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Impact Test Data of ZrH Reactor System

AUTHOR

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ABSTRACT As part of the post impact disassembly studies of the ZrH reactor a series of impact tests have been conducted on the principal reactor materials. This report presents the basic equations used in determining the impact energy balance between the test specimens and the target at impact. With the aid of these equations the energy absorption capacity of the materials tested is determined. The effects of irradiation on 304 SS is presented indicating that the energy absorbing capacity of the reactor vessel will not be affected by irradiation. Modeling laws are shown that indicate that it is possible to predict the post impact configuration of the reactor by scale model testing.			PREPARED BY S. L. Lee DEPT 731 MAIL ADDR LB30 DATE <i>Jan 11 1970</i>		
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I. INTRODUCTION

This report is a part of the post impact disassembly studies of the ZrH reference reactor system. The material presented develops the equations for determining the impact energy distribution between the target and the projectile at impact. Impact test data conducted on cylindrical specimens of the principal reactor materials are analyzed as well as impact tests on LRHS capsules. The effects of long term irradiation on material mechanical properties are shown, and the results of studies of modeling laws are presented.

II. SUMMARY

Analytical Methods

The approach used in analyzing the test results was based on the result of the post-impact analysis of the ZrH reactor system (Ref. 1) where it was concluded that the energy method would offer the best possibility of providing a meaningful basis for predicting the post-impact configuration. From reviewing existing data it becomes apparent that the energy absorbed per pound of material is strongly dependent upon the impact velocity. This approach permits the identification of a factor K which is the ratio of the energy absorbed per pound dynamically to the energy under the normal stress strain curve. K factors for ductile materials increase with an increase in the impact velocity.

Analysis of Impact Test Data

Analysis of the impact test data of pellet specimens of LiH, ZrH, sintered tungsten, 316 stainless steel, and Ta-10W (Ref. 18) and four LRHS capsules (Ref. 8 & 10) was conducted to add validity to the energy method, based on K factors, for predicting the post impact configuration. The results of the impact test analysis is summarized as follows:

- a. K factors vs impact velocity for the two sizes of stainless steel specimens tested were identical, however the values were lower than the theory predicts. Both sizes of specimens fractured at impact velocities above 700 ft/sec.
- b. The plastic deformation pattern at the impact end of both sizes of steel specimens was identical.
- c. The total strain (elastic plus plastic) energy for a brittle material such as LiH, ZrH, and sintered tungsten is very small and therefore the energy absorption capacity under dynamic conditions is very poor.

- d. The rebound kinetic energy and the rotational kinetic energy for stainless steel specimens are very small as compared with the total K. E.
- e. Energy dissipated in the crater volume in the target is also small.
- f. There is no rebound velocity for LiH and ZrH specimens. This indicates that LiH and ZrH is not a continuous matrix.
- g. The damage and deformation at the impact end of all the LRHS capsules is identical. The formation of a symmetrical wave in the longitudinal direction is classified as plastic buckling due to the small radius to wall thickness ratio.
- h. K factors for the cylindrical shells with hemispherical heads of the LRHS capsules is about 16 at an impact velocity of 350 fps. K factors for both solid steel pellets is about 1.8 at an impact velocity of 850 fps.
- i. The Ta-10W had a K factor of 3.2 at an impact velocity of 850 ft/sec. The material appeared to remain ductile with no evidence of fracture as with the stainless steel specimens.

Irradiation Effects

The maximum neutron fluence on the reactor vessel after 40,000 hours of operation is $5. \times 10^{19} \text{ n/cm}^2$. This irradiation will cause a small increase in the yielding stress and a small reduction in the ductility of the 304 SS. The energy absorption capacity of the vessel material will not be affected by this low level of neutron fluence.

Modeling Laws

Studies of modeling laws indicates that the post impact configuration of a prototype can be predicted from the damage and deformation pattern obtained from impact tests conducted on scale models.

III. ANALYTICAL METHODS

Based on the result of the post-impact analysis of ZrH Reactor System (Ref. 1) it was concluded that the energy method would offer the best possibility of providing a meaningful basis for predicting the post-impact configuration of the reactor. From the review of existing data it became apparent that the energy absorbed per pound of material is strongly dependent upon the impact velocity. This approach permits the identification of a factor, "K" which is the ratio of the energy absorbed per pound dynamically to the energy under the normal stress-strain curve.

$$K = \frac{E_{\text{Dynamic}}}{E_{\text{Static}}}$$

The procedure for the evaluation of the K factor is

1. Determine the energy-absorption capacity of the material

A measure of the energy absorption capacity of a material is afforded by the area under its stress-strain curve. The static strain energy to fracture may be approximated as follows:

$$E_s = 1/2 (\sigma_y + \sigma_u) \frac{E_u}{12} \quad (\text{Ft-lb/lb}) \quad \dots\dots\dots(1)$$

where σ_y = yielding stress

σ_u = ultimate strength

E_u = elongation in percentage and

ρ = density lb/in³

2. Determine the velocity of the compressive wave (C) or the velocity of sound in the material

$$C = \sqrt{E/\rho} \quad (\text{FPS}) \quad \dots\dots\dots(2)$$

where

E = modulus of elasticity

3. Determine the time duration of impact using the value of C from (2)

$$\tau = \frac{2L}{C} \quad (\text{seconds}) \quad \dots\dots\dots(3)$$

where L = the length of the metallic cylindrical shell

4. The acoustic impedance ρC of the materials is then

$$\rho C = \frac{144 \times 12\rho}{32.2 \times 144} \quad C = \frac{12\rho}{32.2} \quad (\text{psi/fps}) \quad \dots\dots\dots(4)$$

5. The impact of a capsule with impedance of material, $\rho_C C_C$, onto the target media with an impedance $\rho_t C_t$ generates an interface pressure expressed by the equation

$$P = \frac{\rho_t^c V}{1 + \frac{\rho_t^c}{\rho_c^c}} \quad (\text{psi}) \quad \dots\dots\dots (5)$$

where V = the impact velocity, the subscript c refers to the capsule and the subscript t refers to the target. This interface pressure formula was used in impact test analysis of SNAP 27 (Ref. 6).

6. The energy dissipated in the compressive wave in the target media is expressed by the equation

$$E_{\text{target}} = \frac{2}{3} A \frac{\sigma^2}{E_t} \tau c_t \quad (\text{ft-lbs}) \quad \dots\dots\dots (6)$$

The 2/3 factor relates to the compressive stress distribution in the target media; A = impact area; σ = the compressive stress in the target which can be equal to the interface pressure; E_t = the modulus of elasticity of the target media.

7. The energy dissipated in the compressive wave in the cylindrical capsule is expressed by the equation:

$$E_{\text{capsule}} = \frac{2}{3} A \frac{\sigma^2}{E_c} \tau c_c \quad (\text{ft-lbs}) \quad \dots\dots\dots (7)$$

For a cylindrical shell with hemispherical heads, the energy dissipated in the target, as well as in the capsule, is reduced by a 2/3 factor.

8. The total kinetic energy due to impact and rebound is

$$K.E. = \frac{1}{2} \frac{W_c}{g} (V^2 - V_R^2) \quad (\text{ft-lbs}) \quad \dots\dots\dots (8)$$

where

V_R = rebound velocity. For a cylindrical shell filled powdered material, the rebound velocity is very small compared with the impact velocity.

9. The energy Q dissipated in the crater volume generated in the target media is

$$Q = \alpha \frac{\text{Vol. } E_t}{1000 \times 12} = \alpha 540 \text{ Vol. (ft-lbs)} \dots\dots\dots (9)$$

where

Vol. = the measured crater volume in inch³:

α = the reduction factor for a low impact velocity since this formula was reduced from test data on concrete subjected to hyper-velocity impact.

10. The energy absorbed by the deformed portion of the capsule is

$$E_{\text{deformed portion}} = (8) - (6) - (7) - (9) \dots\dots\dots (10)$$

11. K factor calculation then becomes

$$K = \frac{E_{\text{deformed portion}}}{Wt_{\text{deformed}} \times E_s} \dots\dots\dots (11)$$

where Wt_{deformed} = weight of the deformed portion of the capsule

When the capsule impacts onto the target in an oblique position, the total kinetic energy, $\frac{1}{2} mV^2$, is transformed into the translational energy and the rotational energy. The translational energy at the impact end is reduced to

$$\left\{ 1 - \left[\frac{\sin^2 \phi}{\frac{1}{\sqrt{3}} + \sqrt{3} \sin^2 \phi} \right]^2 \right\} - \frac{1}{2} mV^2$$

ϕ = oblique angle of impact with the axis perpendicular to the impact surface.

IV. ANALYSIS OF IMPACT TEST DATA

The tests from which the data was obtained are described in References 8, 10 and 18. The material and physical properties of the materials tested are tabulated in Tables 1, 2, 7 and 8.

The interface pressures vs the impact velocity for the test specimens of LiH, ZrH, stainless steel, Ta-LOW and sintered tungsten impacted onto the target media (granite) were calculated by formula 5 (Ref. 6). The calculations are tabulated in Tables 2 and 7 and presented in Figure 1.

TABLE 1 PROPERTIES OF MATERIALS AT ROOM TEMPERATURE

MATERIAL	E_t K/IN	E_{10} K/IN ²	E_{100} %	MODULUS OF ELASTICITY 10 ⁴ PSI	P N/IN ²	STATIC ENERGY $E_s = PE/2$	VELOCITY OF SOUND F/S	IMPEDANCE PC PSI/KPS	REMARK
S.S. STEEL 316	30	15	40	29	.288	6,000	16,400	1760	
SINTERED TUNGSTEN	10	220	.6	58	.696	100	14,800	3850	
COMMERCIAL TUNGSTEN	29	80	16	58	.696	1,000	14,800	3850	RECRYSTALLIZED ONE HOUR AT 2900°F
L.H. (COINEX)	982	15	.4	8.5	.0255	157	28,400	270	COMPRESSION IS HIGHER THAN TENSION
Z.H. (COINEX)	36	104	18	4.4	.22	4,750	6,700	550	.14% C 253-B1 NAA-SR-8617 S.T.H. 10/71
GRANITE	~	40	.6	6.5	.102	100	13,000	500	

TABLE 2. TESTED SAMPLES

MATERIAL	SIZE IN	T IMPACT TIME 10 ³ SEC	WEIGHT lbs	AREA IN ²	Pc CL Pi Cp	P=8 PSI	DEFORMED WEIGHT-165				
							V=100	V=350	V=600	V=700	V=850
S.S. 316	1" DIA X 2.50"	1.27	.557	.785	.215	390V	.017	.26 .295	.432 .394	.415	.453 416
S.S. 316	.50 DIA X 2.10"	1.03	.111	.196	.215	390V	.004	.0528 .0520	.068 .071	.047	.0784
SINTERED TUNGSTEN	1.00 DIA X 2.00"	1.18	.104	.785	.13	443V					
	.50 DIA X 1.25"	1.74	.175	.196	.13	443V					
L.H. SOLID	2" DIA X 9.00"	2.67	.72	3.142	1.85	174V					
L.H. STEEL WNL	2" DIA X 9.00"	2.67	.78	3.142	1.85	174V					
L.H. H.C. LOW	2.00 DIA X 9.00"	2.67	.80	3.142	1.15	174V					
L.H. H.C. LAT.	2.00 DIA X 9.00"	2.67 L.H.									
L.H. .016"	2.00 X 9.00	4.95 STEEL	1.01	3.142	1.85 L.H.	174V					
STEEL SHEET					.215 STEEL						
Z.H.	1/2" DIA X 3"	2.14	.128	.196	.91	262V					

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PAT.	Properties of materials	REPORT NO. TI-700-13-013
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DATE: DEC. 22, 1969	FIGURE 1 IMPACT STRESS	MODEL NO.

The deformed weight of the two sizes of stainless steel 316 specimens vs the impact velocities and the crater volumes in the target media, (granite), were measured and plotted in Figure 2.

The total kinetic energy, the rebound kinetic energy, the rotational kinetic energy, the energy dissipated in the compressive wave in the target media, and the energy dissipated in the crater volume vs the impact velocity for the 1 in. diameter, and 1/2 in. stainless steel specimens were tabulated in Tables 3, 4, 5, & 6 and plotted in Figure 3 and Figure 4 respectively.

The total kinetic energy, the energy dissipated in the compressive wave in the target media, and the energy dissipated in the crater volume vs the impact velocity for the 1/2 in. diameter by 1.25 in long Ta-10W specimens were tabulated in Table 7 and plotted in Figure 5. The rebound kinetic energy was not included as it is a small fraction of the K. E. as shown in the plot of the stainless steel specimens.

The LRHS capsules were cylindrical shells with hemispherical heads made of T-111, recrystallized one hour at 3000°F. The properties of T-111 vs the temperature were plotted in Figure 6. The solid curves are reduced from test data (Ref. 3) and the dotted curves are predicted values. The LRHS capsules were heated to 1200° or 2200°F, and then impacted onto the target media (granite) at impact velocities ranging from 240 to 350 fps. The damage and the plastic deformation at the impact end are shown in Figures 7 to 15. No damage to the target was reported. Calculations of the energy dissipated in the compressive wave in the target, as well as in the cylindrical shell, are tabulated in Table 9. K factors for these cylindrical shells with R/t ratios from 6.5 to 13.4 were calculated to be from 8.2 to 16.1.

The results of the analysis of impact test data of solid cylindrical specimens of stainless steel 316, LiH, ZrH, Ta-10W and sintered tungsten, and four LRHS capsules are summarized as follows:

PREPARED BY: <i>L. Lee</i>	ATOMICS INTERNATIONAL A DIVISION OF NORTH AMERICAN AVIATION, INC. FIGURE 2 WEIGHT OF DEFORMED PORTION AND VOLUME OF CRATER IN TARGET	PAGE NO. 14 OF
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FIGURE 2

TABLE 4.
.50" DIA SPECIMANS TEST DATA

SPECIMAN NO.	IMPACT VELOCITY F/S	REBOUND VELOCITY F/S	IMPACT ENERGY FT-LBS	REBOUND ENERGY FT-LB	ANGLE OF IMPACT DEGREE	REBOUND ANGLE DEGREE	REBOUND TUMBLING RAD/SEC	ROTATIONAL KE. FT-LB	
6	140	41	33.7	2.9	7°15'	3°9'	231	.4	
7	350	86	211	12.8	7°15'	22°56'	375	1.14	
4	350	84	211	12.2	5°44'	27°11'	495	1.9	
8	600	98	618	16.5	0	16°40'	114	0.11	
11	600	101	618	17.5	0	19°16'	219	.37	
12	700	26	840	1.1	2°	40°22'	1520	17.5	
10	850	70	1240	8.5	0	27°45'	910	6.5	
9	850	106	1240	19.4	0	23°4'	1210	11.2	

$$I_{\omega} = \frac{W}{g} \left(\frac{a^2}{4} + \frac{L^2}{12} \right) = \frac{.111}{32.2 \times 12} \left(\frac{.25^2}{4} + \frac{2^2}{12} \right) = 9.1 \times 10^{-5} \text{ IN-LB/SEC}^2 = 7.6 \times 10^{-6} \text{ FT-LB/SEC}^2$$

$$\text{ROTATIONAL K.E.} = \frac{1}{2} I_{\omega} \omega^2$$

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TABLE 3.
1.00 DIA STAINLESS STEEL SPECIMANS TEST DATA

SPECIMAN NO.	IMPACT VELOCITY F/S	REBOUND VELOCITY F/S	IMPACT ENERGY FT-LB	REBOUND ENERGY FT-LB	ANGLE OF IMPACT DEGREE	REBOUND ANGLE DEGREE	REBOUND TUMBLING RAD/SEC	R. K.E. $\frac{1}{2} I \omega^2$ FT-LB	% of K.E.	
5	100	28.6	865	7.1	$8\frac{1}{2}$	0	212	1.58	1.85	
1	350	65	1050	36.5	$10\frac{1}{2}$	$33^{\circ}35'$	344	4.3	3.95	
7	350	49.4	1050	21	$5\frac{1}{2}$	$44^{\circ}46'$	144	.72	.7	
9	600	111.1	3110	106	$16\frac{1}{4}$	$66^{\circ}25'$	1050	38.5	1.25	
2	600	119	3110	123	$12\frac{3}{4}$	$54^{\circ}33'$	922	30	1.0	
12	700	53.5	1240	29.2	2	$64^{\circ}24'$	436	6.6	1.55	
10	850	79.5	6250	48	2	$41^{\circ}46'$	538	10.15	1.6	
11	850	103.2	6250	91.5	$5\frac{3}{4}$	$67^{\circ}14'$	810	23	3.7	

$$I_{rr} = \frac{W}{g} \left(\frac{g^2}{4} + \frac{f^2}{12} \right) = \frac{.552}{32.2112} \left(\frac{.121}{4} + \frac{6.21}{12} \right) = \frac{.552}{386} (1.512) = 8.4 \times 10^{-2} \text{ IN-LB X SEC}^2$$

$$= 7.1 \times 10^{-5} \text{ FT-LB X SEC}^2$$

$$\text{ROTATIONAL KINETIC ENERGY} = \frac{1}{2} I_{rr} \omega^2$$

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ENERGY DISSIPATED IN COMPRESSION
WAVE IN THE TARGET. USING EQUATION (17)

$$E_t = \frac{2}{3} A \frac{\sigma^2}{E_t} T C_L$$

FROM THE TABLE (2)

DURATION OF IMPACT

$$T = 1.27 \times 10^{-5} \text{ SEC. FOR } S.S. 347 \text{ } 1.00 \text{ DIA} \times 2.5''$$

$$T = 1.03 \times 10^{-5} \text{ SEC. FOR } S.S. 347 \text{ } .50 \text{ DIA} \times 2.0''$$

VELOCITY OF SOUND IN THE TARGET

$$C_L = 13000 \text{ FPS AND}$$

$$E_t = 6.5 \times 10^6 \text{ PSI}$$

$$E_t = \frac{2}{3} \times .785 \times \frac{\sigma^2}{6.5 \times 10^6} \times 1.27 \times 10^{-5} \times 13,000 = 1.32 \sigma^2 \times 10^{-8}$$

$$E_t = \frac{2}{3} \times .196 \times \frac{\sigma^2}{6.5 \times 10^6} \times 1.03 \times 10^{-5} \times 13,000 = .268 \sigma^2 \times 10^{-8}$$

σ FROM FIGURE (1)

TABLE 5

IMPACT VELOCITY	100	350	600	700	850	
E_t Ft-lb	18.4	174	675	940	1440	1.00" DIA x 2.50"
E_t Ft-lb	3.8	35.5	137	192	293	.50" DIA x 2.0"

ENERGY DISSIPATED IN THE CRATER VOLUME
USING EQUATION (19) AND THE AVERAGE VOLUME
IN THE FIGURE (2)

TABLE 6

IMPACT VELOCITY %	350	600	700	850	
Q Ft-lb	0	51	27	315	1.00" DIA x 2.50"
Q Ft-lb	0	15	8	34	.50" DIA x 2.0"

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FIG 3.

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PREPARED BY: <i>J. Lee</i>	ATOMICS INTERNATIONAL A DIVISION OF NORTH AMERICAN ROCKWELL CORPORATION	PAGE NO. 20 OF
CHECKED BY:		REPORT NO. TI-700-13-013
DATE: <i>Feb 17, 1970</i>	TABLE 7 Ta-10W PELLET TEST DATA	MODEL NO.

PROPERTIES OF Ta-10W AT ROOM TEMPT.
SPECIMAN SIZE 1/2 IN. DIA. BY 1.25 IN. LONG

MATERIAL	σ_f	σ_{max}	ϵ_u	E	P	E_s	C	PC	AREA	W
	K/IN. ²	K/IN. ²	%	10 ⁶ PSI	LB/IN ³	FT-LB/IN	FPS	FPS/PSI	IN. ²	LG.
Ta-10W	68.8	85	37	35	.609	3868	12,400	2810	.196	
GRANITE	~	40	.6	6.5	.102	100	13,000	500	~	TARGET

INTERFACE PRESSURE

$$P_c = \frac{P_{CE}}{1 + \frac{P_{CE}}{P_{CC}}} = 425 V$$

CALCULATION TABLE

IMPACT VELOCITY FPS	350	600	700	850
KINETIC ENERGY FT-LB	285	940	1,140	1,790
P_c K/IN. ²	149	255	297	362
$P_c^2 = \sigma_c^2 \times 10^{10}$	2.22	6.51	8.82	13.1
$\epsilon_{CE} = 13.4 \times 10^6 / 13000$ FT	.174	.174	.174	.174
$E_C = \frac{2}{3} A \frac{P_c^2}{E_s}$ CE FT FT-LB	77	227	308	460
L_D (DEFORMED LENGTH) IN.	.708	.708	.773	.728
W_D (DEFORMED HEIGHT) LBS.	.015	.085	.093	.067
AVERAGE W_D LBS.	.085	.090	.102	.101
$E_s \times W_D$ (AVERAGE) FT-LB	333	372	398	355
CRATER VOLUME IN. ³	0	0	.0392 .0365	.1125 .103
$Q = 504 \times VOL$ FT-LB	~	~	16	60
$K = \frac{K \cdot E}{E_s W_D}$		2.45	2.95	4.65
K INCLUDING E_C & Q		1.75	1.94	3.2

TABLE 7

PREPARED BY: <i>[Signature]</i>	ATOMICS INTERNATIONAL A DIVISION OF NORTH AMERICAN ROCKWELL CORPORATION	PAGE NO. 21 OF
CHECKED BY:	FIGURE 5	REPORT NO. TI-700-13-013
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TABLE 8 PROPERTIES OF MATERIALS

MATERIAL	TEMPERATURE °F	σ_y K/IN ²	σ_{ul} K/IN ²	E_{rel} %	E 10 ⁶ PSI	P 16/IN ³	E_s $\frac{E \cdot 16}{16}$	VELOCITY OF 500-10 C FT/S	IMPEDANCE PC PSI/IPS	INTERFACE PRESSURE PSI	
7-111	1200	37	54	12	24	.604	1750	10,000	2,260	410V	
7-111	2000	36	54	18	22	.604	1170	9,600	2,160	405V	
GRANITE	ROOM		40	16	6.5	.102	100	13,000	500		TARGET

INTERFACE PRESSURE

$$P = \frac{P_c \cdot V}{1 + \frac{P_c}{P_c}}$$

AT 1200°F

$$P = \frac{500 V}{1 + \frac{500}{2,260}} = 410V$$

AT 2000°F

$$P = \frac{500 V}{1 + \frac{500}{2,160}} = 405V$$

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PREPARED BY: <i>[Signature]</i>	ATOMICS INTERNATIONAL A DIVISION OF NORTH AMERICAN AVIATION, INC. FIGURE 6	PAGE NO. 23 OF
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DATE: <i>1 FEB 11 1961</i>	PROPERTIES OF <i>T-111</i>	MODEL NO.

PROPERTIES OF T-111 REF WAH-CHUNG H.B.

DENSITY

.604 lbs/in³

RECRYSTALLIZED ONE HOUR AT 3000°F

PREDICTED

DYNAMIC MODULUS OF ELASTICITY

RT	26×10^6
1400°C	21.8×10^6
1800°C	20.2×10^6
2000°C	19.1×10^6

PREPARED BY: <i>A. J. L.</i>	ATOMICS INTERNATIONAL A DIVISION OF NORTH AMERICAN AVIATION, INC. FIGURE 8	PAGE NO. <i>24</i> OF
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OUTSIDE VIEW

FIG. 8

PREPARED BY:	ATOMICS INTERNATIONAL A DIVISION OF NORTH AMERICAN AVIATION, INC. FIGURE 9	PAGE NO. 25 OF
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END VIEW FIG. 9

WEIGHT OF DETACHED PORTION OF THE HEMI-SPHERICAL SHELL

$$Wt_D = 2\pi R_m H t \quad \text{REF (1)}$$

WHERE R_m IS MEAN RADIUS OF HEMI-SPHERICAL SHELL

t IS THICKNESS OF SHELL
 H IS DEPTH OF MATERIAL
 H IS SHOWN IN FIGURE 2

$$Wt_D = 2\pi \times 1.156 \times 1.40 \times 0.3 \times 0.10 = .355 \text{ lb.}$$

$$H = 1.00$$

$$Wt_D = .355 \times \frac{1.00}{.10} = .315 \text{ lb}$$

Figure 10 Impact Capsule A-3a After Testing at 1200°F at 260 ft/sec.

Figure 11 Impact Capsule A-5a After Testing at 1200°F at 240 ft/sec.
(T-111 Shell .100-in Thick)

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Figure 12 Nose Portion of T-111 Capsule
After Testing

7734-4059

Figure 13 Impact Capsule A-7a After Being
Half-Sectioned (Note Fuel Annulus Intact
After Impact at 1200°F at 346 ft/sec)

TABLE 7													
CALCULATION TABLE													
S/N	IMPACT VELOCITY FPS	ANGLE °	TEMPER- ATURE °F	DIA. IN	THICK- NESS IN	P/E RATIO	WEIGHT lbs	AREA IN ²	WEIGHT PER IMPACT AREA	CROSS- SECTION AREA IN ²	27 R _m ^{1/2} lbs	DEFORMED CYLINDRICAL SHELL	TOTAL DEFORMED WEIGHT lbs
A-3a	260	0	1,200	1.676	.127"	6.5	4.7	2.2	2.18 PSI	.60 IN ²	.288	.5	.474
A-5a	240	0	1,200	1.624	.100"	7.6	4.0	2.06	1.92 PSI	.55 IN ²	.221	.7	.493
A-7a	346	0	1,200	1.718	.127"	6.6	5.2	2.32	2.15 PSI	.63 IN ²	.291	1.00	.691
LIRC	350	18°	2,000	2.406	.090"	13.4	7.26	4.55	1.58 PSI	.653 IN ²	.355	1.00	.605
CONTINUE													
S/N	TOTAL K.E. FT-LB	STATIC ENERGY E _s FT-LB	IMPACT DURATION T SEC.	ENERGY DISSIPATED IN TARGET E _t FT-LB	ENERGY DISSIPATED IN CAPSULE E _c FT-LB	REBOUND ENERGY	ENERGY DISSIPATED IN TARGET AND CAPSULE E _{t+c} FT-LB	NET K.E. FT-LB	E _s YWE _{mf}	K			
A-3a	4,440	1150	1.26 X 10 ⁻⁴	554	150	0	708	4,132	356	11.6			
A-5a	3,600	750	1.26 X 10 ⁻⁴	442	118	0	560	3,040	370	8.2			
A-7a	9,700	1150	1.26 X 10 ⁻⁴	1,055	285	0	1,340	8,360	520	16			
LIRC	13,640	1170	1.06 X 10 ⁻⁴	1,970	285	0	2,255	11,385	710	16.1			
S/N	ROTATIONAL K.E. DUE TO OBLIQUE IMPACT	NETS K.E.	K										
LIRC	2,320	9,065	12.8										

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Calculation sheets

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REMARKS

Calculation sheets

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MODEL NO.

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1. As shown in Figure 1, the interface pressure between LiH and the target is the smallest. Consequently the response de-acceleration will be minimal (Ref. 6). The post impact configuration of the reactor system as determined in Section III, Ref. 1, for configuration A was revised in accordance with Reference 7 and is shown in Figure 20. The increase in LiH thickness from 2.0 inches to 3.0 inches and the low interface pressure of the LiH will reduce the de-acceleration load of the lead shield above the reactor. This factor would in turn reduce the post impact damage of the reactor.

2. LiH breaks up at an impact velocity of 100 fps, at which time the interface pressure is greater than the ultimate compressive strength of LiH.

3. ZrH is anisotropic in nature. It is very brittle in tension and exhibits very little ductility in compression. Its properties vary with the content of carbon (Ref. 2). The total strain (elastic plus plastic) energy is very small.

4. Brittleness and the anisotropic nature of ZrH was verified by the conic fracture at the impact end and by the fracture surfaces at the other sections being parallel to the impact surface as shown in Figure 14 (p. 327 and p. 329 in Reference 5).

5. The elongation of sintered tungsten in both compression and tension is almost zero, as indicated in Reference 4. This was verified by the fractures perpendicular to the impact surface as shown in Figure 15 (P.346, Reference 5). The total strain (elastic plus plastic) energy is very small.

6. With the stainless steel specimen, the rebound kinetic energy; the rotational kinetic energy; and the energy dissipated in the crater volume are very small as compared with the total kinetic energy for the SS specimen.

7. K factors vs impact velocity for both sizes of stainless steel specimens are identical, however they are lower than was expected. Fracture of both sizes of specimens occurred at an impact velocity of 700 fps and above as shown in Figure 16. As reported in Reference 15 a Cr-nickel steel pellet striking a rigid body can withstand an impulse at 1,000 fps without fracture.

8. Damage to the granite by both size steel specimens occurs when the impact velocity is greater than 600 fps. Damage to the granite was also reported by other investigators.

100 %/sec

350 %/sec

Atomics Int
North America

7700-4033

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100 FT/SEC

350 FT/SEC.

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11/21/69

Atomics International
North American Rockwell

7700-4015

100 FT/SEC

350 FT/SEC

600 FT/SEC

700 FT/SEC

850 FT/SEC

Fig 14

11/21/69

Atomics International
North American Rockwell

7700-4016

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9. The plastic deformation patterns at the impact end for both sizes of steel specimens are identical.

10. The Ta-10W tungsten specimens behaved as a ductile material at impact velocities up to 850 ft/sec with no evidence of fracture as shown in Figure 17.

11. Elongation of T-111 at 1200°F is 12%. The elongation of stainless steel 316 at room temperature is about 40%.

12. The K factor for the cylindrical shells of the LRHS capsules is about 16 at an impact velocity of 350 fps. The K factor for both sizes of solid steel pellets is about 1.8 at an impact velocity of 850 fps. The K factor for the Ta-10W was 3.2 at an impact velocity of 850 fps.

13. The damage and deformation at the impact end for LRHS capsule tests are identical. The formation of a symmetrical buckling wave in the longitudinal direction is classified as plastic buckling and is due to the small R/t ratio of the cylinder. The critical stress is above the yielding stress of the material.

14. For thin cylindrical shells with R/t ratios greater than 200, the classic static buckling stresses are below the yielding stress of the material. The buckling pattern will be diamond shaped and the length of the waves in the axial and circumferential directions are about equal. However, under axial impact, the dynamic buckling stress (Reference 16) is higher than the classic static buckling stress, and the axial wavelengths are much shorter than in static buckling.

500 FT. / SEC.

600 FT. / SEC.

700 FT. / SEC.

850 FT. / SEC.

Ta-107 IMPACT SPECIMENS

2/17/70

Alconics International
North American Rockwell

7700-4035

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V. THE EFFECT OF IRRADIATION ON STAINLESS STEEL

The energy absorption capability of a material under a dynamic load is a function of the yield stress, the ultimate strength, ductility of the material and the strain rate. The reactor vessel material as indicated in Reference 13 will probably be an austenitic stainless steel such as SS 304. The effects of the thermal reactor irradiation on the mechanical properties of SS was studied in Reference 14. The change of the yielding stress of 304 stainless steel due to irradiation at 450° are shown in Figure 18 for various testing temperatures and three levels of neutron fluence ($E > 1.0$ MeV). Yielding stress at room temperature is raised to approximately 155 K/in^2 after irradiation to $6 \times 10^{21} \text{ n/cm}^2$, which is nearly a five fold increase in yielding stress from the unirradiated condition.

The effects of thermal reactor irradiation on the ductility of stainless steel irradiated at 450°F are shown in Figure 19 for the same testing temperature and neutron fluence represented in Figure 18. Uniform elongation which is related to strain hardenability, is used here as the measure of ductility, and is nearly 80% at room temperature.

As indicated in Reference 12, the maximum neutron fluence ($E > 1.0$ MeV) on the reactor vessel material for 40,000 hours operation is $5.0 \times 10^{19} \text{ n/cm}^2$ which will result in a small increase of yielding stress and a small reduction in ductility. It seems reasonable to assume that the energy absorption capacity of the vessel material due to this low level of neutron fluence will remain unchanged. However, the ductility of a material subjected to a neutron fluence of $6 \times 10^{21} \text{ n/cm}^2$ will be reduced nearly to zero and the strain (elastic plus plastic) energy will be very small.

PREPARED BY:	ATOMICS INTERNATIONAL A DIVISION OF NORTH AMERICAN AVIATION, INC. FIGURE 18	PAGE NO. 36 OF
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THE EFFECT OF TEST TEMPERATURE AND FLUENCE
LEVEL ON THE 0.2% YIELD STRENGTH OF ANNEALED
AISI TYPE 304 STAINLESS STEEL
(IRRADIATIONS WERE PERFORMED AT 290 °C)

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The Effect of Test Temperature on the Uniform Elongation of Annealed
 AISI 304 Stainless Steel
 (Irradiated at 290 °C)

VI. MODELING LAWS

The capsules and the reactor fuels are still radioactive after their time in orbit. In order to prevent this radioactive material from being dispersed over a wide area upon earth impact the capsules and the reactor vessel must remain structurally intact. Since analytical methods are still quite limited for the designing of the reactor vessel and the cylindrical shell gamma shield to withstand impulsive kinetic energy, experimental studies continue to be an important source of data for use in the design. Previous work in Reference 17 has demonstrated that experiments with small-scale models can be used to predict the post impact damage of full size casks and the modeling laws in Reference 11 indicate that data obtained from cylindrical scale models have proven useful in predicting the terminal trajectories of some missile types. However, modeling laws in the reactor application must demonstrate that the post impact damage to a model based on the energy absorption capacity of the model materials can be assumed to represent the damage to the full size reactor impacted at the same impact velocity. Therefore studies of modeling laws for this application are discussed as follows:

1. There must be complete geometrical similarity between the scale model and the full size capsule.
2. Impact velocity must be the same

$$V_m = V_f \quad \text{..... (1)}$$

where the subscript m refers to the scale model and the subscript f refers to the full size capsule.

$$3. \text{ Let } S = \text{scale} = \frac{T_m}{T_f} = \frac{L_m}{L_f} = \frac{D_m}{D_f} \quad \text{..... (2)}$$

where T = the thickness of the vessel wall

D = the diameter

L = the length

W = the weight

$$W_m = \left(\frac{D_m}{D_f} \right)^3 W_f = S^3 W_f \quad \text{..... (3)}$$

4. Kinetic energy of the model and full size capsule

$$(K.E.)_m = \frac{1}{2} \frac{W_m}{g} V_m^2; (K.E.)_f = \frac{1}{2} \frac{W_f}{g} V_f^2$$

$$\text{Therefore, } (K.E.)_m = S^3 (K.E.)_f \dots\dots\dots (4)$$

5. Kinetic energy/unit weight

$$\left(\frac{K.E.}{W} \right)_m = \frac{1}{2} \rho V_m^2$$

$$\left(\frac{K.E.}{W} \right)_f = \frac{1}{2} \rho V_f^2$$

$$\left(\frac{K.E.}{W} \right)_m = \left(\frac{K.E.}{W} \right)_f = \frac{1}{2} \rho V^2 \dots\dots\dots (5)$$

6. Energy absorbed by the weight of the deformed portion of the structural materials assuming that all the K.E. is absorbed by the deformed portion. The subscript d refers to the deformed material and A = deformed area

$$\left(\frac{K.E.}{\rho A_D L_D} \right)_m = \left(\frac{S^3 K.E.}{\rho A_D S^2 \cdot L_D \cdot S} \right)_f = \left(\frac{K.E.}{\rho A_D L_D} \right)_f \dots\dots\dots (6)$$

Formula 5 indicates that the energy absorption capacity of the materials is the same for both the model and the full-size capsule, providing that the impact velocities are the same.

Formula 6 indicates that the K. E. absorbed by the deformed and damaged portion of the capsule is the same for both the model and the full-size capsule and the K factor obtained from model test data can be used to predict the damage and deformation pattern of a full-sized capsule.

Figure 22 is a suggested scale model of the reactor system that could be tested in the AI gas gun. The reactor impact configuration is shown in Figure 20. The ablation depths of the LiH shield during reentry was predicted in Reference 7 and the remaining weight of the reactor was calculated to be 5,875 lbs at impact. The LiH shield along the side of the gamma

shield will be broken into pieces at the instant of impact and is assumed to have no effect on the damage of the impact end. Figure 20 was reduced to Figure 21. Since the diameter of the gas gun is limited to 2.00", the scale 11.5 to 1 was used.

Ta-10W 246 lbs
 LiH 76

TOTAL ~~322~~

Ta-10W 636 lbs
 LiH 290 lbs
 STEEL 180 lbs
 REACTOR 1,650 lbs
 TOTAL 2,786 lbs

LiH 1140 lbs
 STEEL 627 lbs
 CAR. MOLY STEEL 87.6 lbs
 LEAD 1,015.6 lbs
 TOTAL 2,770.6 lbs

TOTAL REMAINING WEIGHT = 5,875 lbs.

FIG. 20

REPAIR IT.	ATOMIC INTERNATIONAL A DIVISION OF NORTH AMERICAN AVIATION, INC.	2400 NO. 41
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PART		MOORE NO.

SCALE: $\frac{1}{8} = 1.00"$

WEIGHT
TO-TON 246
L.H. 76
TOTAL 322 lbs

SECTION I

WEIGHT
TO-TON 626
REACTOR 1,680
STEEL 63
TOTAL = 2,379

SECTION II

L.H. 336
LEAD 1,015.6
CR-MY STEEL 87.6
TOTAL 1,437.2

SECTION III

FIG. 21

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$$S = SCALE = \frac{1}{11.5}, \quad S^2 = \frac{1}{132.5}, \quad S^3 = \frac{1}{1520}$$

$$(t_{STEEL})_m = \frac{1.83}{11.5} = .016"$$

STAINLESS STEEL $t = .016$

$t_{Ti-10W} = .053$

$$W'_m = \frac{522}{1520} = 21116$$

$$W_{Ti} = \frac{2.379}{1520} = 1.57165$$

$$(W_{LEAD})_m = \frac{1.015.6}{1520} = 1.88165$$

$$(t_{Ti-10W})_m = \frac{.50}{11.5} = .044"$$

$$W_m = \frac{2.770.6}{1520} = 1.82165$$

$$(t_{STEEL})_m = \frac{.10}{11.5} = .0084"$$

$$(t_{STEEL})_m = \frac{1.83}{11.5} = .016$$

$$(t_{Ti-10W} + t_{STEEL})_m = .053"$$

FIG. 22