below:

Test #1:	Normal Free Drop Test: top end drop orientation
Test #2:	30-ft Free Drop Test: side oblique drop orientation
Text #3:	Puncture Test: impact on the zone near lift lug fin #4
Test #4:	Puncture Test: impact on the cylindrical fireshield
Test #5:	Puncture Test: impact on the fixed skid lower plate
Test #6:	30-ft. Free Drop Test: top end drop orientation
Text #7:	Puncture Test: impact on the crush shield upper plate
Test #8:	Puncture Test: impact on the cylindrical fireshield (nameplate zone)

In Appendix 2.10.13, the differences between the F-294 test packaging and the F-294 transport package are identified. The impact of these differences is also assessed.

In Appendix 2.10.14, the stress analysis of the components of the F-294 transport package, subjected to the deceleration loads measured and expected in a 30-ft. free drop, is presented.

2.7.1.1 Test Temperature

All free drop testing was conducted between 5°C and 10°C. The stainless steel, which surrounds the lead shielding of the F-294 container, suffers no loss of ductility at low temperatures.

2.7.1.2 Test Method

Based on the maximum damaging drop orientation assessment (presented in Appendix 2.10.11) and other considerations, the following test program emerged: two (2) distinct sets of Hypothetical Accident Conditions of Transport (HACOT) drop tests in the side oblique and top end orientations, preceded by a single NORMAL drop test in the top end drop orientation. The sequence of drop testing on a single F-294 test packaging shall be as follows:

1) Normal drop test in top end orientation.
2) Combination of:
    - 30-ft free drop test in side oblique orientation, followed by
    - puncture test to detach the crush shield, followed by
    - additional puncture tests in other zones (side of cylindrical fireshield, bottom of fixed skid)
3) Combination of:
    - 30-ft drop test in top end orientation, followed by
    - puncture test on upper plate of crush shield
4) Any unplanned tests.

The F-294 tests were carried out as per Test Plan document (Ref. [48]) and Quality Plan document) Ref. [49]). Eight (8) drop tests were carried out on a single full-scale F-294 test packaging in the specified sequence:

Test #1:	Normal Free Drop Test: top end drop orientation
Test #2:	30-ft Free Drop Test: side oblique drop orientation
Text #3:	Puncture Test: impact on the zone near lift lug fin #4
Test #4:	Puncture Test: impact on the cylindrical fireshield
Test #5:	Puncture Test: impact on the fixed skid lower plate
Test #6:	30-ft. Free Drop Test: top end drop orientation
Text #7:	Puncture Test: impact on the crush shield upper plate
Test #8:	Puncture Test: impact on the cylindrical fireshield (nameplate zone)

A single, full-scale F-294 test packaging was subjected to the 30-ft free drop test in *two* different orientations. The 21,482-lb. weight of the F-294 test packaging is marginally greater than the design maximum weight of the F-294 transport package of 21,000 lb. Neither the cask, the closure plug, the crush shield, the fireshield, the removable shipping skid components nor the F-294 fasteners were replaced in between the drop tests; they were untouched throughout the drop testing program. This over-testing and extra test weight ensured a significant degree of cumulative damage and gave an added measure of conservatism to the test results.

The radioactive contents were simulated using eight (8) dummy, inactive full-scale C-188 capsules evenly spaced around a full-scale F-313 source carrier. The eight (8) dummy C-188s and the F-313 source carrier were in the F-294 test packaging throughout the drop testing. The F-457 source carrier, loaded with 80 C-188 capsules, weighs only 23 lb. more than the fully loaded F-313 source carrier. It is expected that the F-294 with the F-457 source carrier will behave similarly to the F-294 with F-313 source carrier since the F-294/F-457 configuration still weighs less than the test packaging.

2.7.1.3 Objectives

The purpose of the tests was to generate the maximum loads on the key structural components and design features. These are:

- the closure plug
- the retention of crush shield (with top integral fireshield)
- the retention of the cylindrical fireshield
- the integrity of stainless steel shell surrounding the lead shielding
- the lead shielding in the closure plug or the container assembly (lead slump)

2.7.1.4 Package Orientations and Justification

2.7.1.4.1 30-ft Free Drop: side-oblique drop orientation (i.e., side corner)

In this drop orientation, large deformation and low deceleration (g's) are expected. In this drop orientation, the lift lug fin of the container shall be impacted and the high loads shall be transmitted to the primary shell of the container, which has the potential to breach the container shell. In addition, the fasteners of the crush shield shall be highly loaded such that they may fail; consequently, the crush shield may be detached sufficiently to cause the reduction in thermal protection. Also, the closure plug fasteners shall be subjected to shear loads and therefore cause its failure and subsequently the detachment or displacement of the closure plug.

2.7.1.4.2 30-ft Free Drop: top end drop orientation (i.e., vertical inverted)

In this drop orientation, small deformation and large deceleration (g's) are expected. In this drop orientation, the closure plug fasteners shall be subjected to maximum loads and therefore cause its failure and subsequently the detachment of the closure plug.

2.7.1.5 Acceptance/rejection Criteria and Justification

1. The test packaging shall be radiation surveyed prior to drop tests and after the drop tests. The Design Acceptance Criteria (DAC) shall be 80% of the regulatory allowable 1,000 mrem/h radiation at 1.0 m. from the surface of the drop tested packaging, based on maximum radioactive contents in the package (Para 71.51 (a) (2) of Ref. [1]).
2. There shall be no weld fractures or fractures in the primary stainless steel shell that envelopes the lead shielding in the plug and in the container assembly. Fractures in the fillet weld between the fin and container shell or fractures in the fin shall not be a cause of rejection.
3. There shall be no loss of thermal protection (i.e., no loss of the crush shield or the fireshield or the fixed skid) such that the container wall is directly exposed to the flame of fire in the hypothetical thermal test. Minor openings in the thermal protection due to puncture pin damage shall not be a cause for rejection, provided the area of opening is less than 1% of the total area of the thermal protection.
4. The damage and displacement of the thermal protection is to be less than 10% of the total insulated area.
5. After the drop tests, the dummy capsules C-188s to meet the leaktightness of 1×10^{-7} std. cc/sec of air.

2.7.1.6 Target

The drop test facility is located at AECL-Research Co., Chalk River, Ontario, Canada. It consists of an impact pad and a hoisting tower (Ref. CRL Drawing E-4511-2001). The base pad is fabricated from reinforced concrete (of size approximately 10 ft. x 10 ft. x 10 ft.) resting on a solid bedrock. The upper surface of the pad is covered with an 8-ft x 6-ft x 4-inch thick alloy steel plate (Specification ASTM A-203 Grade E: YS = 56.7 ksi) and secured with the reinforced concrete (CRL drawing E-4511-2002). The top steel plate has a provision for mounting a target pin for puncture tests. The overall view of the drop test facility is shown in Figure 2.7.1-F2.

2.7.1.7 Test Results

In this section, the key test results are recaptured from Appendix 2.10.12. See Appendix 2.10.12 for details of the test results.

2.7.1.7.1 30-ft Free Drop Test #2: side-oblique drop orientation (i.e., side corner)

See Figures 2.7.1-F3, 2.7.1-F4 and 2.7.1-F5 respectively. The closure plug, the crush shield, the cylindrical fireshield were all retained and remained securely attached. The principal damaged zones were centered around the container lift lug #4. However, there was no breach of the primary container shell. The test observations are:

1. Dummy weight transferred, so both dummy weights are on same side of the fireshield.
2. Measured angle = 36.5° from horizontal. Could not attain 40° drop angle, due to C.O.G. of F-294 packaging.
3. Crush shield deformed on impact face.
4. Shipping skid deformed on impact face.
5. Fixed skid mostly intact; horizontal crack (on skid) located below nameplate. Horizontal crack (on skid) also at location of lead weights.
6. Nine broken welds on inner fin attachment of the crush shield.
7. Three side-crush-shield-to-container fasteners are loose.
8. Some welds intact on shipping skid.
9. Fireshield deformed on impact face.
10. Balance of fireshield intact.
11. Upper fireshield intact. No damage.
12. Shipping skid landed just outside the steel pad, but on the reinforced concrete pad.
13. Side/top of the container (lift lug fin #4) zone impacted on the steel pad.

2.7.1.7.2 30-ft. Free Drop Test #6: top end drop orientation (i.e., vertical inverted)

See Figures 2.7.1-F6, 2.7.1-F7 and 2.7.1-F8 respectively. The closure plug, the crush shield, and the cylindrical fireshield were all retained and remained securely attached. The principal damaged zones were centered around the crush shield fins. However, there was no breach of the primary container shell nor the closure plug. The test observations are:

1. Crush shield as per photographs.
2. Crush shield top retaining bolts still in place. Crush shield retained (jammed) on top of the container.
3. Part of crush shield top ring missing.
4. Most severe deformation on half of circumference.
5. Most crush shield fins attached. Some crush shield fins with broken pieces. Some fins flattened.
6. Fireshield intact. Slight outward bowing along top circumference.

2.7.1.7.3 *Leaktightness of the Cavity of F-294*

Before the eight (8) drop tests, the F-294 cavity was air pressure tested and helium leak tested. The cavity was leaktight.

After eight (8) drop tests, the F-294 cavity was air pressure tested and helium leak tested. The cavity was leaktight.

The details of the air pressure test and the helium leak test are presented in Chapter 2, Appendix 2.10.12.

2.7.1.7.4 *Shielding Tests*

Before the eight (8) drop tests, the F-294 was radiation surveyed using 375,360 curies of cobalt-60 as of Jan 7 1998. See Table 2.7.1-T1 and Figure 2.7.1-F9.

After eight (8) drop tests, the F-294 was radiation surveyed using 365,221 curies of cobalt-60 as of Mar. 24 1998. See Table 2.7.1-T1 and Figure 2.7.1-F9.

The details of the F-294 radiation surveys (shielding tests) before and after the eight (8) drop tests are presented in Chapter 2, Appendix 2.10.12 and in Chapter 5. The radiation survey tests demonstrate that the cask shielding meets the regulatory requirements.

2.7.1.8 Overall 30-ft. Free Drop Test Summary

1. The F-294 tests were carried out as per Test Plan document (Ref. [48]) and Quality Plan document) Ref. [49]). On February 25 1998, at Chalk River Laboratory (CRL) of Atomic Energy Of Canada Limited (AECL), Chalk River, Ontario, Canada eight (8) drop tests were carried out on a single full-scale F-294 test packaging in the specified sequence:

Test #1:	Normal Free Drop Test: top end drop orientation
Test #2:	30-ft Free Drop Test: side oblique drop orientation
Text #3:	Puncture Test: impact on the zone near lift lug fin #4
Test #4:	Puncture Test: impact on the cylindrical fireshield
Test #5:	Puncture Test: impact on the fixed skid lower plate
Test #6:	30-ft. Free Drop Test: top end drop orientation
Text #7:	Puncture Test: impact on the crush shield upper plate
Test #8:	Puncture Test: impact on the cylindrical fireshield (nameplate zone)

2. Two (2) 30-ft. free drop tests of the F-294 test packaging were carried out in the orientation specified below:
    1. side oblique corner drop (36.5° from the horizontal) (Test #2)
    2. top end (inverted) drop (Test #6).

3. After the drop tests, the damage to the F-294 test packaging is as follows:
    1. There were no cracks in the F-294 cavity wall or the external primary shell of the container (flask). there were no cracks in the closure plug.
    2. Some container fin-to-fin welds were fractured. Some container-to-fin welds were fractured. Some container fins had deformed significantly.
    3. The closure plug was in place and had not come loose. The "neoprene" gasket of the closure plug bolted joint was not damaged. The lift lug of the closure plug was compressed by 0.66 in., primarily due to puncture pin impact.
    4. The fins of the crush shield and the container buckled in the standard J-shape or S-shape.
    5. The cylindrical fireshield and the crush shield were retained.

4. Integrity of Thermal Protection:

   On the F-294 test packaging, there is 9,257 in^2 area of the thermal protection surrounding the F-294 flask. After the drop, there was an opening of 21 in^2 (due to Puncture Pin Test # 4) and 6 in^2 (due to Puncture Pin test #8). The 27 in^2 opening area out of 9,257 in^2 total thermal protection area represent a loss of 0.3 % of thermal protection area.

   The damage to the thermal protection was approximately 800 in^2 out of total thermal protection of 9,257 in^2. This represents 8.6 % of total thermal protection area was damaged.

5. F-294 Cavity Leaktightness:

   Before the eight (8) drop tests, the F-294 cavity was air pressure tested and helium leak tested. The cavity was leaktight.

   After eight (8) drop tests, the F-294 cavity was air pressure tested and helium leak tested. The cavity was leaktight.

6. C-188 Dummy Capsules Leaktightness:

   Before the eight (8) drop tests, the C-188 dummy capsules were helium leak tested. They were leaktight.

   After eight (8) drop tests, the C-188 dummy capsules were helium leak tested. They were also leaktight.

7. Deformation Profile:

   The deformation profile of the F-294 test packaging as a result of eight (8) drop tests is depicted in Dwg. F629401-022. see Figure 2.7.1-F10.

8. Shielding Test:

   Before the eight (8) drop tests, the F-294 was radiation surveyed using 375,360 curies of cobalt-60 as of Jan 7 1998. The test radiation source was similar to the radioactive source for shipping configuration. See Table 2.7.1-T1 and Figure 2.7.1-F9.

   After eight (8) drop tests, the F-294 was radiation surveyed using 365,221 curies of cobalt-60 as of Mar. 24 1998. See Table 2.7.1-T1 and Figure 2.7.1-F9.

   The details of the F-294 radiation surveys (shielding tests) before and after the eight (8) drop tests are presented in Chapter 2, Appendix 2.10.12 and in Chapter 5. The radiation survey tests demonstrate that the cask shielding meets the regulatory requirements.

9. Measured Decelerations and Duration of Impact:

   In the 30-ft. free drop test, in the side oblique drop orientation, the measured maximum deceleration was 136 g's on top of the closure plug of F-294 and the duration of impact was 30 milli-seconds.

   In the 30-ft. free drop test, in the top end (inverted) drop orientation, the measured maximum deceleration was 132 g's on top of the closure plug of F-294 and the duration of impact was 24 milli-seconds.

2.7.1.9 Conclusions

The F-294 transport package will maintain its structural, containment system and shielding integrity under the hypothetical accident conditions free drop tests. These results will be the same whether an F-313 or an F-457 source carrier is used.

Table 2.7.1-T1
F-294 Radiation Surveys: Before and After the Drop Test

	Before the Drop mrem/h	After the Drop mrem/h
1.0 m from Surface Location		
1	0.4	0.8
2	0.4	0.8
3	0.35	0.8
4	0.95	1.4
5	1.8	1.8
6	1.2	1.6
7	0.8	1.0
8	1.4	1.8
Contact with Surface		
1	2.2	4.0
2	2.0	2.6
3	1.0	1.6
4	2.8	5.0
5	12.0	16.0
6	6.5	5.5
7	0.3	0.6
8	14.0	30.0

Figure 2.7.1-F1
Drop Test Orientations

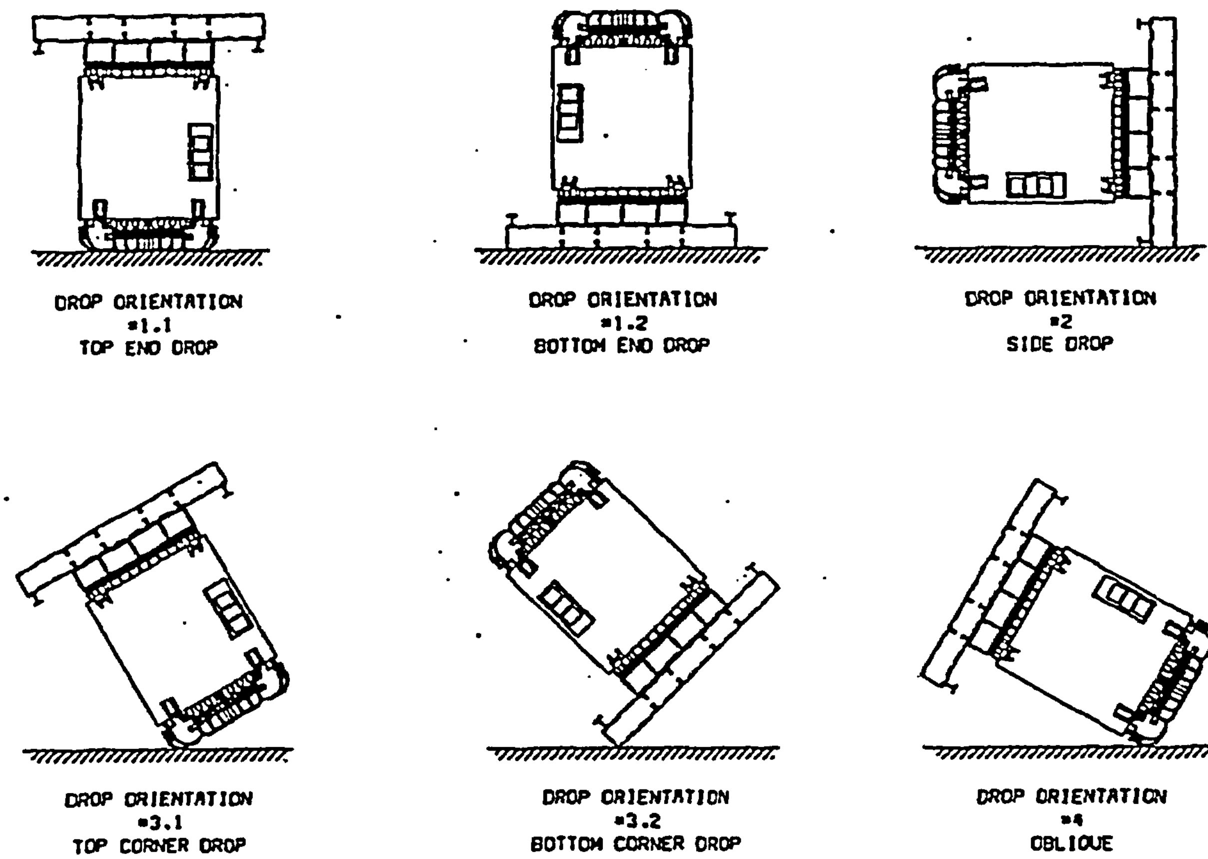
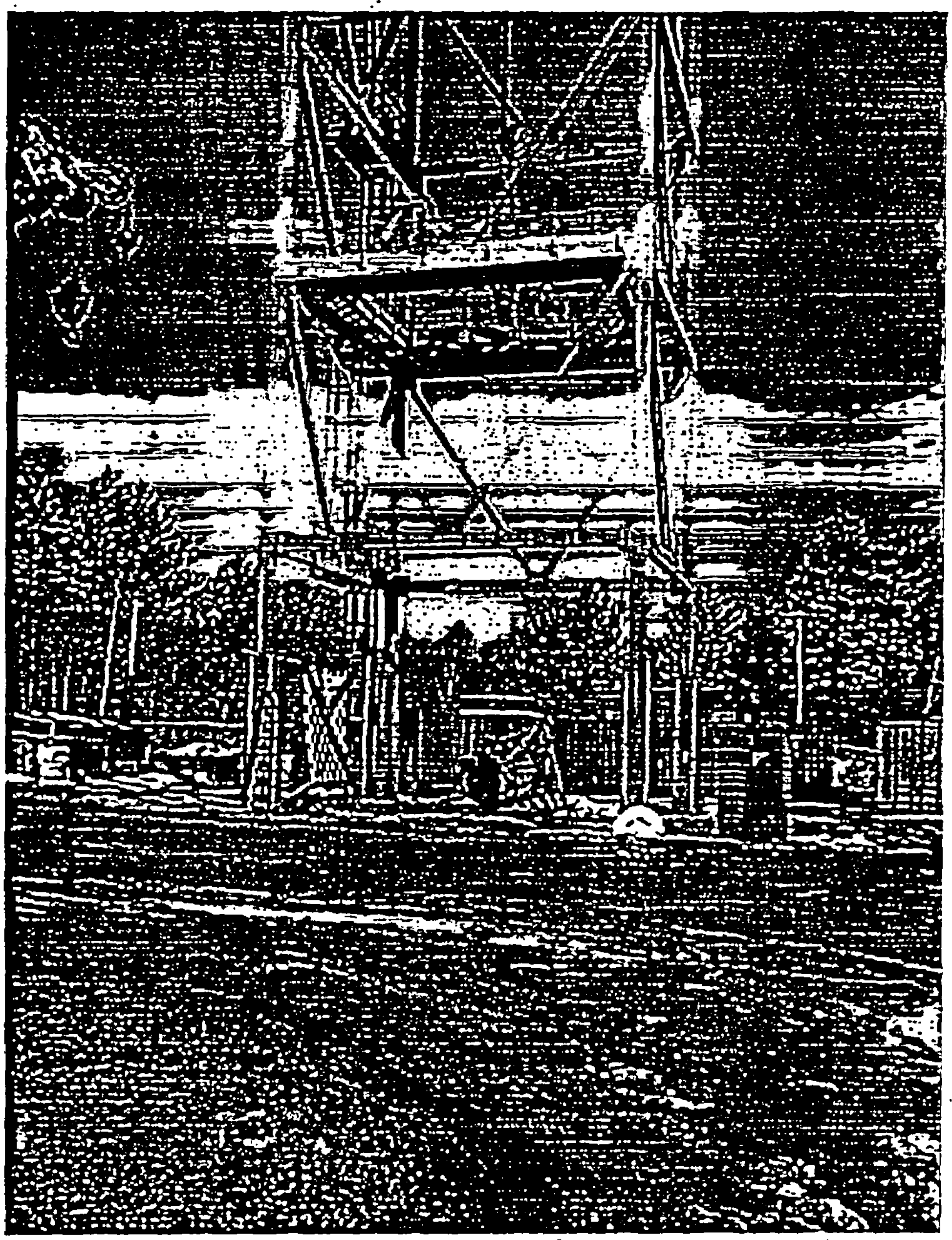


Figure 2.7.1-F2
CRL Drop Test Facility



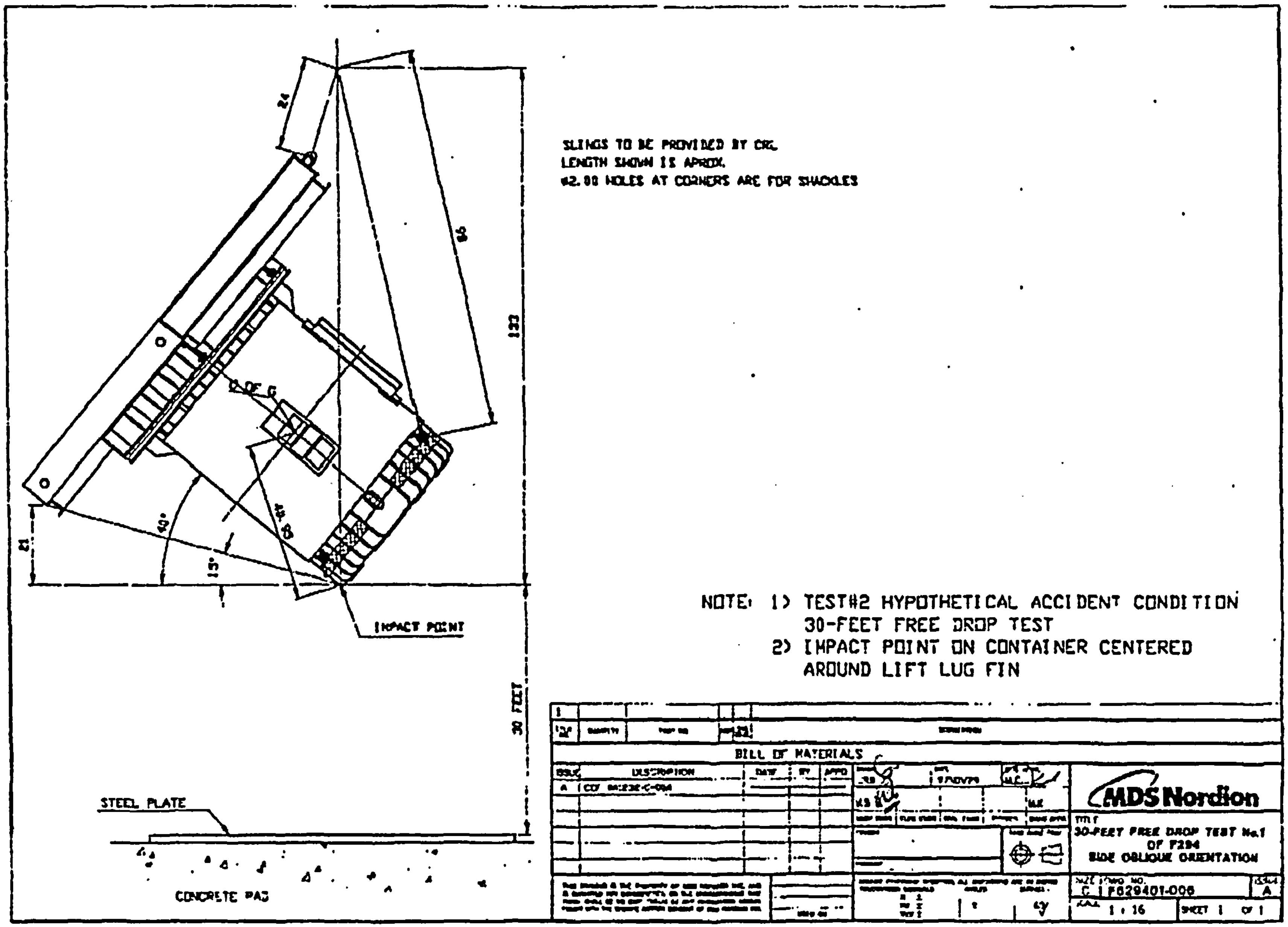


Figure 2.7.1-F3
30-ft Free Drop Test #2 in Side-Oblique Orientation

Figure 2.7.1-F4
30-ft Free Drop Test #2: F-294 Before the Drop Test
(Photo MDSN-F294-0032)

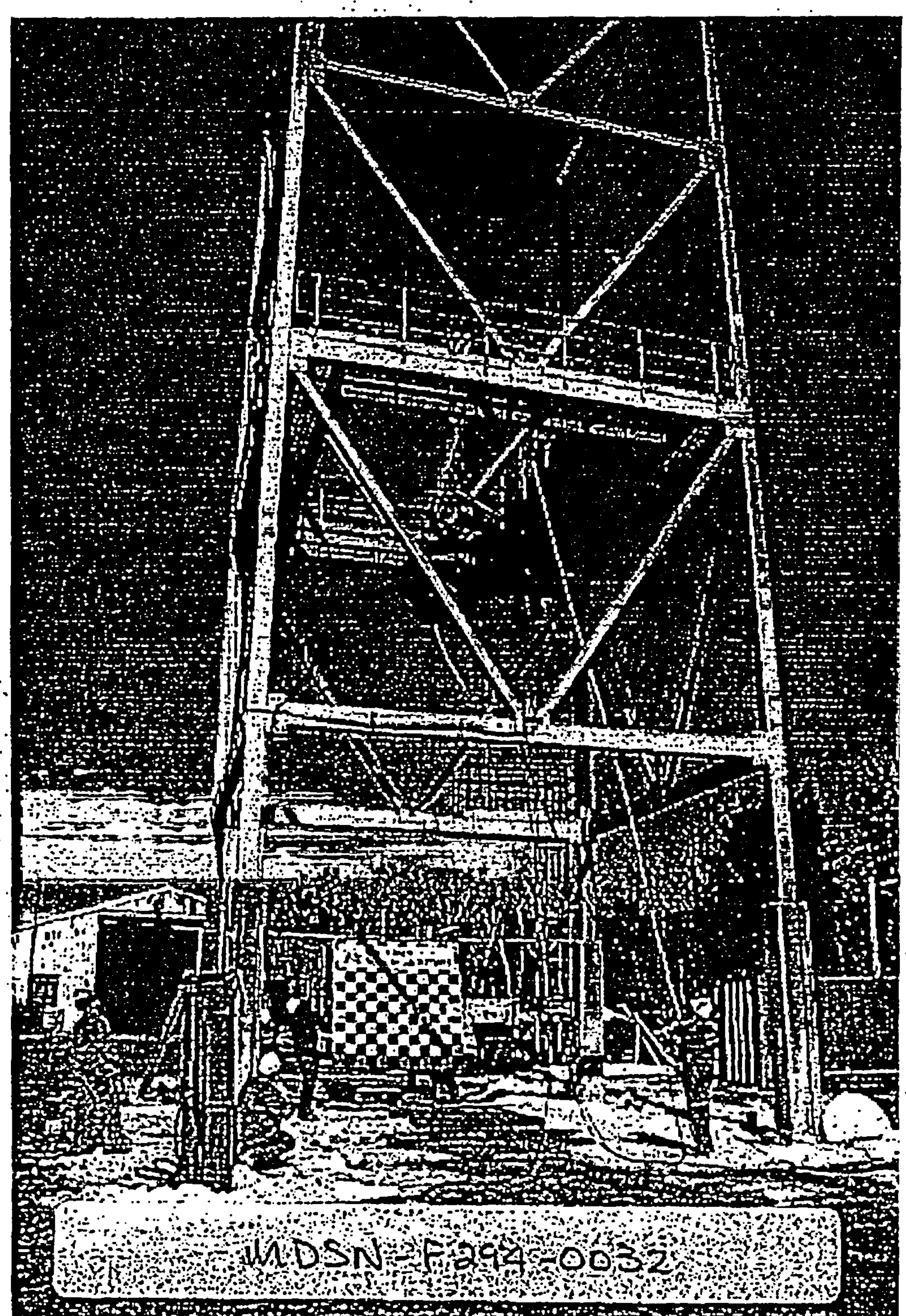
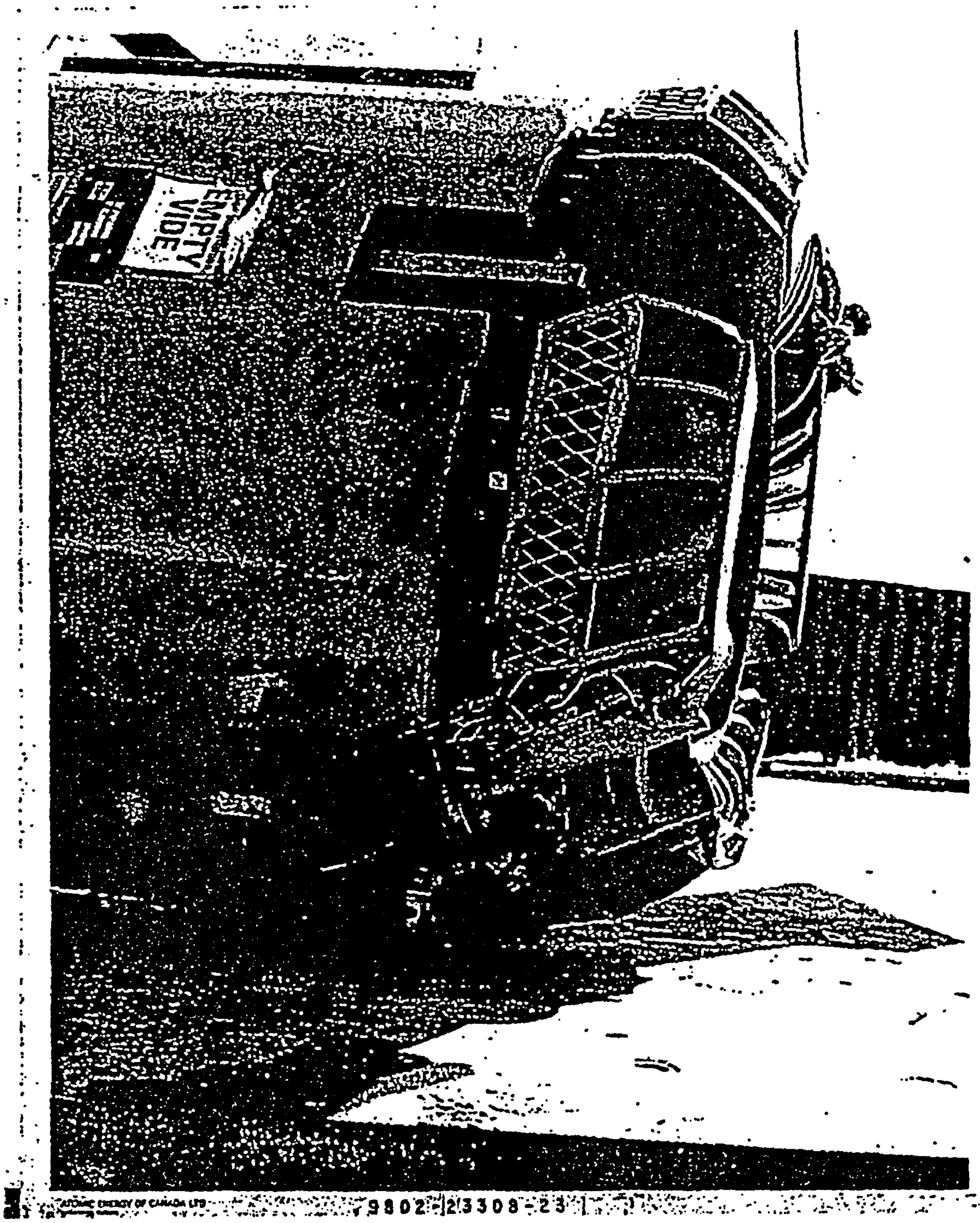


Figure 2.7.1-F5
30-ft Free Drop Test #2: F-294 After the Drop Test
(Photo 9802-23308-23)



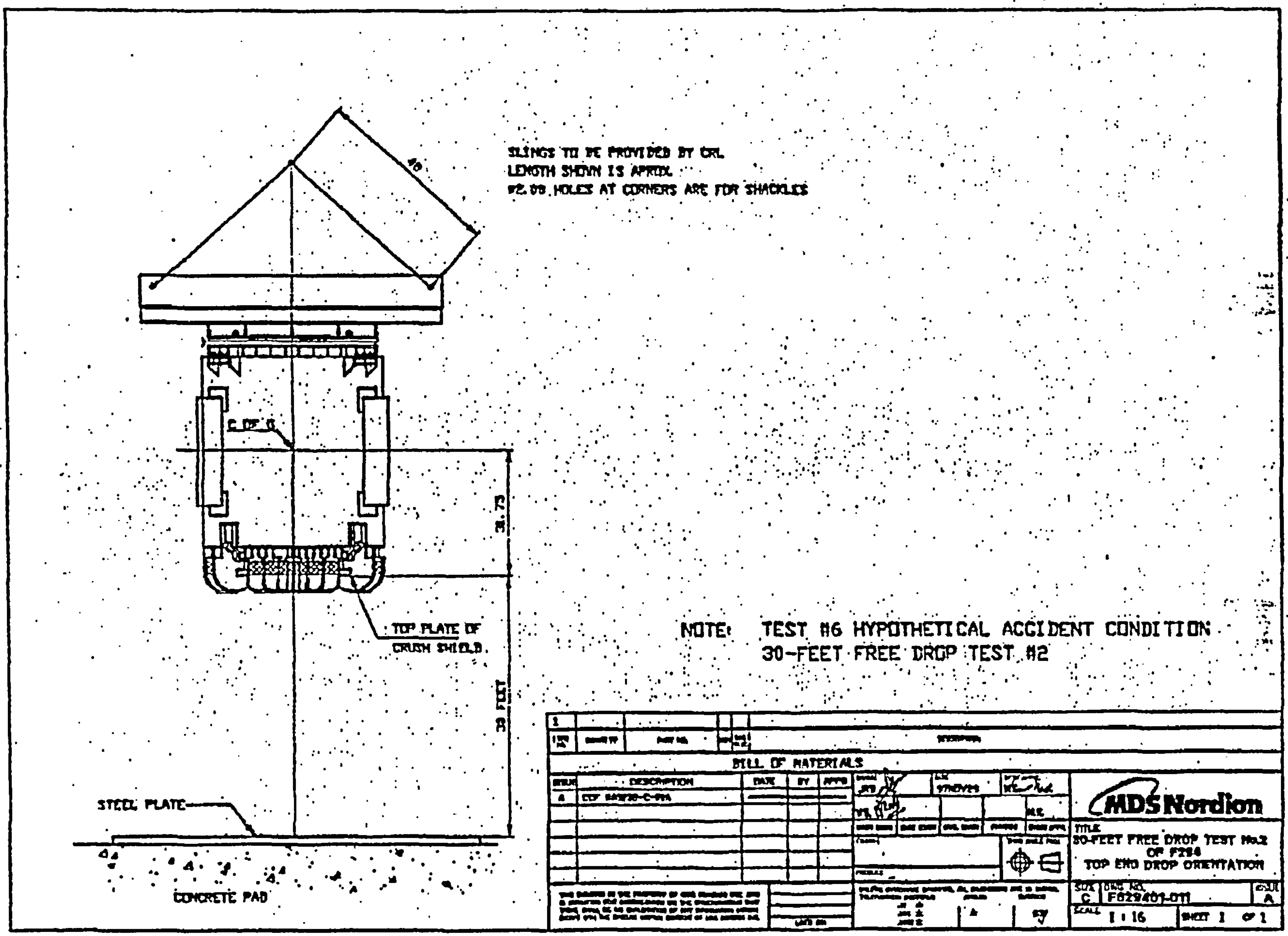


Figure 2.7.1-F6
30-ft Free Drop Test #6 in Top End Orientation

Figure 2.1.7-F7
30-ft Free Drop Test #6: F-294 Before the Drop Test
(Photo 9802-23308-77)

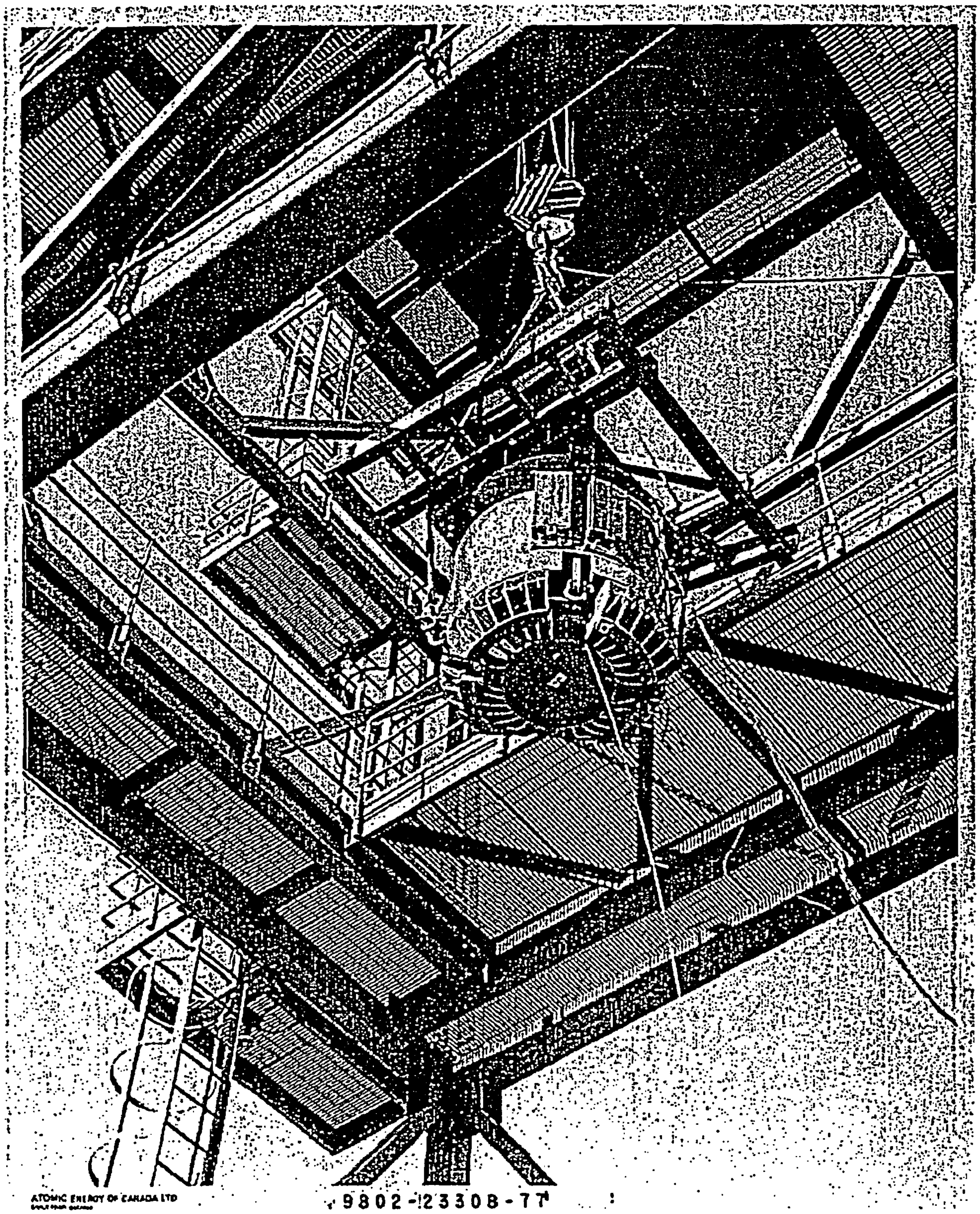


Figure 2.7.1-F8
30-ft Free Drop Test #6: F-294 After the Drop Test
(Photo 9802-23308-78)

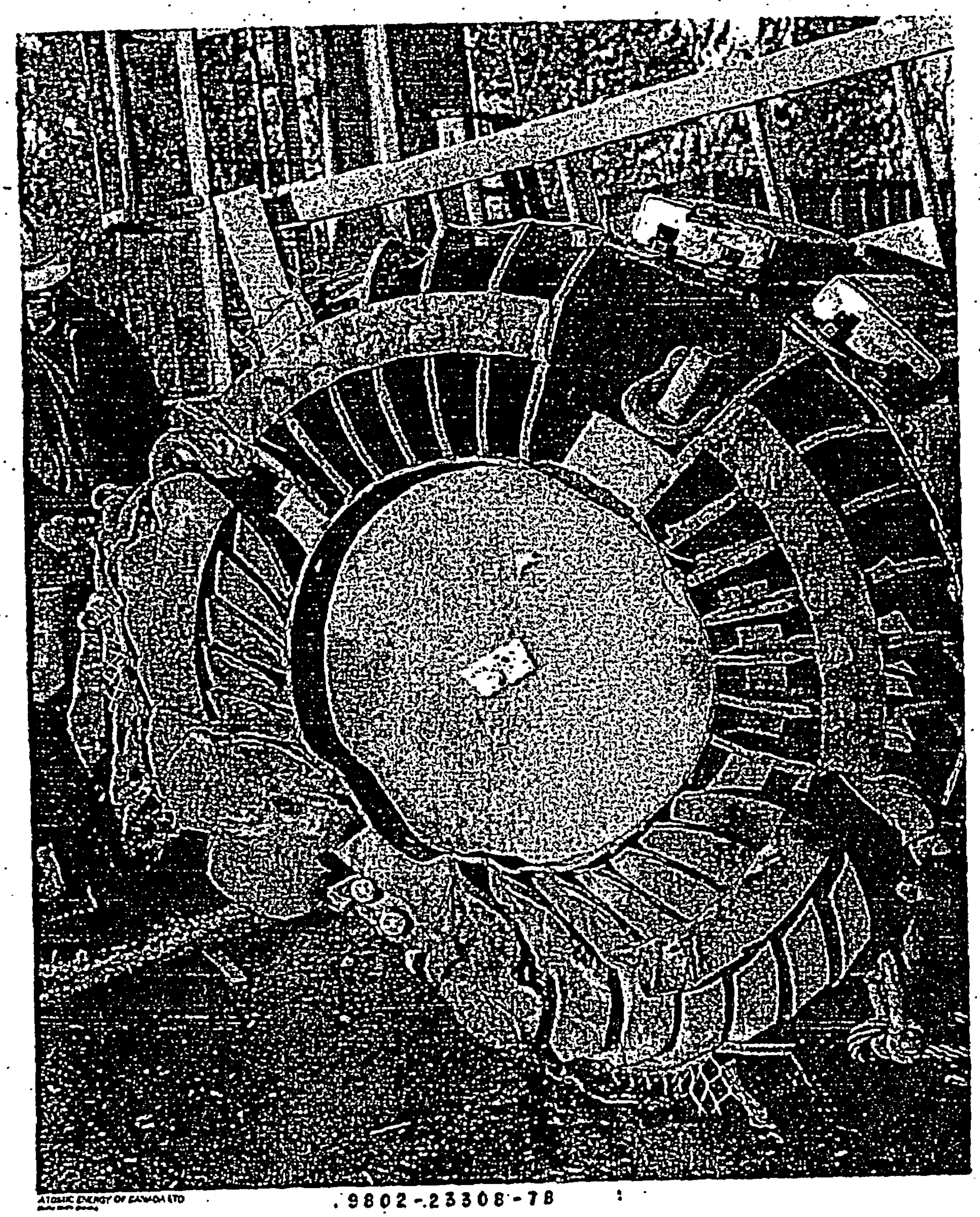


Figure 2.7.1-F9
Identification of the Locations of the F-294 During Radiation Survey
(Shielding Test)

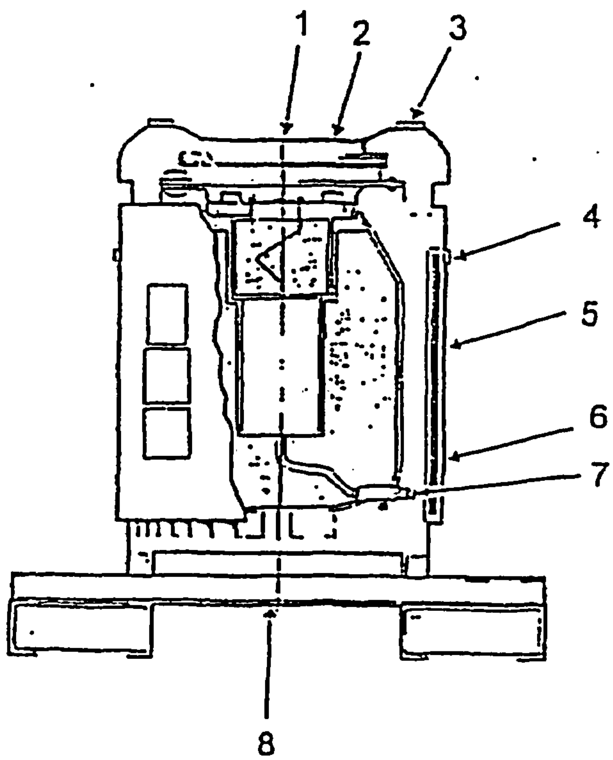
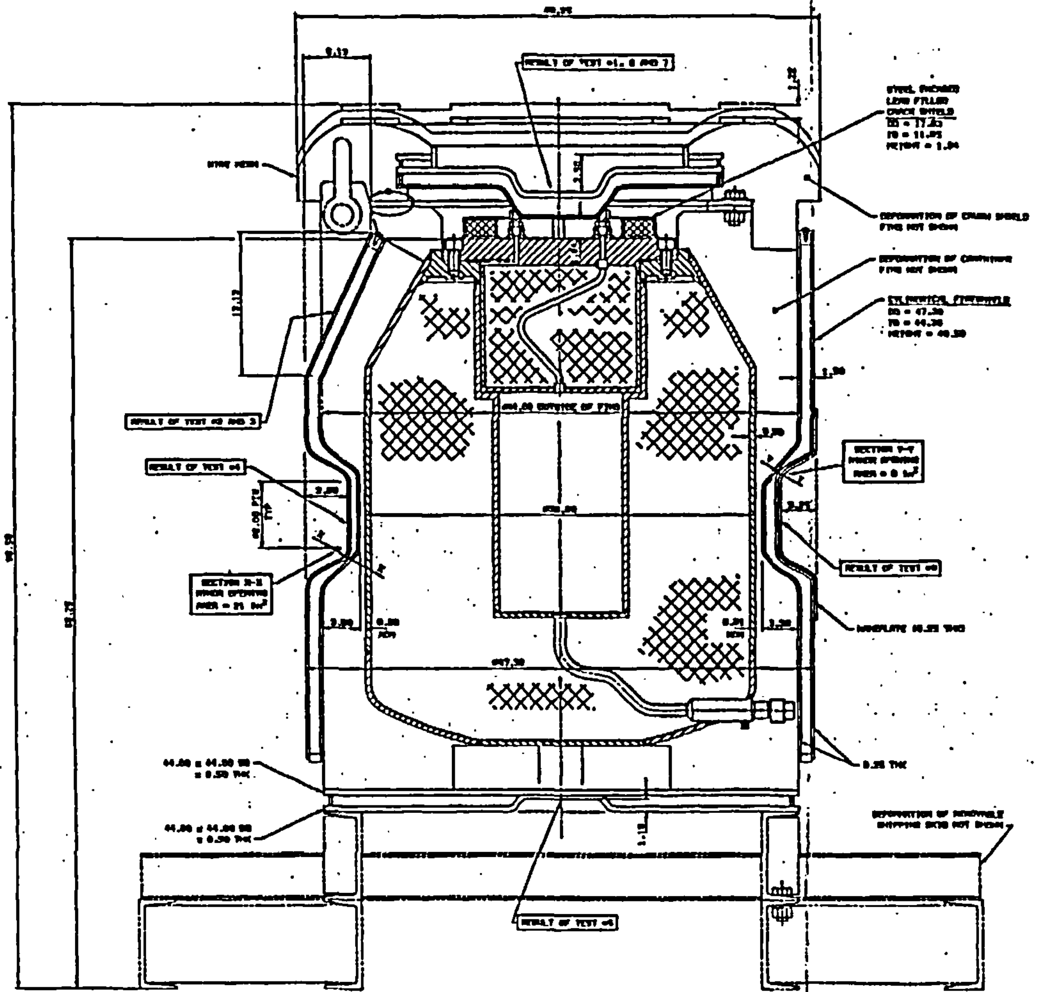


Figure 2.7.1-F10
F-294 Test Packaging Approximate Deformation Profile (After 8 Drop Tests)
(Dwg. F629401-022)



NOTES

1. LIST OF TESTS:
   TEST #1 – NORMAL FREE DROP TEST, TOP END ORIENTATION (3 FOOT DROP)
   TEST #2 – 30 FOOT FREE DROP. SIDE OBLIQUE DROP ORIENTATION (ON LIFT LUG #1)
   TEST #3 – PUNCTURE TEST: IMPACT ON THE ZONE NEAR LIFT LUG PIN #4 (40 INCH DROP)
   TEST #4 – PUNCTURE TEST: IMPACT CYLINDRICAL FIRESHIELD (40 INCH DROP AT MIDHEIGHT OF FIRESHIELD, ON LIFT LUG #4 AXIS)
   TEST #5 – PUNCTURE TEST: IMPACT ON FIXED SKID LOWER PLATE (40 INCH DROP)
   TEST #6 – 30 FOOT DROP TEST: TOP END DROP ORIENTATION
   TEST #7 – PUNCTURE TEST: IMPACT ON THE CRUSH SHIELD UPPER PLATE (40 INCH DROP AT CENTER ZONE OF CRUSHSHIELD)
   TEST #8 – PUNCTURE TEST: IMPACT CYLINDRICAL FIRESHIELD (40 INCH DROP AT MIDHEIGHT ON NAME PLATE ZONE)

2. PHANTOM (DASHED) LINES SHOW THE PROFILE PRIOR TO DROP TEST. SOLID LINES ARE AFTER DROP TEST.

Exemption 2

2.7.2 PUNCTURE

The F-294 package can be dropped in any of the six designated free drop orientations shown in Figure 2.7.2-F1. The drop orientations are identified as

Orientation #1.1	-	End Drop - Top
Orientation #1.2	-	End Drop - Bottom
Orientation #2	-	Side Drop
Orientation #3.1	-	Corner Drop - Top
Orientation #3.2	-	Corner Drop - Bottom
Orientation #4	-	Oblique Drop

In Chapter 2, Appendix 2.10.12, the details of eight (8) drop tests carried out on a full -scale F-294 test packaging are presented, inclusive of pre-drop tests and post-drop tests. The eight (8) drop tests that were carried out, in the specified sequence, are listed below:

Test #1:	Normal Free Drop Test: top end drop orientation
Test #2:	30-ft Free Drop Test: side oblique drop orientation
Test #3C:	Puncture Test: impact on the zone near lift lug fin #4
Test #4:	Puncture Test: impact on the cylindrical fireshield
Test #5:	Puncture Test: impact on the fixed skid lower plate
Test #6:	30-ft Free Drop Test: top end drop orientation.
Test #7:	Puncture Test: impact on the crush shield upper plate
Test #8:	Puncture Test: impact on the cylindrical fireshield (nameplate zone)

2.7.2.1 Test Temperature

All puncture testing was conducted betweem 5°C and 10°C. The stainless steel, which surrounds the lead shielding of the F-294 container, suffers no loss of ductility at low temperatures.

2.7.2.2 Test Method

The F-294 puncture tests were carried out as per Test Plan document (Ref. [48]) and Quality Plan document (Ref. [49]). Eight (8) drop tests were carried out on a single, full -scale F-294 test packaging in the specified sequence:

Test #1:	Normal Free Drop Test: top end drop orientation
Test #2:	30-ft Free Drop Test: side oblique drop orientation
Test #3C:	Puncture Test: impact on the zone near lift lug fin #4
Test #4:	Puncture Test: impact on the cylindrical fireshield
Test #5:	Puncture Test: impact on the fixed skid lower plate
Test #6:	30-ft Free Drop Test: top end drop orientation.
Test #7:	Puncture Test: impact on the crush shield upper plate
Test #8:	Puncture test: impact on the cylindrical fireshield (nameplate zone)

A single, full-scale F-294 test packaging was subjected to five (5) puncture tests in different drop orientations. The puncture tests are listed above. The 21,482 lb. weight of the F-294 test packaging is marginally greater than the design maximum weight of the F-294 transport package of 21,000 lb. Neither the cask, the closure plug, the crush shield, the fireshield, the removable shipping skid components nor the F-294 fasteners were replaced in between the drop tests; they were untouched throughout the drop testing program. This over-testing and extra test weight ensured a significant degree of cumulative damage and gave an added measure of conservatism to the test results.

The radioactive contents were simulated using eight (8) dummy, inactive, full-scale C-188 capsules evenly spaced around a full-scale F-313 source carrier. The eight (8) dummy C-188s and the F-313 source carrier were in the cavity of the F-294 test packaging throughout the drop testing. The F-457 source carrier loaded with 80 C-188 capsules weighs only 23 lb. more than the fully loaded F-313 source carrier. It is expected that the F-294 with the F-457 source carrier will behave similarly to the F-294 with the F-313 source carrier since the F-294/F-457 configuration still weighs less than the test packaging.

2.7.2.3 Objectives

The purpose of the puncture tests was to generate maximum loads on the key structural components and design features. These are:

1. the closure plug
2. the retention of crush shield (with top integral fireshield)
3. the retention of the cylindrical fireshield
4. the integrity of stainless steel shell surrounding the lead shielding
5. the lead shielding in the closure plug or the container assembly (lead slump)

2.7.2.4 Package Orientations and Justification

a) **Puncture Test #3C** Impact on the zone near lift lug fin #4 (i.e., side corner)

Planned puncture Test #3A (Dwg. F629401-007) or puncture Test #3B (Dwg. F629401-008) were not carried out because after the 30-ft. free drop test in the side oblique drop orientation (i.e. Test #2), the crush shield was jammed solid against the top /side corner of the F-294 thus making it difficult to detach the crush shield as originally planned for Test #3A & Test #3B. Therefore an alternative puncture Test #3C was proposed and discussed.

In Puncture Test # 3C drop orientation, the lift lug fin #4 of the container shall be impacted and the high loads shall be transmitted to the primary shell of the container, which has the potential to breach the container shell. In addition the impact load may affect the closure plug fasteners and cause its failure and subsequently the detachment or displacement of the closure plug.

b) **Puncture Test #4** Impact on the cylindrical fireshield

In this drop orientation, the cylindrical fireshield sandwich shells shall be subjected to maximum loads and cause its failure. This shall cause a full through hole in the thermal protection and consequent exposure of the side container wall to flames of fire. In addition, this test shall indicate if the container (cask) wall is damaged due to the continuation of the puncture pin impact progression beyond the fireshield sandwich shell.

c) **Puncture Test #5** Impact on the fixed skid lower plate

In this drop orientation the fixed skid sandwich plates shall be subjected to maximum loads and cause its failure. This shall cause a full through hole in the thermal protection and consequent exposure of the bottom container wall to flames of fire.

d) **Puncture Test #7** Impact on the crush shield upper plate

In this drop orientation, the crush shield sandwich plates shall be subjected to maximum loads and cause its failure. This shall cause a full through hole in the thermal protection and consequently exposing the top closure plug to flames of fire. In addition, the closure plug may be severely impacted as a result of the puncture pin impact progression being arrested by the lift lug of the closure plug.

e) **Puncture Test #8** Impact cylindrical fireshield (nameplate zone)

This test is similar to puncture Test #4, as specified above. The purpose of this test is to examine the influence of the reinforced shell of the fireshield on the puncture pin progression during the impact.

2.7.2.5 Acceptance/Rejection Criteria and Justification:

1. The test packaging shall be radiation surveyed both prior to and after the drop tests. The Design Acceptance Criteria (DAC) shall be 80% of the regulatory allowable 1,000 mrem/h radiation at 1.0 m. from the surface of the drop tested packaging, based on maximum radioactive contents in the package (Para 71.51 (a) (2) of Ref. [1]).
2. There shall be no weld fractures or fractures in the primary stainless steel shell that envelopes the lead shielding in the plug and in the container assembly. Fractures in the fillet weld between the fin and container shell or fractures in the fin shall not be a cause of rejection.
3. There shall be no loss of thermal protection (i.e., no loss of the crush shield or the fireshield or the fixed skid) such that the container wall is directly exposed to the flame of fire in the hypothetical thermal test. Minor openings in the thermal protection due to puncture pin damage shall not be a cause for rejection, provided the area of opening is less than 1% of the total area of the thermal protection.
4. The damage and displacement of the thermal protection is to be less than 10% of the total insulated area.
5. After the drop tests, the dummy C-188s to meet the leaktightness of 1×10^{-7} std. cc/sec of air.

2.7.2.6 Target

The drop test facility is located at AECL-Research Co., Chalk River, Ontario, Canada. It consists of an impact pad and a hoisting tower (Ref. CRL Drawing E-4511-2001). The base pad is fabricated from reinforced concrete (of size approximately 10 ft. x 10 ft. x 10 ft.) resting on solid bedrock. The upper surface of the pad is covered with an alloy steel plate (8 ft. x 6 ft x 4 in. thick). (Specification ASTM A-203 Grade E: YS = 56.7 ksi) and secured with the reinforced concrete (CRL drawing E-4511-2002). The top steel plate has a provision for mounting a target pin for puncture tests. The overall view of the drop test facility is shown in Figure 2.7.1-F2.

2.7.2.7 Target Pin

A full-scale target puncture pin (Material AISI C-1045) was used. It is depicted in Figure 2.7.2-F2 (Ref. Dwg. F629401-004). It is constructed of a 6-inch diameter x 26-inch high steel bar welded vertically to a 1-inch thick steel plate. The puncture pin plate (1 inch thick) was secured (bolted) at each of four (4) corner locations to the drop test pad plate (4 in. thick). If the puncture pin head was damaged, a backup identical puncture pin was used.

2.7.2.8 Test Results

In this section, the key test results are recaptured from Chapter 2, Appendix 2.10.12. See Appendix 2.10.12 for details of the test results.

a) Puncture Test #3C: impact on the zone near lift lug fin #4 (i.e., side corner). See Figures 2.7.2-F3, 2.7.2-F4, and 2.7.2-F5 respectively. The test observations are:
   - Severe local deformation of crush shield.
   - Crack on fireshield at impact point.
   - Upper fireshield intact.
   - All bolting intact.
   - One (strip) piece of metal broke free (approx. 1/2-inch wide by 8 in. long).
   - Lift lug severely deformed.
   - Puncture pin damaged (to be switched for next test).
   - 26-inch high puncture pin used.
   - The puncture pin fastening to the steel pad was checked before and after the test. The puncture pin did not move during the test.
   - The puncture pin top face was damaged during the test.

b) Puncture Test #4: Impact cylindrical fireshield. See Figures 2.7.2-F6, 2.7.2-F7, and 2.7.2-F8 respectively. The test observations are:

- Severe local deformation and shearing in a circular pattern.
- Both layers (walls) of fireshield penetrated.
- Dished head through puncture. Area cut is 2/3 of circumference of puncture pin.
- Approximately 2-inch displacement of entire shell (deformed zone).
- 6-inch diameter puncture.
- Approximately 101/2-to-11-inch diameter deformed zone.
- The shipping skid did not bottom out first.
- 26-inch high puncture pin (second pin) was used.
- The puncture pin fastening to the steel pad was checked before and after the test. The puncture pin did not move during the test.
- The pin face was not damaged after the test.

c) Puncture Test #5: Impact on fixed skid lower plate. See Figures 2.7.2-F9, 2.7.2-F10, and 2.7.2-F11 respectively. The test observations are:

- Local deformation, no penetration.
- Deformation indentation zone similar to pin diameter.
- Deformation zone 10 in. diameter.
- 26-inch high puncture pin (second pin) used.
- The puncture pin fastening to the steel pad was checked before and after the test. The puncture pin did not move during the test.
- The pin face was not damaged after the test.

d) Puncture Test #7: Impact on the crush shield upper plate. See Figure 2.7.2-F12, 2.7.2-F13, and 2.7.2-F14 respectively. The test observations are:

- 6-inch diameter main deformation, 16-inch diameter gradual deformation.
- No penetration. However, footprint of the pin on the upper plate of the crush shield.
- Approximately 2 in. vertical deformation.
- 26-inch high puncture pin (second pin) was used.
- The puncture pin fastening to the steel pad was checked before and after the test. The puncture pin did not move during the test.
- The puncture pin face was not damaged after the test.

e) Puncture Test #8: Impact cylindrical fireshield (nameplate zone). See Figures 2.7.2-F15, 2.7.2-F16, and 2.7.2-F17 respectively. The test observations are:

- Shipping skid cleared the steel pad (impact plate).
- Packaging remained balanced on pin (pin penetrated fireshield).
- 1-foot diameter deformation by 1-1/2 inch deep.
- 2/3 circumference (of 6-inch diameter indent) penetrated.
- 26-inch high puncture pin (second pin) used.
- The puncture pin fastening to the steel pad was checked before and after the test. The puncture pin did not move during the test.
- The puncture pin top face was not damaged after the drop test.
- The shipping skid landed on the reinforced concrete pad just outside the steel pad. The shipping skid did not bottom out first.

f) Leaktightness of the cavity of F-294:

Before the eight (8) drop tests, the F-294 cavity was air pressure tested and helium leak tested. The cavity was leaktight.

After the eight (8) drop tests, the F-294 cavity was air pressure tested and helium leak tested. The cavity was leaktight.

g) Shielding tests

Before the eight (8) drop tests, the F-294 was radiation surveyed using 375,360 curies of cobalt-60 as of January 7, 1998 (see Table 2.7.1-T1 and Figure 2.7.1-F9).

After the eight (8) drop tests, the F-294 was radiation surveyed using 365,221 curies of cobalt-60 as of March 24, 1998 (see Table 2.7.1-T1 and Figure 2.7.1-F9).

The test demonstrates that the cask shielding meets the regulatory requirements.

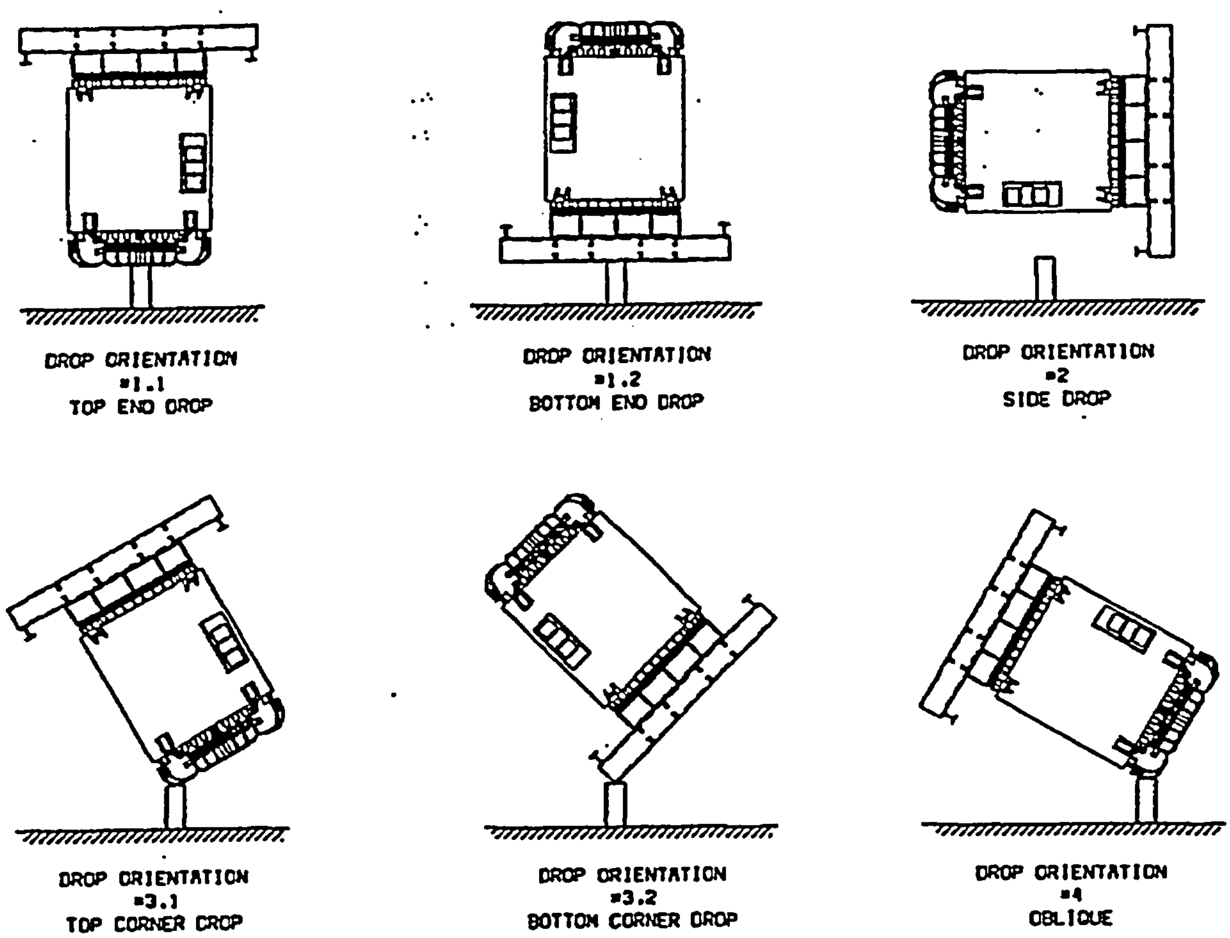
2.7.2.9 Overall Summary of Puncture Tests on F-294

1. The F-294 was subjected to five (5) puncture pin tests.
2. Test #3C: The puncture pin, impacting the zone near lift lug #4, left a foot print and gouged the fins in the impact zone.
3. Test #4: The puncture pin, impacting the cylindrical fireshield, resulted in a small tear and opening of area 21 in^2.
4. Test # 5: the puncture pin, impacting the fixed skid, left a foot print only and did not tear the plate.
5. Test # 7: The puncture pin, impacting the crush shield, left a foot print only and did not tear the plate. The lift lug of the closure plug was compressed 0.66 in. as a result of pin progression until arrested.
6. Test #8: The puncture pin, impacting the cylindrical fireshield at the nameplate zone, resulted in a small tear and opening of area 6 in^2.
7. The deformation profile of the F-294 test packaging as a result of eight (8) drop tests is depicted in Dwg. F629401-022 (see Figure 2.7.1-F10).

2.7.2.10 Conclusions

The F-294 transport package shall maintain its structural, containment system and shielding integrity under the hypothetical accident conditions puncture tests. These results will remain the same whether an F-313 or an F-457 source carrier is used.

Figure 2.7.2-F1
Drop Test Orientations for F-294 Puncture Pin Test



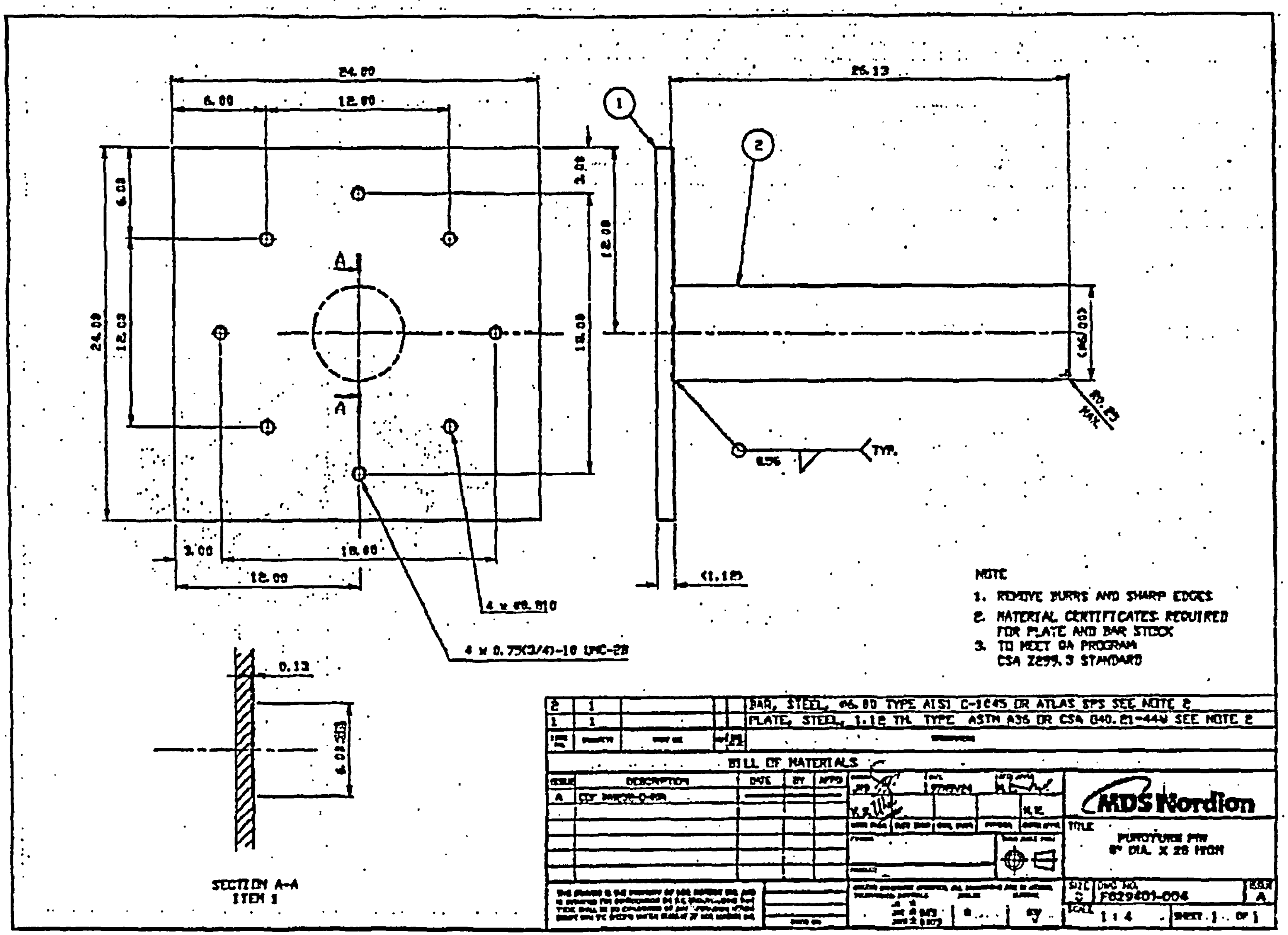


Figure 2.7.2-F2
26-in high Puncture Pin

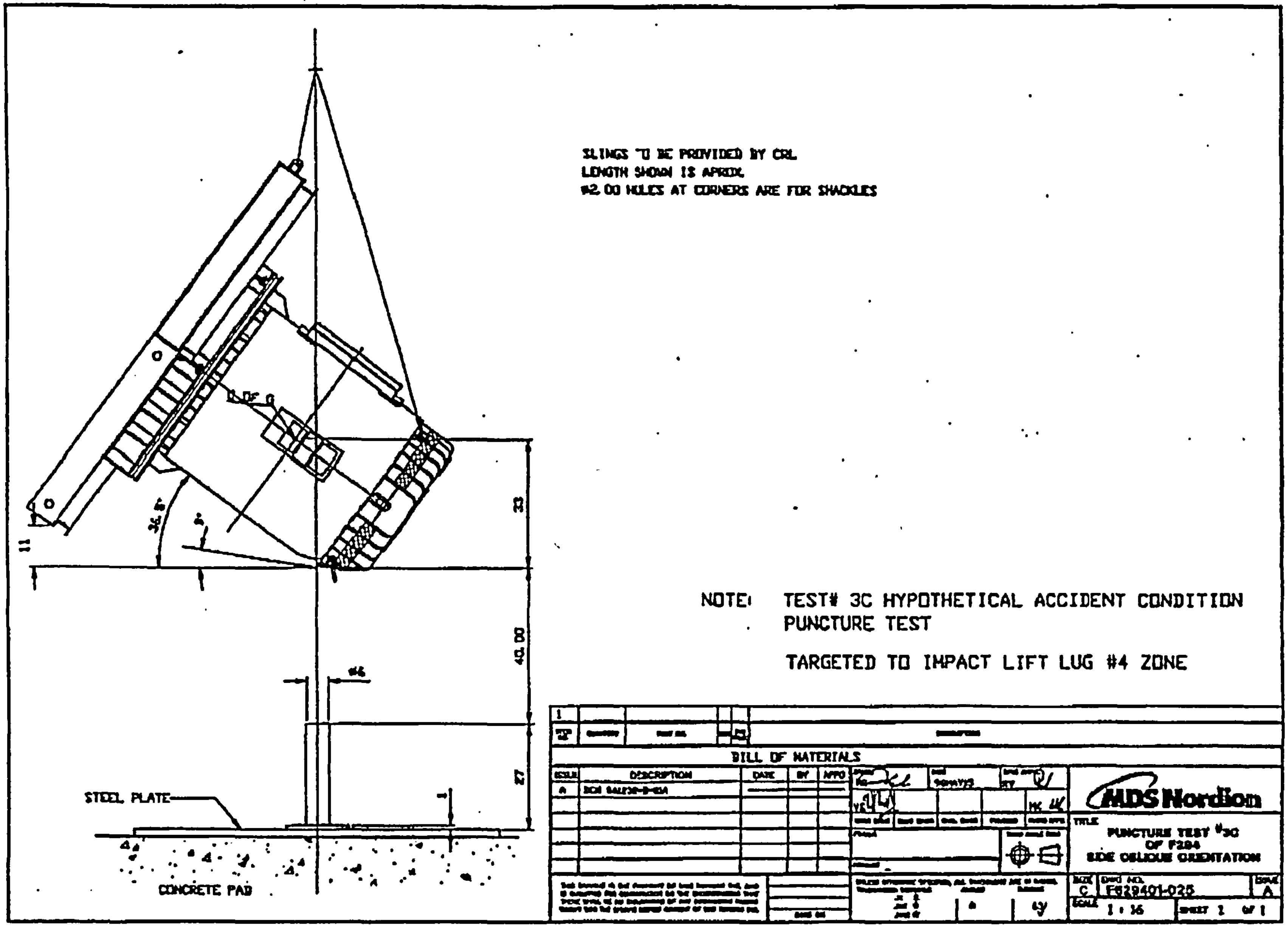


Figure 2.7.2-F3
Puncture Test #3C: Drop Orientation

Figure 2.7.2-F4
Puncture Test #3C: Before the Drop
(Photo MDSN-F294-0063)

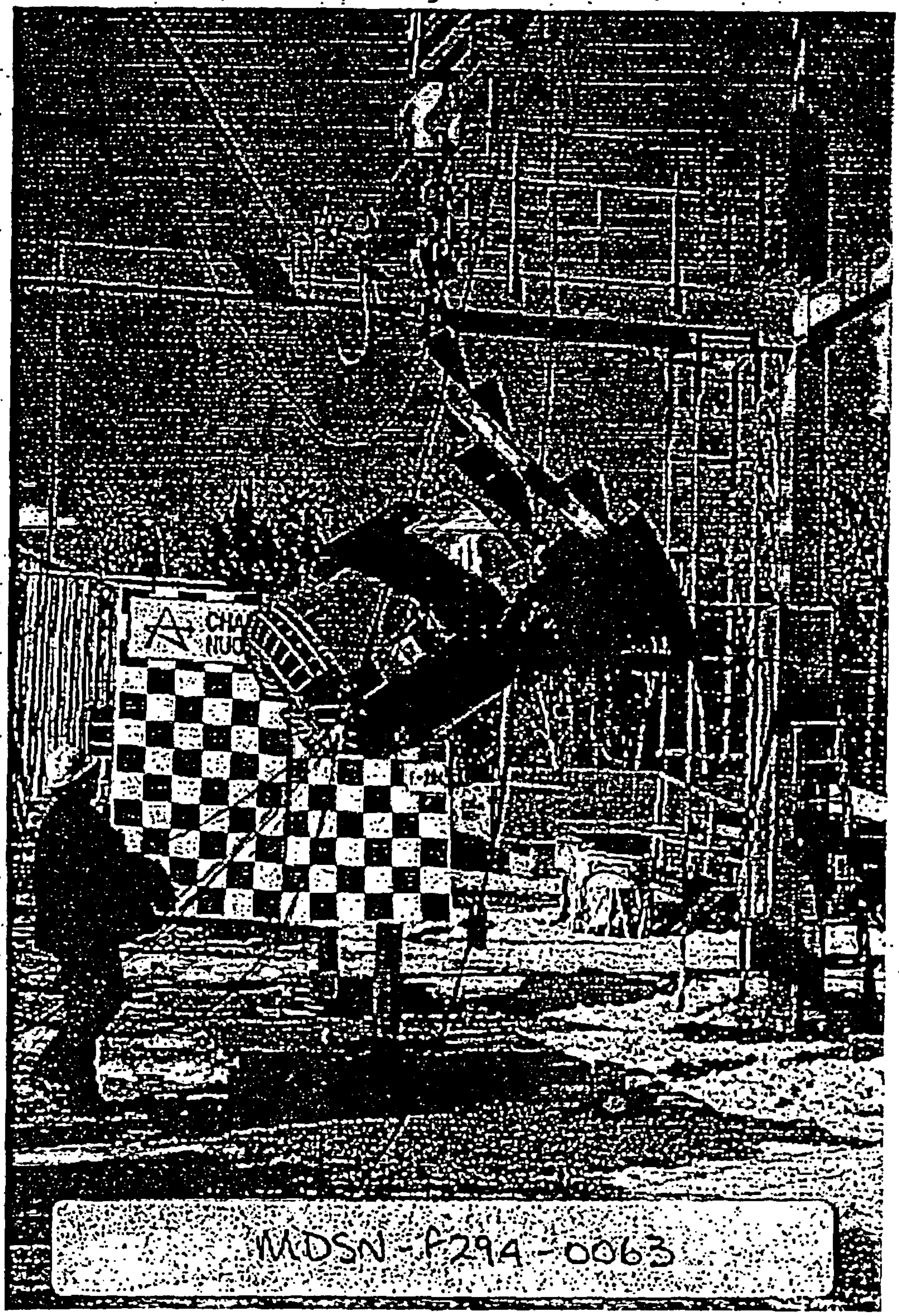
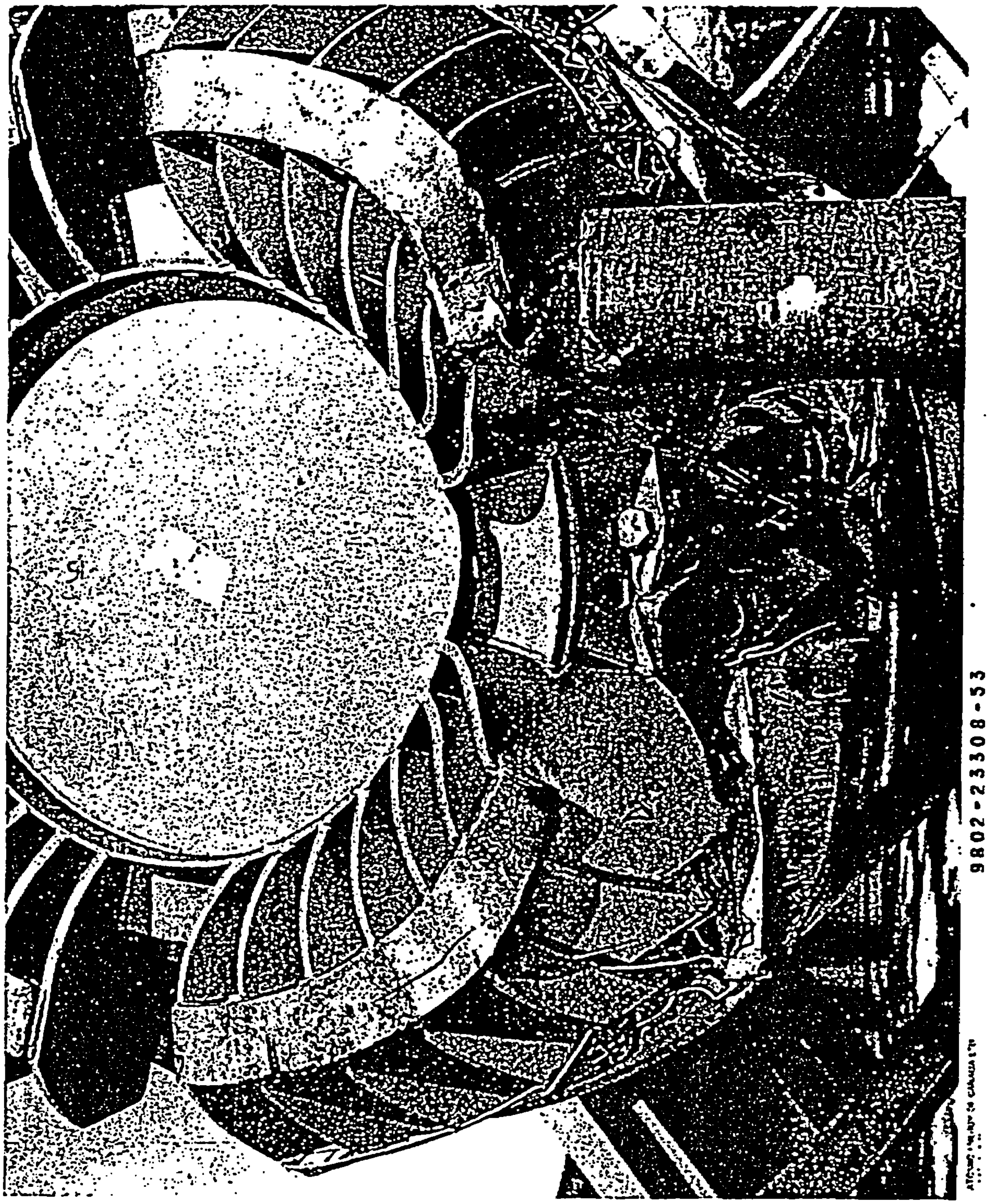


Figure 2.7.2-F5
Puncture Test #3C: After the Drop
(Photo 9802-23308-53)



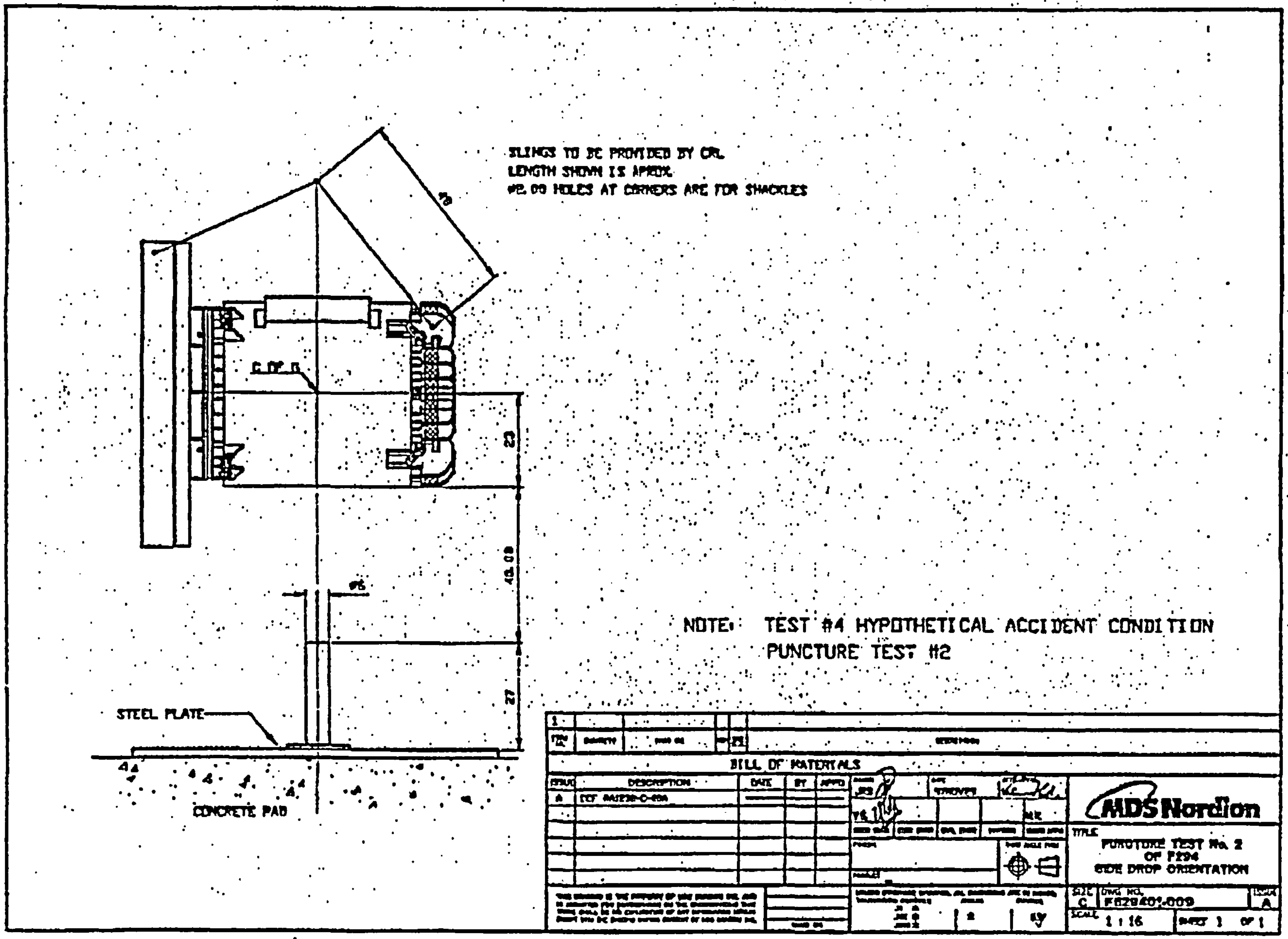


Figure 2.7.2-F6
Puncture Test #4: Drop Orientation

Figure 2.7.2-F7
Puncture Test #4: Before the Drop
(Photo 9802-23308-62)

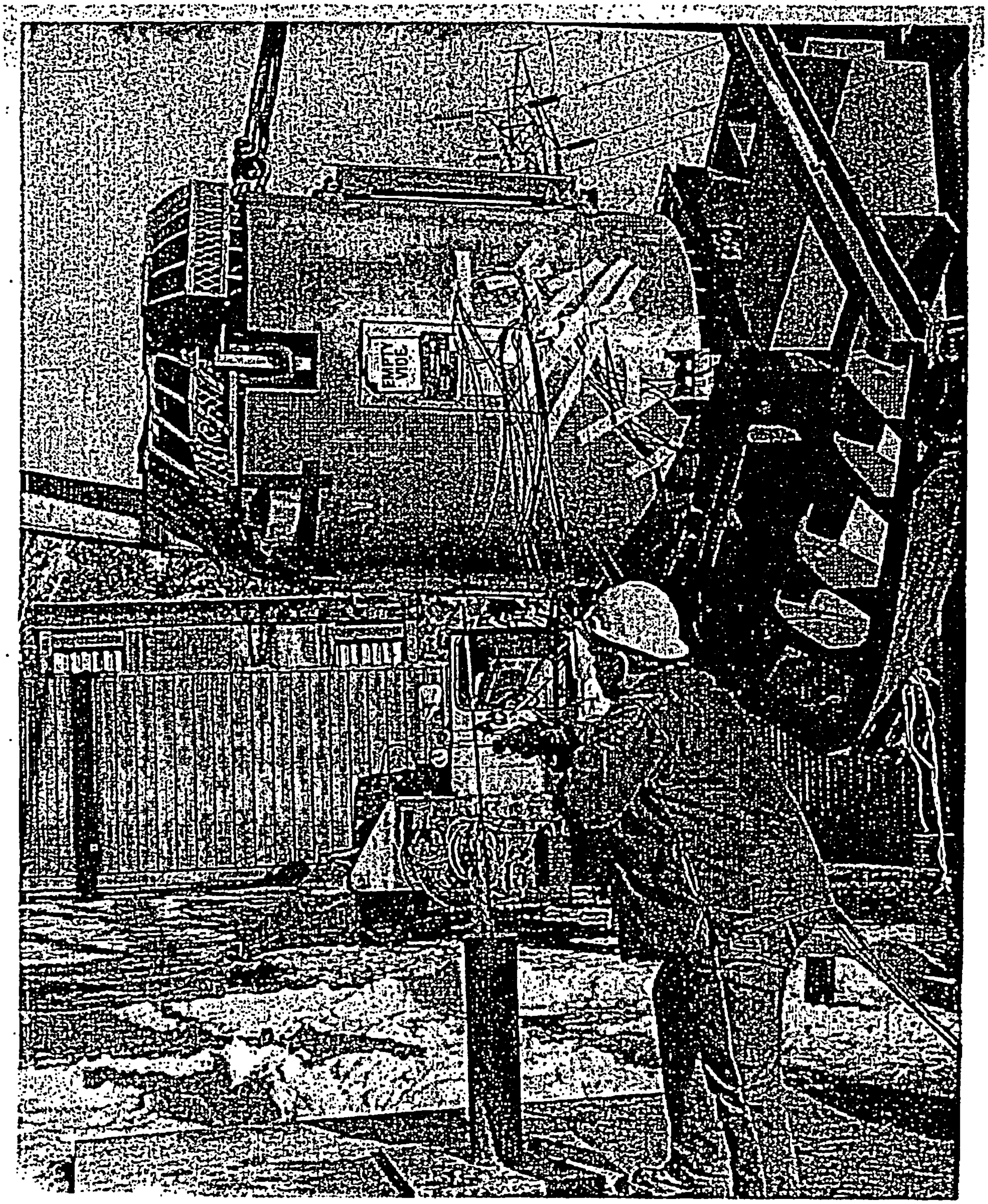


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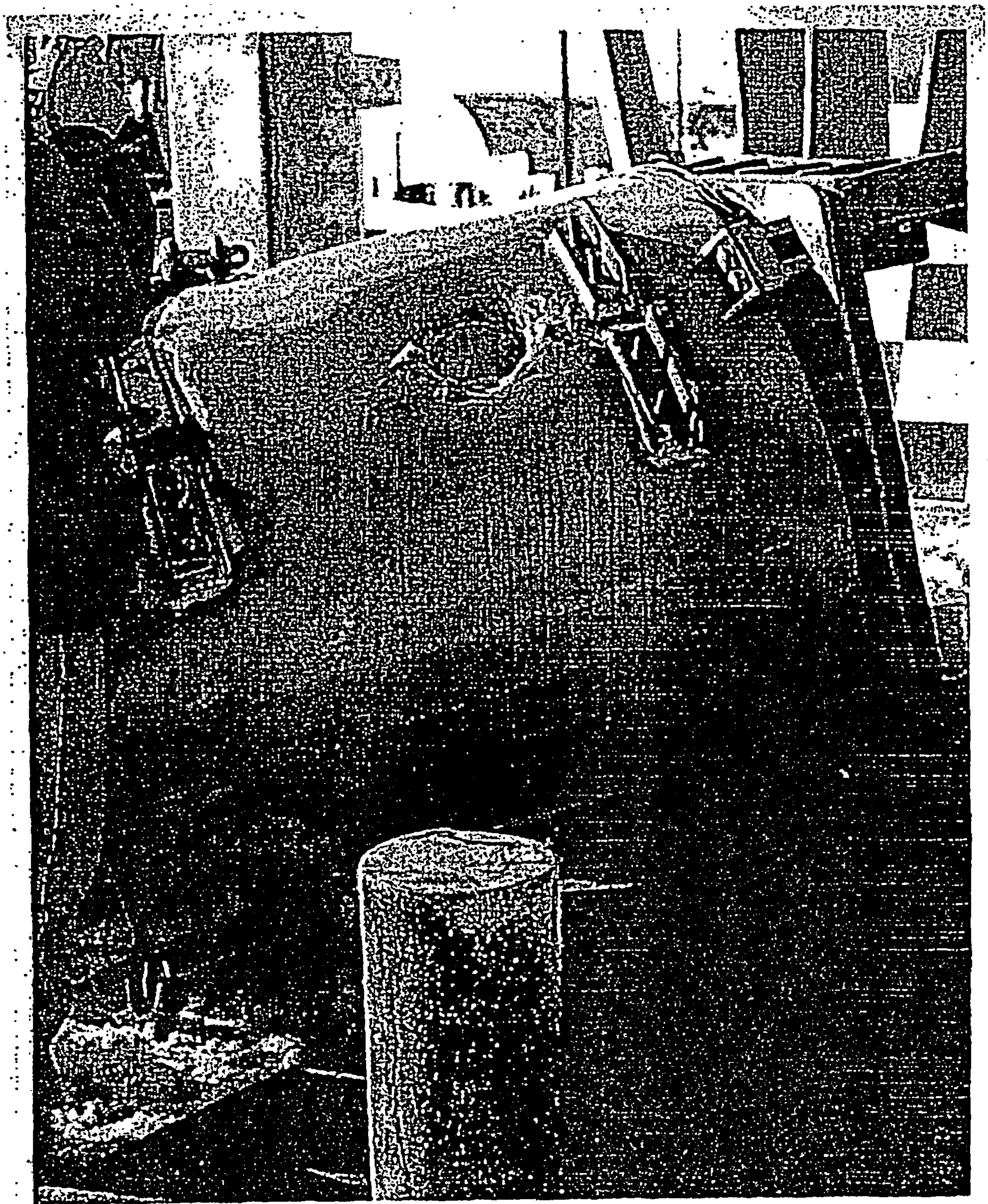
Figure 2.7.2-F8
Puncture Test #4: After the Drop
(Photo 9802-23308-63)



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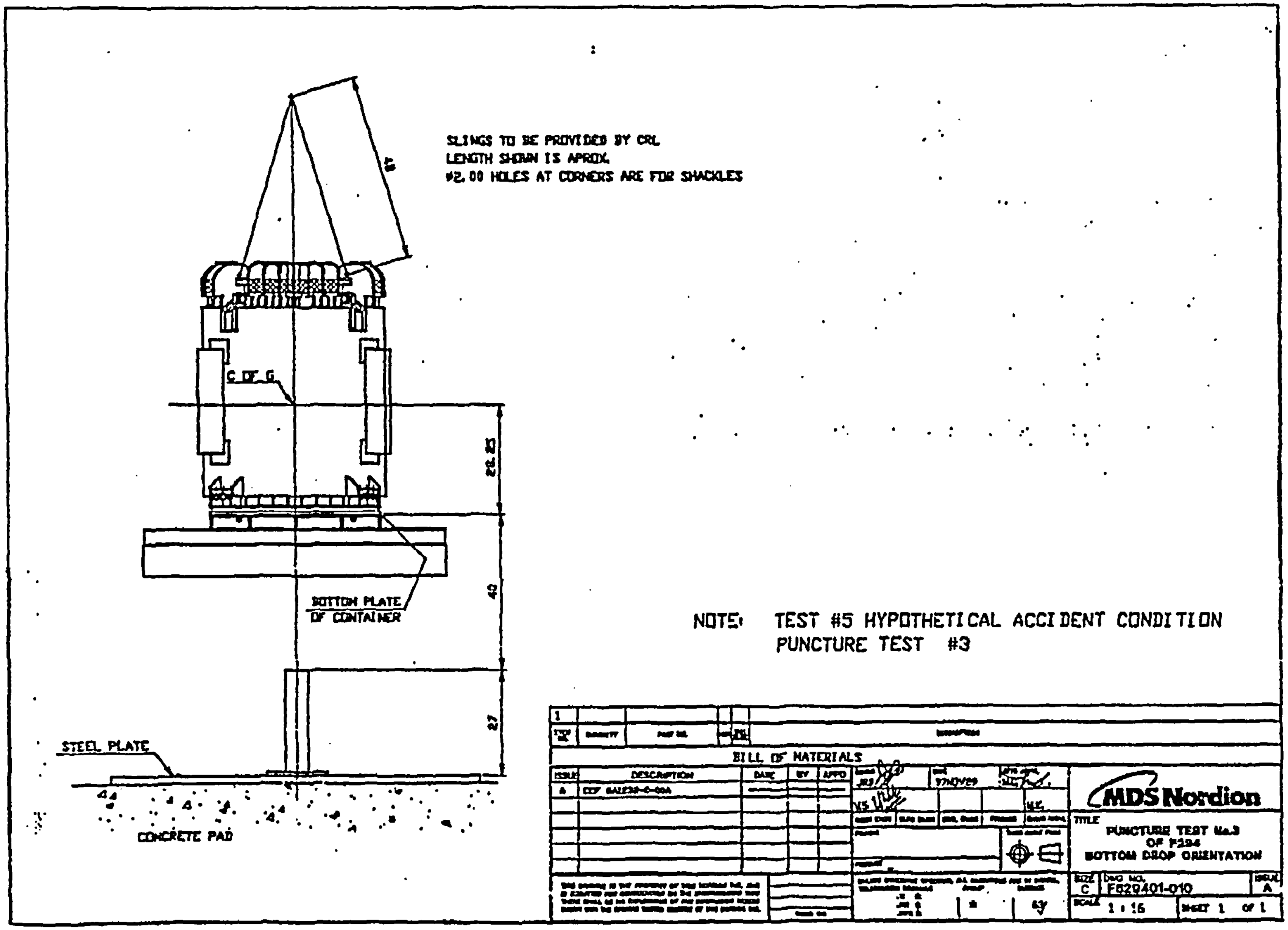

Figure 2.7.2-F9
Puncture Test #5: Drop Orientation

Figure 2.7.2-F10
Puncture Test #5: Before the Drop
(Photo 9802-23308-69)

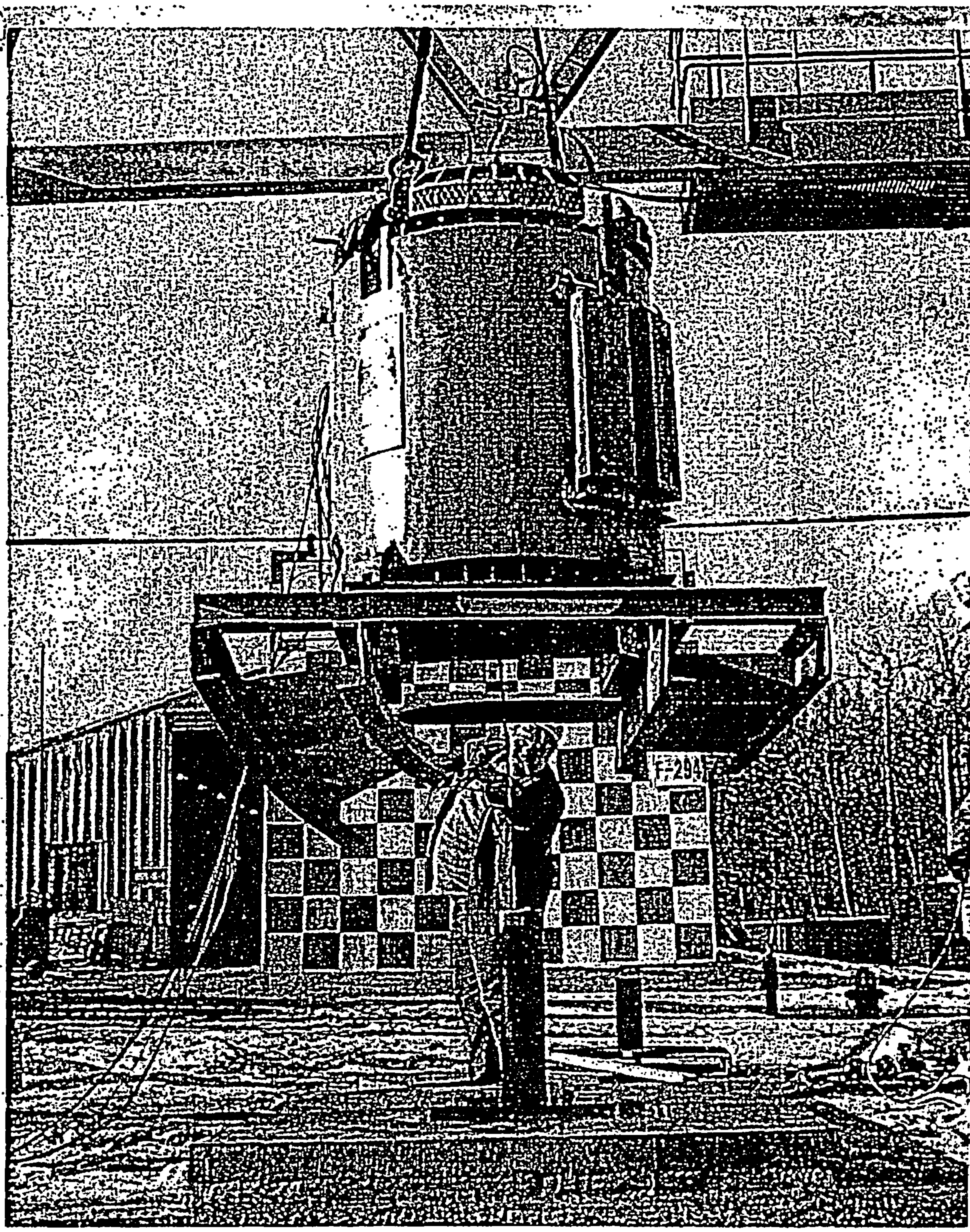

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Figure 2.7.2-F11
Puncture Test #5: After the Drop
(Photo 9802-23308-72)

Figure 2.7.2-F12
Puncture Test #7: Drop Orientation

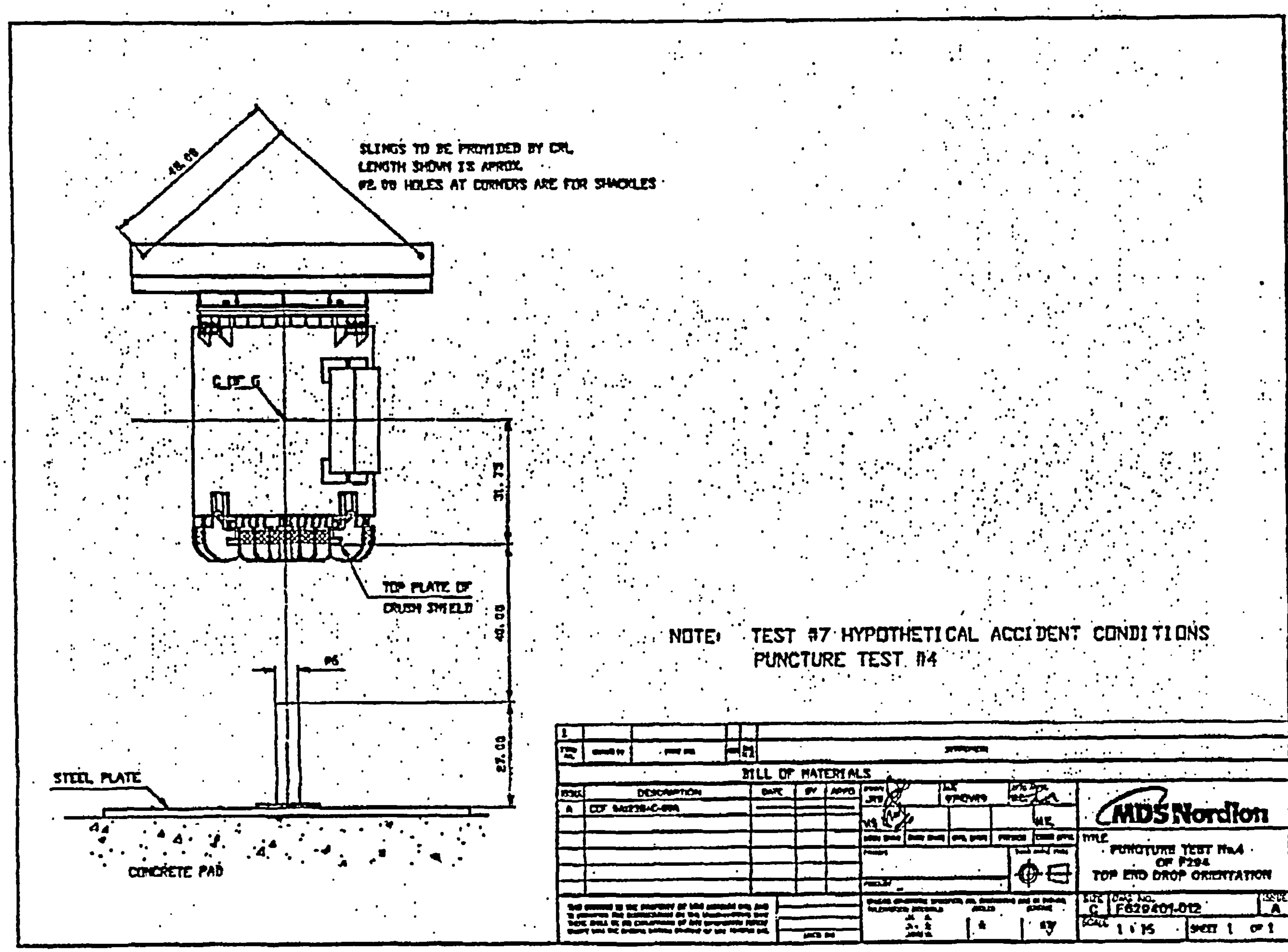

Figure 2.7.2-F13
Puncture Test #7: Before the Drop
(Photo 9805-23308-85)

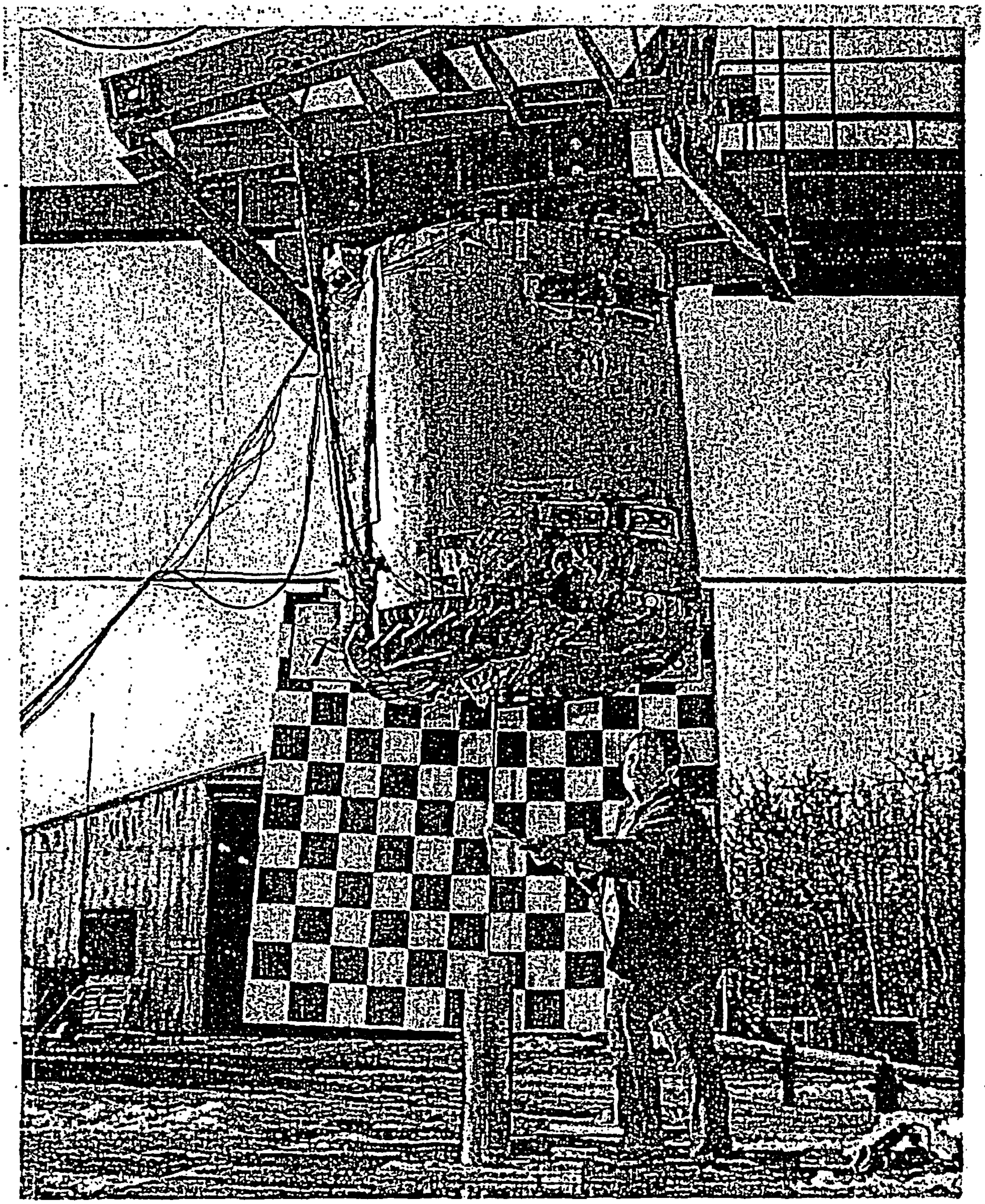

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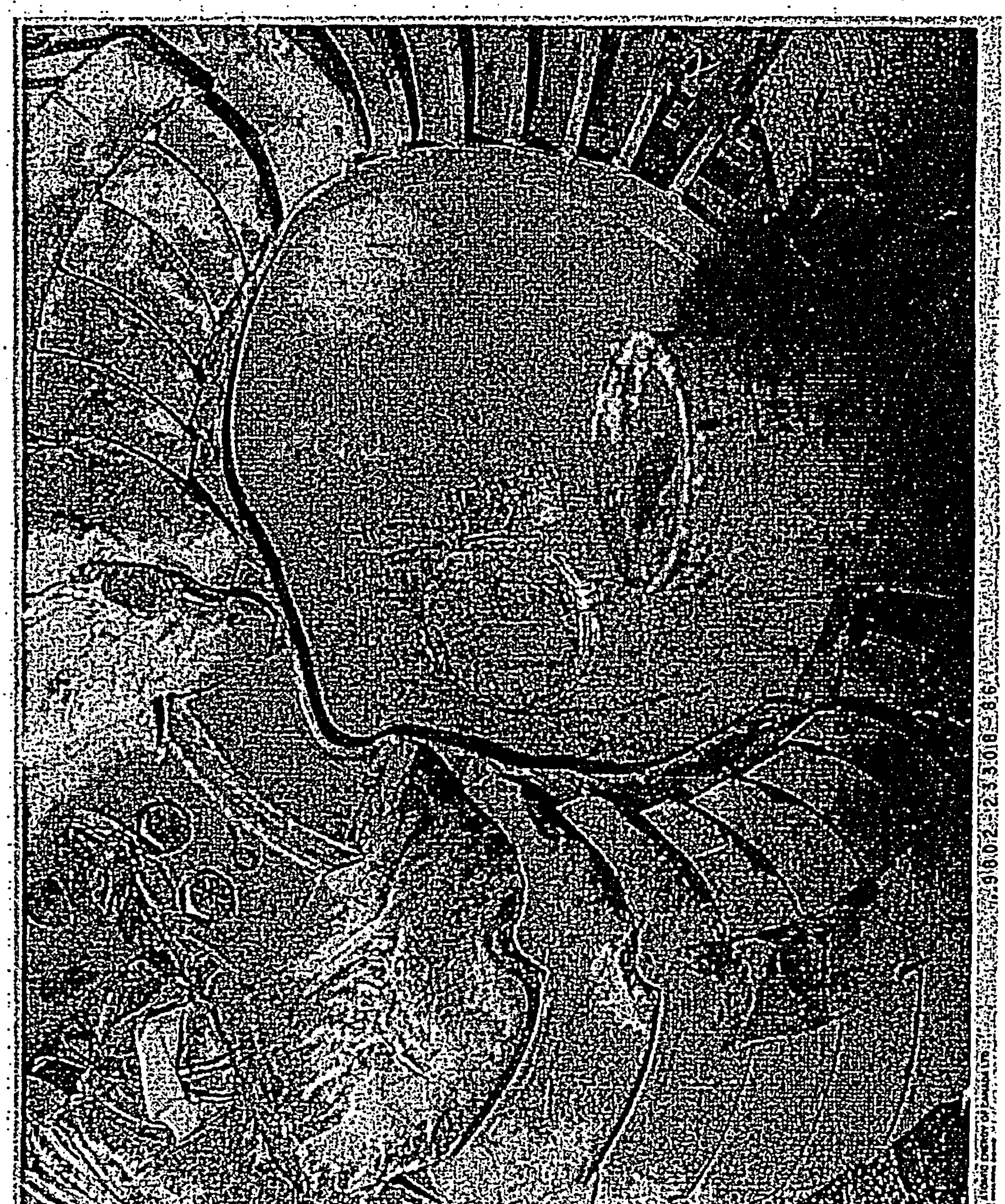
Figure 2.7.2-F14
Puncture Test #7: After the Drop
(Photo 9802-23308-86)



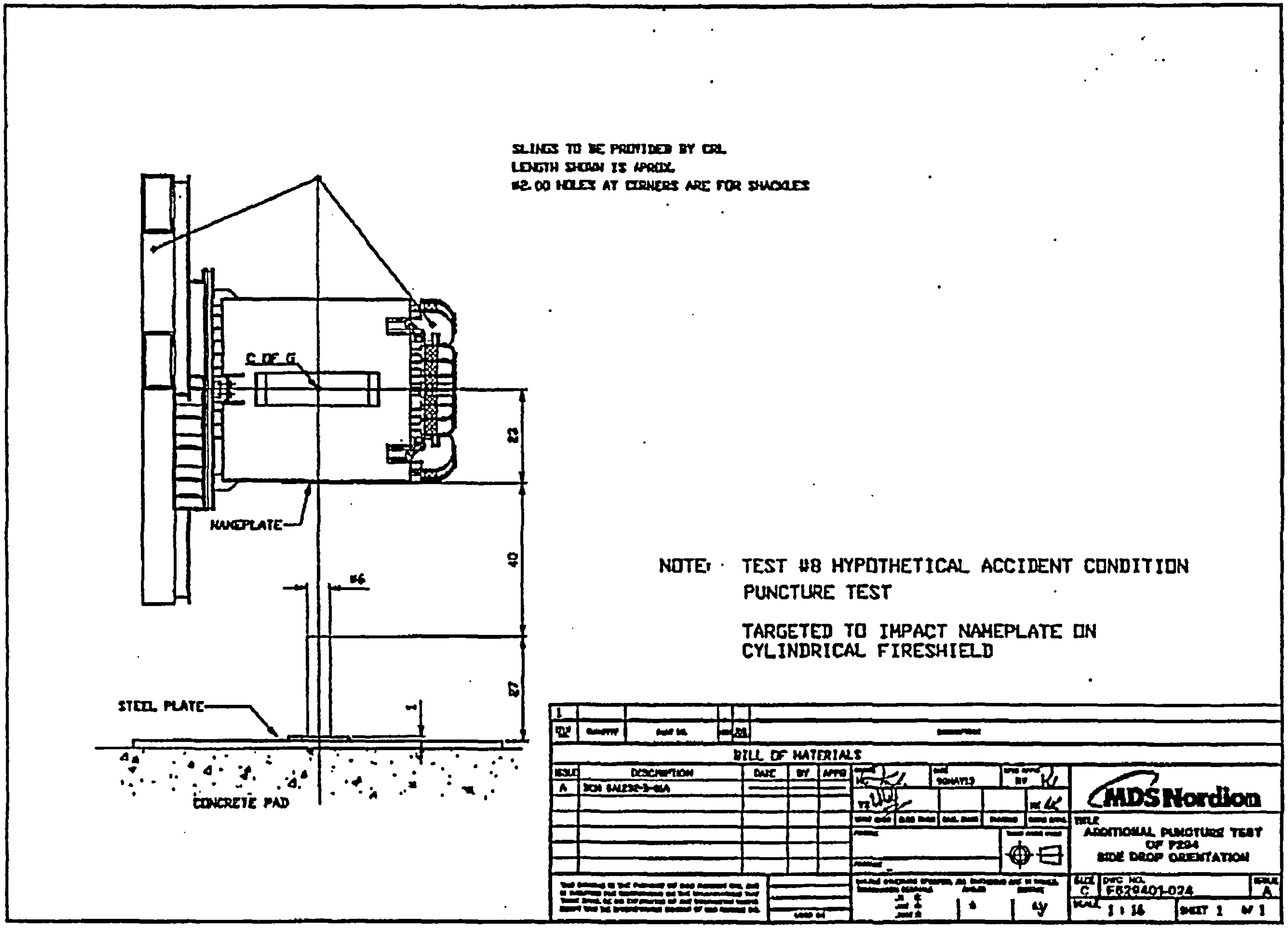


Figure 2.7.2-F15
Puncture Test #8: Drop Orientation

Figure 2.7.2-F16
Puncture Test #8: Before the Drop
(Photo 9802-23308-91)

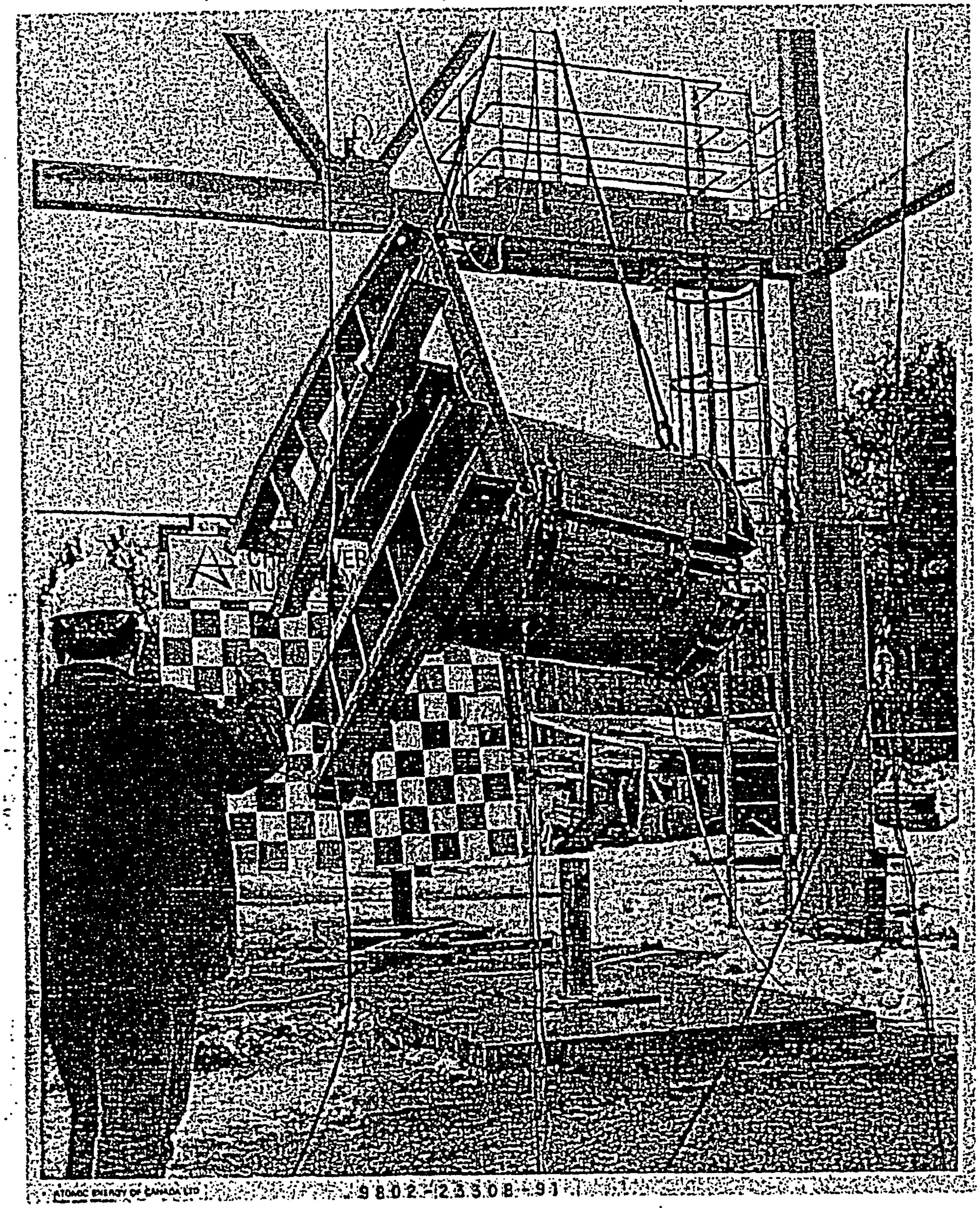
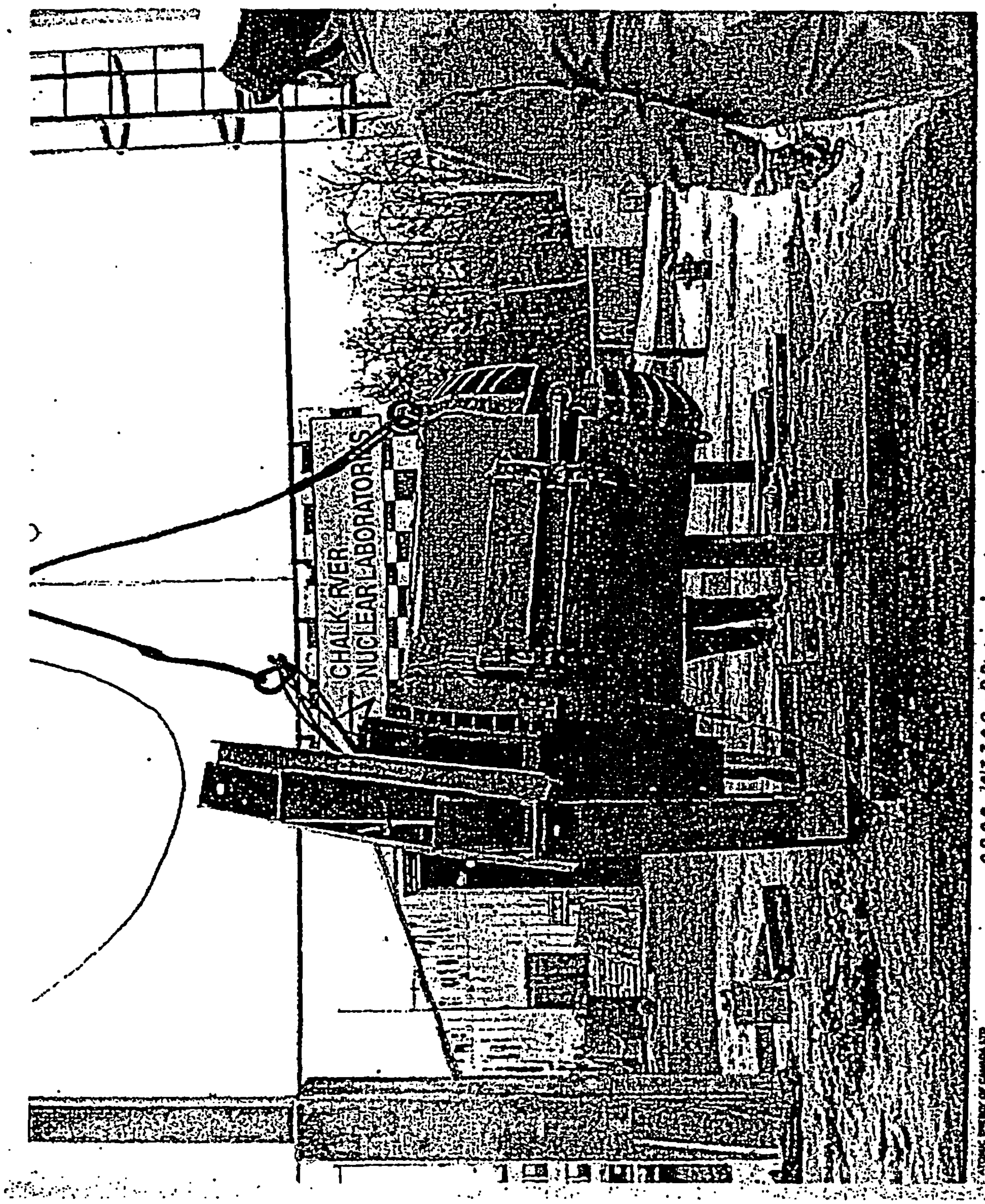


Figure 2.7.2-F17
Puncture Test #8: After the Drop
(Photo 9802-23308-92)



2.7.3 THERMAL

The F-294 test packaging has 9,257 in^2 of thermal protection area surrounding the flask. The F-294 transport package has 11,167 in^2 area of thermal protection surrounding the cask. The condition of the F-294 test packaging prior to the hypothetical accident condition of transport thermal test is that all the fireshields (thermal protection) are retained around the F-294 lead shielded container (cask); however about 800 in^2 out of 9,257 in^2 of total thermal protection is compressed due to the puncture test, 30-ft free drop test and other considerations. At some locations, the fireshields are flattened, i.e., the thermal insulation is compressed. Also, due to puncture pin tests, the total area of openings in the fireshields is 27 in^2 out of 9,257 in^2. This represents loss of thermal protection of 0.3% of total area. The impact of the degradation of the thermal protection around the F-294 has been investigated in Chapter 3, Appendix 3.6.4.

The temperature increases within the F-294 package resulting from the hypothetical accident thermal evaluation are presented in Chapter 3, Section 3.5 and in Appendix 3.6.4. These temperature increases have minimal effects on the performance and integrity of the package. This is further discussed in Chapter 3.

2.7.3.1 Summary of Pressures and Temperatures

The pressure increases in the F-294 package after the hypothetical accident condition of transport thermal test are as follows:

In the cavity of F-294, the pressure build up is as follows:

T_1 = Average Temperature of F-294 Cavity in NCOT = 606°F
P_1 = Pressure of the cavity in NCOT = 29.6 psia
T_2 = Average Temperature of the cavity after fire test = 721°F
P_2 = Pressure of the cavity after fire test = ? (unknown) psia

$$
\begin{aligned}
P_2 &= P_1 \times [T_2 + 460]/[T_1 + 460] \\
&= 29.6 \times [721 + 460]/[606 + 460] \\
&= 29.6 \times 1{,}181/1{,}066 \\
&= 32.8 \text{ psia} \\
&= 18.1 \text{ psig} \\
&= 20 \text{ psig (design)}
\end{aligned}
$$

Therefore the cavity of F-294 in accident conditions of transport is at 20 psig and average temperature of 721°F. The cavity wall is at nominal temperature of 500 °F. Given that the maximum activity within the cavity is the same regardless of the source carrier used, temperatures and pressures of the cavity of the F-294 container are expected to be the same for both F-313 and F-457 source carriers.

In the C-188 assembly, the pressure build up is as follows:

T_1 = Temperature of C-188 in underwater pool = 70°F
P_1 = Internal Pressure of C-188 in underwater pool = 14.7 psia
T_2 = Temperature of C-188 in HACOT of F-294 = 940°F
P_2 = Pressure of C-188 in HACOT of F-294 = ? (unknown) psia

$$
\begin{aligned}
P_2 &= P_1 \times [T_2 + 460]/[T_1 + 460] \\
&= 14.7 \times [940 + 460]/[70 + 460] \\
&= 14.7 \times 1{,}400/530 \\
&= 38.83 \text{ psia} \\
&= 24.1 \text{ psig.} \\
&= 27 \text{ psig (design)}
\end{aligned}
$$

During accident conditions of transport, the C-188 has an internal pressure of 27 psig and temperature of 940°F

2.7.3.2 Stress Calculations

1. C-188 Sealed Source: Due to build up of internal pressure.
   See Chapter 4, Appendix 4.4.5. for detailed stress calculations.
   Due to internal pressure of 27 psig in the C-188 during ACOT of F-294,
   1. the hoop stress in the tube away from joint = 192 psi
   2. the hoop stress in the tube at the joint = 282 psi
   3. the bending stress in the end cap = 5 psi.

   Based on yield stress of 15,000 psi for ss316L at 940°F, C-188 has a Safety Factor of 52 and Margin of Safety of 51. Therefore the containment, i.e., the outer assembly of C-188 sealed source, shall maintain its structural integrity.
2. Closure plug bolted joint subject to internal pressure and G-loads

   Due to build-up of internal pressure, the main plug bolted closure is examined in detail. The internal pressure in the cavity is 20 psig (see Chapter 4, Appendix 4.4.6).

   2.1. Internal pressure load, W_{OP}

   The internal pressure load, W_{OP} is calculated as follows:

$$
\begin{aligned}
W_{OP} &= \Delta P * \text{Area} \\
&= \Delta P * [\pi * G^2/4] \\
&= 20 * \pi * 15.91^2/4 \text{ [psi * in}^2\text{]} \\
&= 4{,}000 \text{ lb.}
\end{aligned}
$$

   where

   ΔP = 20 psi (internal pressure - outside the F-294 container at atmospheric pressure)

   G = gasket reaction diameter = 15.91 in.

   2.2 Gasket seating Load, F_{SG}

$$F_{SG} = \pi * b * G * y$$

   where

   b = effective gasket seating width

   G = gasket diameter

   y = gasket seating stress = 200 psi
   (Ref. [17] i.e., ASME VIII Div. I: Table UA-49-1)

Basic gasket seating width, b_O = actual width of gasket/2

= (16.38 − 15.44) x 0.5/2

= 0.235 in.

When $b_O \leq 1/4$ in., the effective gasket seating width, $b = b_O = 0.235$ in.

When $b_O \leq 1/4$ in., diameter at location of gasket reaction, G

G = Mean diameter of gasket contact face

= (16.38 + 15.44) x 0.5

= 15.91 in.

Gasket seating Load, F_{SG}

F_{SG} = π * b * G * y

= π * 0.235 * 15.91 * 200

= 2,400 lb.

Therefore, gasket seating and internal pressure load acting on the plug,

$W_{bolt\ load\ required}$ = FSG + WOP

= 2,400 + 4,000

= 6,400

Design check: what is the total bolt load available on basis of UTS of the bolt material?

16 cap screws (1-8-UNC: UNBRAKO 1960) 1-in. are specified as closure plug bolts.

For UNBRAKO 1960 cap screw material, UTS = 180,000 psi; YS = 155,000 psi.

Bolt data - 1-in. nominal diameter

stress area per bolt = 0.551 in^2

root diameter = 0.838 in

UNC = coarse thread

8 threads per inch (8 tpi).

$W_{bolt\ load\ available}$ = no. of bolts x bolt area x allowable stress

= 16 x 0.551 x [UTS]

= 16 x 0.551 x 180,000

= 1,586,800 lb.

As $W_{bolt\ load\ available}$ (1,586,800 lb.) > $W_{bolt\ load\ required}$ (6,400 lb.), the closure plug bolting design is more than adequate to resist the forces on the closure plug due to internal pressure.

Now let us consider additional forces on the closure plug due to 132 g's on F-294 resulting from 30-ft free drop test of F-294, in top end drop orientation.

$W_{G\text{-}LOAD}$ = Load due to G-load = W x G_{HACOT} = 1,115 lb. x 132 g's

= 147,200 lb.

where

$W = W_{PLUG} + W_{CONTENT} = 1{,}070 + 45 = 1{,}115$ lb.

The total load on the closure plug required to maintain flanged, gasketed joint in HACOT is

$W_{required\ closure\ plug,HACOT}$ = $F_{SG} + W_{OP} + W_{G\text{-}LOAD}$

= 2,400 + 4,000 + 147,200 lb.

= 153,200

As $W_{bolt\ load\ available}$ (1,586,800 lb.) > $W_{required\ closure\ plug,HACOT}$ (153,200 lb.), the closure plug bolting design is more than adequate to resist the forces on the closure plug due to internal pressure and G-loads on F-294 arising from hypothetical accident drop tests.

Safety factor (SF) $= W_{\text{bolt load available}}/W_{\text{required closure plug, HACOT}}$
$= 1,586,800 \text{ lb.}/153,200$
$= 10.35$

Margin of Safety = SF – 1 = 10.35 – 1 = 9.35

As the margin of safety (MS) is greater than zero, the bolted joint as specified shall be maintained during the hypothetical accident conditions of transport (HACOT) of F-294 package.

3. Cavity wall due to build -up of internal pressure:

3.1 The hoop stress in the lower cavity tube, without taking lead restraint into account, is as follows:

$$\sigma_{hoop} = p\, d/2t$$

where

p = 20 psig internal pressure
d = mean diameter of lower cavity tube = 12.0 in.
t = 0.500 in.
σ_{hoop} = 20 x 12/2 x 0.5 = 240 psi.

For ss304L at 500°F, yield stress = 15,500 psi.

Safety Factor (SF) = allowable stress/applied stress
$= 0.667 \times YS/\sigma_{hoop}$
$= 0.667 \times 15,500/240$
$= 43$

Margin of Safety (MS) = SF – 1 = 43 – 1 = 42

3.2 The bending stress in the lower cavity end cap, without taking restraint of lead into account, is as follows:

$$\sigma_b = cp/[t/d]^2$$

where

c = constant based on joint geometry
= 0.2 based on ASME VIII, Division 1, Figure UG = 34 (i)
p = internal pressure = 20 psig
t = thickness of end cap = 0.75 in.
d = internal diameter of the tube = 11.5 in.
$\sigma_b = 0.2 \times 20/[0.75/11.5]^2 = 940$ psi.

For Hastelloy C-276, YS, yield stress at 500 °F = 36,000 psi

Safety Factor (SF) = allowable stress/applied stress
$= 0.667 \times YS/\sigma_b$
$= 0.667 \times 36,000/940$
$= 25.5$

Margin of Safety (MS) = SF – 1 = 25.5 – 1 = 24.5

Therefore, the lower cavity assembly under build-up of pressure of 20 psig has sufficient margin of safety that the structural integrity of the cavity assembly shall not be compromised.

2.7.4 WATER IMMERSION

10 CFR 71.73(c)(6) requires that "a separate, undamaged specimen must be subjected to water pressure equivalent to immersion under a head of water of at least 15 m (50 ft.) for a period of not less than eight (8) hours. For test purposes, an external pressure of water of 150 kPa (21.7 psi) gauge is considered to meet these conditions".

An external pressure equal to 21.7 psig would have no effect on the package. In Chapter 2, Appendix 2.10.5, it is shown that the container shall withstand 45 atmospheres (664 psia or 649 psig) without taking credit for lead shielding and external cooling fin stiffening restraint. Therefore, the F-294 container shall have no difficulty withstanding the external pressure equal to 21.7 psig.

The package is designed to transport C-188 radioactive sealed sources. These sealed sources have been designed, tested and certified to meet the Class 5 external pressure test requirements of the ANSI N542 Standard (Ref. [10]) (also see Chapter 4, Appendix 4.4.2). This test requires that the capsule be subjected to external pressure ranging from 3.6 psia to 10,150 psia without any loss of integrity. Hence, the source capsule is designed to withstand external pressures ranging from 0.25 atmospheres (3.6 psia to 690 atmospheres (1,0150 psia). Consequently the integrity of the containment (C-188) is sound.

Hence, in summary, a separate, undamaged F-294 container specimen would be unaffected by an external pressure equal to 21.7 psig or immersion under a head of water of 50 ft. for a period of at least eight (8) hours.

2.7.5 SUMMARY OF DAMAGE

1. The F-294 tests were carried out as per Test Plan document (Ref. [48]) and Quality Plan document) Ref. [49]). On February 25 1998, at Chalk River Laboratory (CRL) of Atomic Energy Of Canada Limited (AECL), Chalk River, Ontario, Canada eight (8) drop tests were carried out on a single full-scale F-294 test packaging in the specified sequence:

Test #1:	Normal Free Drop Test: top end drop orientation
Test #2:	30-ft Free Drop Test: side oblique drop orientation
Text #3:	Puncture Test: impact on the zone near lift lug fin #4
Test #4:	Puncture Test: impact on the cylindrical fireshield
Test #5:	Puncture Test: impact on the fixed skid lower plate
Test #6:	30-ft. Free Drop Test: top end drop orientation
Text #7:	Puncture Test: impact on the crush shield upper plate
Test #8:	Puncture Test: impact on the cylindrical fireshield (nameplate zone)

2. After the drop tests, the damage to the F-294 test packaging is as follows:
   1. There were no cracks in the F-294 cavity wall or the external primary shell of the container (flask). there were no cracks in the closure plug.
   2. Some container fin-to-fin welds were fractured. Some container-to-fin welds were fractured. Some container fins had deformed significantly.
   3. The closure plug was in place and had not come loose. The "neoprene" gasket of the closure plug bolted joint was not damaged. The lift lug of the closure plug was compressed by 0.66 in. primarily due to puncture pin impact.
   4. The fins of the crush shield and the container buckled in the standard J-shape or S-shape.
   5. The cylindrical fireshield and the crush shield were retained.

3. Integrity of Thermal Protection:

   On the F-294 test packaging, there is 9,257 in^2 area of the thermal protection surrounding the F-294 flask. After the drop, there was an opening of 21 in^2 (due to Puncture Pin Test # 4) and 6 in^2 (due to Puncture Pin Test #8). The 27 in^2 opening area out of 9,257 in^2 total thermal protection area represents a loss of 0.3 % of thermal protection area.

   The damage to the thermal protection was approximately 800 in^2 out of total thermal protection of 9,257 in^2 This represents 8.6% of total thermal protection area was damaged

4. F-294 Cavity Leaktightness:

   Before the eight (8) drop tests, the F-294 cavity was air pressure tested and helium leak tested. The cavity was leaktight.

   After eight (8) drop tests, the F-294 cavity was air pressure tested and helium leak tested. The cavity was leaktight.

5. C-188 Dummy Capsule's Leaktightness:

   Before the eight (8) drop tests, the C-188 dummy capsules were helium leak tested. They were leaktight.

   After eight (8) drop tests, the C-188 dummy capsules were helium leak tested. They were also leaktight.

6. Deformation Profile:

   The deformation profile of the F-294 test packaging as a result of eight (8) drop tests is depicted in Dwg. F629401-022 (see Figure 2.7.1-F10.)

7. Shielding test:

   Before the eight (8) drop tests, the F-294 was radiation surveyed using 375,360 curies of cobalt-60 as of January 7, 1998. The test radiation source was similar to the radioactive source for shipping configuration. See Table 2.7.1-T1 and Figure 2.7.1-F9.

   After eight (8) drop tests, the F-294 was radiation surveyed using 365,221 curies of cobalt-60 as of March 24, 1998. See Table 2.7.1-T1 and Figure 2.7.1-F9.

   The details of the F-294 radiation surveys (shielding tests) before and after the eight (8) drop tests are presented in Chapter 2, Appendix 2.10.12 and in Chapter 5. The radiation survey tests demonstrate that the cask shielding meets the regulatory requirements.

8. Measured Decelerations and Duration of Impact.

   In the 30-ft. free drop test, in the side oblique drop orientation, the measured maximum deceleration was 136 g's on top of the closure plug of F-294 and the duration of impact was 30 milli-seconds.

   In the 30-ft. free drop test, in the top end (inverted) drop orientation, the measured maximum deceleration was 132 g's on top of the closure plug of F-294 and the duration of impact was 24 milli-seconds.