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REACTIVITY EFFECTS OF THE
PROPOSED SNPO-C COUNTERMEASURE
EXPLOSIVE PROJECTILE DESTRUCT SYSTEM
(TITLE UNCLASSIFIED)

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TABLE OF CONTENTS

<u>Section</u>		<u>Page</u>
1	INTRODUCTION	1-1
2	DESCRIPTION AND COMPOSITION OF SYSTEM	2-1
3	ANALYTICAL MODEL	3-1
4	ANALYTICAL RESULTS	4-1
5	LITERATURE REFERENCES	5-1
<u>Appendix</u>		
A	SUMMARY OF CALCULATED MATERIALS REACTIVITY	A-1
B	EFFECTS OF RADIATION ON THE DESTRUCT SYSTEM	B-1

LIST OF ILLUSTRATIONS

<u>Figure</u>		
2-1	Geometry of Compaction Cases Considered for the 105 mm Projectile	2-4
2-2	One-Dimensional DTK Geometry	2-5
3-1	(r, θ) CURE Geometry for Projectile Reactivity Worth Analysis	3-4
4-1	Reactivity Worth of One Centrally Located Explosive Projectile with Medium Material Compaction from 9-Group Radial DTK Calculations	4-4
4-2	Radial Fission Distribution from (r, θ) CURE Calculations (Traverse Through Projectiles)	4-7

LIST OF ILLUSTRATIONS (Continued)

<u>Figure</u>		<u>Page</u>
4-3	Radial Fission Distribution from (r, θ) CURE Calculations (Traverse Between Projectiles)	4-8
4-4	Radial Fission Distribution from DTK Calculations	4-9
B-1	Schematic of Destruct System - 105 mm Projectile	B-2

LIST OF TABLES

2-1	Projectile Composition, Dimensions, and Weights	2-1
2-2	Composition of Titanium 662 Alloy	2-2
3-1	Energy Breakpoints of the 9-Group Structure	3-2
3-2	Absorption Cross Sections for B_{10} Ring	3-2
4-1	CURE Results for Explicitly Represented Projectiles	4-2
4-2	DTK Results for One Centrally Located Projectile	4-3
4-3	DTK Results for Titanium Worth (all cases with medium compaction)	4-5
4-4	Titanium Casing Absorption Rate (105 mm Projectile)	4-5

SUMMARY AND CONCLUSIONS

An evaluation is presented of the reactivity changes in the NRX-A reactor caused by the insertion of four titanium cased explosive projectiles. The projectiles are for use as an in-flight destruct system. The basic tool utilized in the calculations of reactivity changes was the (r, θ) CURE diffusion theory code. In addition, the effect of radiation heating on the projectile system before insertion into the core was estimated.

It was found that all the projectiles considered (90, 105 and 120 mm) are feasible, since they introduce less reactivity than the maximum shutdown available (4.35\$). The 120 mm projectile is outstanding, however, because it introduces much less reactivity than the other projectiles. This is due mainly to the thicker (0.375 inch) titanium casing. The worth of four 120 mm projectiles was calculated to be about +1.03\$ using the actual material number densities. If, as a conservatism, the carbon and hydrogen concentration in the explosive is corrected by the experimental-to-calculated reactivity coefficient ratio (approximately 11/7), the resulting worth of the projectiles is increased to about 1.50\$. In comparison, the corrected worth of four 105 mm shells having 0.25 inch casings is approximately 4.05\$, which is only 30% lower than the shutdown margin.

It is therefore recommended that either the as-designed 120 mm projectile be used, or a smaller projectile with a heavier casing (greater than 0.25 inch). As an alternate, if practicable from a radiation heating standpoint, thermal absorber material could be placed in the projectile to reduce the reactivity insertion.

The radiation heating rates in the destruct system were estimated for full power (1120 MW thermal) operation. The results and calculational procedure are given in Appendix B. This analysis was performed for first look values.

SECTION 1 INTRODUCTION

This report presents the results of an evaluation of the reactivity effects of a proposed countermeasure explosive projectile destruct system. The system is designed to provide a means of in-flight destruction of a NERVA reactor in the event of a malfunction. The proposed destruct system consists basically of four externally mounted projectiles which can penetrate the core at the dome end at a slight angle and be detonated in the order of milliseconds.

The purpose of this study is to evaluate the magnitude of the reactivity introduced by the insertion of the projectiles. It must be demonstrated that in such a situation the reactor will not start a positive period that would cause activation of the fuel elements prior to their destruction, thus creating radioactive fallout. During launch, the reactor control drums will be full in, yielding a shutdown of approximately 4.35\$. The projectiles must not introduce reactivity exceeding this amount.

SECTION 2
DESCRIPTION AND COMPOSITION OF SYSTEM

2.1 SYSTEM DESCRIPTION

Four 55-inch long projectiles (described in table 2-1) will be fired into the dome end of the reactor through the pressure vessel and will penetrate the core length-wise at a distance from the core centerline of approximately 21.9 cm. The projectiles will be evenly spaced in the azimuthal direction, one in each quadrant of the reactor. Each projectile will enter at a slight angle, the ends approximately coinciding with the top and bottom of the 52-inch long fuel elements. Table 2-2 shows the composition of the titanium 662 alloy used for the projectile casing.

TABLE 2-1
PROJECTILE COMPOSITION, DIMENSIONS, AND WEIGHTS

Material:

Projectile Casing - Type 662 Titanium

Explosive Material - TACOT $C_{12}H_4N_8O_8$ (A = 388.212)

Dimensions:

<u>Projectile Case OD, mm</u>	<u>Case Thickness, inch</u>	<u>Length inches</u>	<u>Titanium Weight, kg</u>	<u>TACOT Weight, kg</u>
90	0.25	55	10.5	10.6
105	0.25	55	12.3	15.1
120	0.375	55	20.8	18.0

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TABLE 2-2
COMPOSITION OF TITANIUM 662 ALLOY *

<u>Material</u>	<u>Weight, %</u>
Aluminum	5.0 - 6.0
Vanadium	5.0 - 6.0
Tin	1.5 - 2.5
Iron	0.5 - 0.9
Copper	0.5 - 0.9
Oxygen	0.2 maximum
Nitrogen	0.05 maximum
Carbon	0.08 maximum
Hydrogen	0.015 maximum
Titanium	Remainder

* Alloy to be used in the projectile casing.

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2.2 GEOMETRICAL MODEL USED IN (r, θ) CALCULATIONS

The NRX-A2 PAX Critical Assembly was used as the basic configuration for all calculations. As a conservatism, a worst case geometry is assumed in which all the core material remains in the reactor and on impact is compacted into the region adjacent to the projectile. The compaction effect is taken into account by considering three cases referred to as small, medium, and large compaction.

In the large compaction case, the displaced core material is assumed to be spread uniformly over the entire fueled volume of the core. In the medium compaction case, the compacted region is assumed to be a cylinder concentric with the projectile, with an outer boundary tangent to the boundary of the first core loading zone. The compacted region in the small compaction case is assumed to be a concentric cylinder with one-half of the volume of the medium compaction case. Figure 2-1 shows schematically the assumed midplane geometry of the three cases used in the (r, θ) CURE¹ calculation for the 105 mm projectile.

Also indicated in figure 2-1 is the increase of core material density resulting from the insertion of the 105 mm projectile. When considering the other projectiles, the volume of the compacted region is adjusted to preserve mass rather than recalculate cross sections for a new compacted density.

2.3 GEOMETRICAL MODEL USED IN RADIAL CALCULATIONS

A considerable part of the analysis was performed using radial Sn theory DTK² calculations in an attempt to separate effects and to provide a check on the CURE results. These runs were made by placing a single projectile in the center of the core and by representing the compact region as an annular zone adjacent to the projectile. The DTK calculations were also necessary to reduce the transfer matrices to the required CURE input format by the COLLAPSE³ code (see Section 4). Figure 2-2 shows each radial geometry representation out to the edge of Zone 1 (37.433 cm). The reactor mockup is identical for all problems beyond this point. A radial AIM⁴ diffusion theory calculation was also run with the geometry of Case 4 (a 105 mm projectile with medium compaction) to obtain a direct comparison between diffusion and transport theory.

Figure 2-1. Geometry of Compaction Cases Considered for the 105 mm Projectile

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1) Base Case

2) 90 mm Projectile, Medium Compaction

3) 105 mm Projectile, Small Compaction

4) 105 mm Projectile, Medium Compaction

5) 120 mm Projectile, Small Compaction

6) 120 mm Projectile, Medium Compaction

Figure 2-2. One Dimensional DTK Geometry

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SECTION 3

ANALYTICAL MODEL

All of the nuclear calculations were performed within the framework of the newly developed Improved Nuclear Standard Design Method, NSDM-II.⁵

3.1 CROSS SECTIONS

One iteration GAM⁶(epithermal) and TNS⁷(thermal) calculations were performed weighting stored microgroup libraries over proper region-dependent input spectra obtained from 40-group DTK calculations for the PAX assembly to obtain four-group epithermal and five-group thermal cross sections. The group structure is shown in table 3-1. The central core region spectrum was used as the weighting function to obtain cross sections for the normal Zone 1 region, the compacted Zone 1 region, and the projectile materials. Cross sections for the other normal and compacted regions were weighted using their proper spatial dependent spectra. Although the spectrum in the vicinity of the projectile differs from the normal inner region spectrum, using the latter as the weighting function for projectile cross sections should be adequate. It is shown in Reference 5 that with the NSDM-II nine-group structure, cross sections are relatively insensitive to spectral variations.

The GAM-TNS procedure produces cross sections containing the full transfer coefficient matrix, transfer being allowed between all groups. However, the CURE diffusion theory code used in (r, θ) calculations allows removal only to the next lowest group. It was therefore necessary to collapse the multigroup TNS transfer matrix to a self-scattering and single down-scattering form. This was achieved by performing a neutron balance calculation using nine-group DTK fluxes and multigroup cross sections using an IBM 7094 FORTRAN program, COLLAPSE.

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TABLE 3-1
ENERGY BREAKPOINTS OF THE 9-GROUP STRUCTURE

<u>Group</u>	<u>Energy</u>
1	0.821 - 10.0 mev
2	5.53 - 821 kev
3	78.9 - 5530 ev
4	1.86 - 78.9 ev
5	0.30 - 1.86 ev
6	0.12 - 0.30 ev
7	0.06 - 0.12 ev
8	0.02 - 0.06 ev
9	0 - 0.02 ev

TABLE 3-2
ABSORPTION CROSS SECTIONS FOR B₁₀ RING

<u>Group</u>	<u>Σ_a</u>
1	0.0023
2	0.0291
3	0.0892
4	0.304
5	0.407
6	0.468
7	0.527
8	0.593
9	0.740

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Only the ratio of the DTK fluxes between groups is used in collapsing the CURE transfer matrix and not the absolute magnitude of the flux, which varies with radial position. For this reason, it is felt that the DTK's which were run (see Section 3) are adequate for the compacted and projectile regions even though they are located in the center of the DTK calculation and at about 21.9 cm radius in the CURE. However, due to the rapid variation in the thermal spectrum in the vicinity of the titanium casing (and thus, a rapid variation in the one effective down-scattering term) the compacted zone and the region containing the explosive material were subdivided in the DTK and CURE analysis. The collapsed cross sections for the CURE projectile and compaction regions were obtained using the DTK fluxes in these regions.

It should also be noted that since NSDM-II cross sections underestimate the worth of moderator materials, additional analysis was necessary to take this into account. In many cases, additional runs were made with the hydrogen and carbon density increased by the experimental-to-calculated hydrogen worth ratio. The 11/7 ratio used for this purpose was calculated from homogeneous worths measured over the entire reactor,⁵ and is assumed to hold for the heterogeneous arrangement in this case.

3.2 REACTIVITY CALCULATIONS

The primary analytical tool used in this study was CURE, a two-dimensional (r, θ) diffusion theory code. CURE calculations were set up to represent a 45-degree sector of the reactor using a reflective azimuthal boundary condition, with an explicit representation of the projectile. Figure 3-1 illustrates the CURE mockup used for the 105 mm medium compaction case.

To conserve machine time, since the calculations are concerned only with reactivity differences, the control vanes were represented as single strips in which volume and the location of the center of the mass were preserved.

Radial DTK transport theory calculations were used to supply fluxes for collapsing the multigroup transfer matrix to obtain CURE input, as well as for supplementing CURE reactivity calculations. The geometry of these cases was described in Section 2. In DTK control vanes are represented by an annular B_{10} ring located at a radius of 55.659 cm in the reflector.

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Figure 3-1. (r, θ) CURE Geometry for Projectile Reactivity Worth Analysis

The absorption cross sections for the B_{10} ring are given in table 3-2.

All reactivity calculations are made by comparing the value of $\bar{k}_{eff}$ calculated in a perturbed calculation, relative to the base case k_{eff} for the NRX-A2 PAX. The reactivity change in $\$$ is:

$$\rho(\$) \equiv \frac{k_o (\bar{k}_{eff} - k_{eff})}{\beta_{eff} \bar{k}_{eff} k_{eff}}$$

where $\beta_{eff} = 0.0078$

k_o = calculated eigenvalue for critical PAX drum at 90 degrees
(defined as unity)

SECTION 4 ANALYTICAL RESULTS

4.1 CURE RESULTS

Five CURE problems were run in addition to the base case with the drums at the full in (zero degrees) position. The results, presented in table 4-1, indicate that the small and medium compactations yield about the same worth, while the large compaction is significantly less. Also, as expected, the increased amount of hydrogen and carbon increases the worth of the projectiles. Perhaps more significant is the decreased worth of the 120 mm projectiles. All reactivity values were multiplied by the ratio 55/52 to account for the fact that the projectiles are actually inserted at a slight angle. To better understand and further analyze these results, several one-dimensional DTK's were run.

TABLE 4-1
CURE RESULTS FOR EXPLICITLY REPRESENTED PROJECTILES

<u>Case</u>	<u>Projectile Size (mm)</u>	<u>TACOT Hydrogen and Carbon Density</u>	<u>Size of Compacted Region</u>	<u>k_{eff}</u>	<u>Reactivity Worth in \$ for 4 Missiles</u>	<u>Worth per Missile</u>
Base	----	----	----	0.97296	----	----
1	105	Normal	Medium	0.99029	\$2.44	61¢
2	105	Normal X 11/7	Medium	1.00201	4.04	101
3	105	Normal	Large	0.98477	1.67	42
4	105	Normal	Small	0.98994	2.39	60
5	120	Normal	Small	0.98013	1.03	26

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4.2 DTK RESULTS

Table 4-2 lists the results of several DTK problems containing one centrally located projectile. Again the worths have been multiplied by the ratio 55/52 to account for the slight angle at which the projectile is inserted. Cases 5 and 6 verify the conclusion from CURE that there is essentially no change in reactivity between the small and medium compaction. Case 7 indicates that if the core material is removed from the core rather than compacted, a large negative reactivity (-98%) is introduced to the system. Cases 1, 8 and 11 show the effect of increasing the size of the projectile if the titanium casing thickness is kept at 0.25 inch. However in Case 10, the designated casing thickness for the 120 mm shell is 0.375 inch which results in a significantly lower worth. This is in general agreement with CURE which calculated a low worth for the 120 mm shell. Also Case 6 was rerun using AIM to find the comparison between transport and diffusion theory results. The AIM worth was $+34.2\%$ as compared to $+29.9\%$ calculated by DTK indicating a generally higher worth is calculated by diffusion theory.

Figure 4-1 illustrates the results of the calculations in table 4-2. The normal and 11/7 H and C density curves set reasonable bands on the worths of central projectiles. The effect of increased thickness of casing is pronounced; switching from a 0.25 inch case to a 0.375 inch case changes the projectiles from a reactivity source to a reactivity sink. Because of the important reactivity effect of the titanium casing, additional analysis was performed to determine its worth. Table 4-3 is a tabulation of the results obtained by removing the titanium casing from three DTK problems. In the first two problems, Cases 12 and 13, the shell was replaced with core material and the result had to be corrected. Due to the increase in thermalization, increasing the H and C concentration increases the absolute worth of titanium from 1.27\$ to 1.57\$. Table 4-4 shows the absorption rate normalized to 1 neutron in the reactor for these two cases. The increased internal moderation makes the projectile a more efficient "flux-trap". The worth of titanium for the 120 mm projectile ($14.2\%/kg$) is slightly higher than that of the 105 mm projectile ($12.8\%/kg$). This can be explained by the fact that there is more hydrogen in the 120 mm projectile and also by the fact that there was no transverse leakage into the void created when the 120 mm casing was removed.

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TABLE 4-2

DTK RESULTS FOR ONE CENTRALLY LOCATED PROJECTILE

<u>Case</u>	<u>Projectile Size (mm)</u>	<u>TACOT H and C Density</u>	<u>Ti Thickness</u>	<u>Size of Compaction Region</u>	<u>K_{eff}</u>	<u>Worth μ</u>
Base	--	--	--	--	1.01675	--
1	90	Normal X 11/7	0.25"	Medium	1.02061	51.0
2	90	Normal	0.25"	Medium	1.01804	16.9
3	90	Normal X 11/7	0.375"	Medium	1.01589	-11.6
4	90	Normal	0.375"	Medium	1.01417	-33.8
5	105	Normal	0.25"	Small	1.01890	28.1
6	105	Normal	0.25"	Medium	1.01904	29.9
7	105	Normal	0.25"	Core Material Removed	1.00901	-98.0
8	105	Normal X 11/7	0.25"	Medium	1.02129	59.3
9	120	Normal	0.375"	Small	1.01404	-35.6
10	120	Normal X 11/7	0.375"	Medium	1.01494	-23.8
11	120	Normal X 11/7	0.25"	Medium	1.02164	63.9

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Figure 4-1. Reactivity Worth of One Centrally Located Explosive Projectile
with Medium Material Compaction from 9-Group Radial DTK Calculations

TABLE 4-3

DTK RESULTS FOR TITANIUM WORTH

(All Cases with Medium Compaction)

<u>Case</u>	<u>Projectile Size (mm)</u>	<u>TACOT H and C Density</u>	<u>K_{eff}</u>	<u>Titanium Worth</u>	
				<u>Total \$</u>	<u>¢/Kg</u>
12	105	Normal	1.03248	-\$ 1.27*	- 10.3
13	105	Normal X 11/7	1.03838	-1.57*	- 12.8
14	120	Normal X 11/7	1.03892	-2.95**	- 14.2

* Results had to be corrected for the core material used to replace the Titanium.

** Titanium was replaced by void region.

TABLE 4-4

TITANIUM CASING ABSORPTION RATE

(105 mm Projectile)

	<u>Normal Hydrogen and Carbon</u>	<u>Normal Hydrogen and Carbon X 11/7</u>
Fast Neutrons	0.00486	0.00483
Thermal Neutrons	<u>0.00131</u>	<u>0.00234</u>
TOTAL	0.00617	0.00717

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The consistency of these results gives confidence in the treatment of titanium and verifies its large effect on system reactivity. If the thickness of the titanium in the 120 mm projectile is reduced to 0.25 inch, the reactivity of the system is increased by about 90¢ based on the worth of 14.2¢/kg in table 4-3, which agrees with the difference between Cases 10 and 11.

Additional DTK calculations were run to separate the reactivity effects of the other projectile materials, so that each could be separately adjusted to the experimental reactivity coefficients. Such a correction was not possible, however, since the reactivity effects of the various constituents were non-additive (non-separable). A summary of the calculated results is given in Appendix A.

Although the DTK results give good qualitative explanations for the trends shown in the CURE results, the absolute values of the reactivity effect of the projectiles calculated in DTK are too low. This can be attributed to the fact that the projectile is placed in the center of the DTK and thus excludes all fissions in the region where the worth of a fission neutron is the greatest, and because diffusion theory gives higher worths as mentioned previously.

Figures 4-2 and 4-3, drawn from explicit (r, θ) CURE results, illustrate the perturbation on the power distribution due to the insertion of the projectiles. Figure 4-2 is a traverse through the projectiles and figure 4-3 is a traverse between the projectiles. The power peaking in the vicinity of the projectile is quite evident. The peak power increases as the volume of the compacted region becomes smaller. Therefore, if an excursion should occur before reactor destruction, some material would be much more radioactive than the rest.

Figure 4-4 shows the effect on the fission distribution caused by a projectile at the center of the core, as calculated by DTK.

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Figure 4-2. Radial Fission Distribution from (r, θ) CURE Calculations
(Traverse Through Projectiles)

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Figure 4-3. Radial Fission Distribution from (r, θ) CURE Calculations
(Traverse Between Projectiles)

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Figure 4-4. Radial Fission Distribution from DTK Calculations

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SECTION 5
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APPENDIX A

SUMMARY OF CALCULATED MATERIALS REACTIVITY

In order to separate the reactivity effect due to the projectile, the materials in the projectile were individually treated to find the effect of each. The calculations were performed using (1) the normal amount of hydrogen and carbon, and (2) 11/7 times the normal amount. The DTK with a 105 mm projectile and medium compaction was used as the base case. The following table itemizes these results:

REACTIVITY WORTH (¢) OF PROJECTILE MATERIALS

<u>Material</u>	<u>With Normal Hydrogen and Carbon</u>	<u>With 11/7 X Normal Hydrogen and Carbon</u>
Oxygen	+5	+6
Carbon	+14	+18
Hydrogen	+74	+97
Nitrogen	-32	-73
Titanium	<u>-133</u>	<u>-166</u>
Net Worth	-72	-118

These values do not compare with the net worths calculated by DTK, which were +29¢ for the normal case and +58¢ for the increased carbon and hydrogen case. The results, therefore, clearly show the non-separability of the effects of the various elements which compose the projectile.

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APPENDIX B

EFFECTS OF RADIATION ON THE DESTRUCT SYSTEM

RESULTS OF CALCULATIONS

An investigation of the effects of radiation on the destruct system was conducted. The radiation environment was assumed to be that which would be present when the NRX-A reactor was operating under full power. Figure B-1 is an approximate schematic of the projectile(s) showing its relationship to the center of the core.

Using the latest radiation environment data⁸ on NRX-A reactors operating at 1120 MW (thermal), the direct energy deposition by core gammas in titanium at this location was determined to be 4.82×10^{-2} watts/gm titanium. An estimate was made for this heating due to capture α 's in the Ti considering both core fluxes and neutrons slowing down in the explosive mixture within the casing. This source was found to produce another 4.10×10^{-2} watts/gm Ti. The total, then, is 8.92×10^{-2} watts/gm titanium. Details of this calculation are given later in this Appendix.

The radiation heating in the explosive was investigated and was found to be 4.45×10^{-2} watts/gm due to the gammas in the core, and an additional 7.85×10^{-2} watts/gm due to secondary sources, for a total heat deposition of 12.30×10^{-2} watts/gm.

These values are conservative, since the heating rate due to the core gammas was calculated at the nose of the projectile, and no attenuation was assumed with position through the projectile.

Using the relationship

$$Q = mc (\Delta T)$$

the rate of increase of the projectile temperature was calculated to be 1095°F/hr for titanium and 1153°F/hr for the explosive material during full power operation. The calculation assumed no heat losses due to conduction through the support system or by radiation. Using these results, the temperature of the titanium would increase to about 433°F after a 20 minute run, well below its melting point of 3300°F . Temperature effects on the explosive material, however, may make it necessary to provide cooling or shielding for the system.

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Figure B-1. Schematic of Destruct System - 105 mm Projectile

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Taking into account the heat lost due to radiation, the equilibrium temperature of the system was calculated to be 962°F for infinite operation. An emissivity, ϵ , of 0.5 was used for the projectile surface. If the missile is considered to be a black-body ($\epsilon = 1.0$), the equilibrium temperature is reduced to 736°F.

If the reported radiation heating indicates that the reliability of the proposed destruct system is marginal, it is recommended that a more sophisticated analysis be performed by the Radiation and Shielding Section (NE 8030). Also, a mockup projectile could be mounted outside the reactor during a forthcoming power test to determine the radiation heating effect.

CALCULATION OF ENERGY DEPOSITION IN PROJECTILE

This calculation was performed for a 105 mm projectile in accordance with the following procedure:

- 1) The fast neutron flux (> 0.85 mev) was obtained from calculated radiation environment⁸ at the nose of the projectile ($d = 12.5$ feet $\alpha = 37$ degrees, in figure B-1. This flux was found to be 4.82×10^{11} n/cm²/sec at 1120 MW (thermal).
- 2) The fluxes for four energy groups were obtained by scaling the neutron flux value by group flux ratios obtained from a hot TDC calculation. The group structure used and the fluxes obtained were as follows:

Group, g	E	ϕ (TDC)	ϕ_g/ϕ_1	ϕ (Normalized to Group 1)
1	0.821 to 10.0 mev	4.18 (-7)	1.0	4.82×10^{11} n/cm ² /sec
2	5.53 kev to 0.821 mev	3.94 (-6)	9.43	45.4×10^{11} "
3	1.86 to 5530 ev	3.77 (-6)	9.02	43.6×10^{11} "
4	0 to 1.86 ev	9.79 (-7)	2.34	11.3×10^{11} "

- 3) The macroscopic scattering cross sections of the explosive were then determined:

Group	Σ_s (H)	Σ_s (non-H)	Total Σ_s
1	0.026*	0.413	0.439
2	0.107	0.413	0.520
3	0.200	0.413	0.613
4	0.200	0.413	0.613

*Weighted over neutron spectrum from environmental data.

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- 4) The total scattering rate in the explosive was then determined:

<u>Group</u>	<u>Scattering</u>
1	2.12×10^{11}
2	23.6×10^{11}
3	26.7×10^{11}
4	6.93×10^{11}
Total	59.3×10^{11}

- 5) The ratio of absorption in the titanium to scattering in the explosive was found from a radial DTK problem with the projectile in the core center and was applied to the above scattering rate.

$$\frac{\text{Absorption per sec in titanium}^*}{\text{Scattering per sec in explosive}} = 0.0053$$

This gives an absorption rate in the 0.25 inch titanium casing of:

$$59.3 \times 10^{11} \frac{\text{scat}}{\text{cc/sec}} \times \frac{9.341 \times 10^3 \text{ cc of explosive}}{2.75 \times 10^3 \text{ cc of titanium}} \times .0053 \frac{\text{capt}}{\text{scat}} = 1.07 \times 10^{11} \text{ cap/cc/sec}$$

- 6) The capture rates in the titanium due to core flux are as follows:

<u>Group</u>	<u>ϕ, n/cm²/sec</u>	<u>Σ_a</u>	<u>Cap/cc/sec</u>
1	4.82×10^{11}	0.00016	0
2	45.4×10^{11}	0.0011	0.05×10^{11}
3	43.6×10^{11}	0.0235	1.02×10^{11}
4	11.3×10^{11}	0.094	1.06×10^{11}
		Total	2.13×10^{11}

* From neutrons thermalized in explosive.

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- 7) The total capture rate in the titanium is then the sum of the rates obtained in steps (5) and (6) above or:

$$\text{Total Capture Rate} = (1.07 + 2.13) \times 10^{11} = 3.20 \times 10^{11} \text{ capt/cc/sec}$$

The same capture rate is also assumed for the 0.875 inch projectile container, which is an overestimate of the captures resulting from slowing down in the projectile.

- 8) The gamma yield of the titanium casing per 100 captures is as follows:

<u>Gamma Energy (mev)</u>	<u>$\bar{E}$</u>	<u>Number of Gammas</u>
0 - 1.0	0.5	50
1.0 - 3.0	2.0	100
3.0 - 5.0	4.0	33
5.0 - 7.0	6.0	99
> 7.0	8.0	<u>10</u>
Total		292

To minimize the gamma leakage out the projectile, an average gamma energy of 3 mev may be assigned and the assumption made that all gammas are born uniformly in the titanium. To obtain an approximate pessimistic estimate of the fraction of the gamma energy leaking, the following simplified slab model was used with equation 1-4.2 in Rockwell⁹.

$$\mu_{ti} \text{ at 3 mev} = 0.156 \text{ cm}^{-1} *$$

$$\mu_{ex} \text{ at 3 mev} = 0.054 \text{ cm}^{-1} **$$

With this model it was found that the gammas were distributed as follows:

36 percent of the gammas leaked out

19 percent of the gammas were absorbed in explosive

45 percent of the gammas were absorbed in titanium

* μ_{ti} is the mass absorption coefficient of titanium

** μ_{ex} is the mass absorption coefficient of the explosive

All gamma interactions were assumed to be an energy absorption process and a yield of 8.0 mev/cap is used, this being the binding energy for titanium.

9) The Heating Rates (HR) using the values derived in step 8 are calculated as follows:

a) For titanium

$$\begin{aligned} \text{HR} &= 3.20 \times 10^{11} \frac{\text{capt}}{\text{cc sec}} \times 8.0 \frac{\text{mev}}{\text{capt.}} \times 1.6 \times 10^{-13} \frac{\text{watt sec}}{\text{mev}} \times \frac{\text{cc}}{4.5 \text{ gmTi}} \quad (0.45) \\ &= 4.10 \times 10^{-2} \text{ watt/gm} \end{aligned}$$

b) For explosive

$$\begin{aligned} \text{HR} &= 3.20 \times 10^{11} \frac{\text{capt}}{\text{cc sec}} \times 8.0 \frac{\text{mev}}{\text{capt}} \times 1.6 \times 10^{-13} \frac{\text{watt sec}}{\text{mev}} \times \frac{(0.19)\text{cc}}{1.61 \text{ gm}} \times \frac{1.516 \cdot 10^4 \text{ cc of Ti}}{9.347 \cdot 10^3 \text{ cc of Ex}} \\ &= 7.85 \times 10^{-2} \text{ watt/gm} \end{aligned}$$

Heating due to elastic scattering and explosive capture gammas was negligible.

10) Using the radiation environment data, the heating rate in titanium Due to core gammas was calculated to be:

$$4.82 \times 10^{-2} \text{ watt/gm of titanium}$$

The heating rate in the explosive, assuming that the explosive has the same gamma absorption properties as carbon, was calculated to be:

$$4.45 \times 10^{-2} \text{ watt/gm of explosive}$$

11) To calculate the temperature increase during operation, assuming no losses due to radiation and conduction, the relationship $Q = mc \Delta T$ was used:

$$\therefore \Delta T = \frac{Q/m}{c}$$

a) For titanium

$$\begin{aligned} \Delta T &= (0.0410 + 0.0482) \frac{\text{watt}}{\text{gm}} \cdot \frac{\text{lb}^\circ\text{F}}{0.126 \text{ BTU}} \times \frac{453.6 \text{ gm}}{\text{lb}} \times \frac{3.412 \text{ BTU}}{\text{hr watt}} \\ &= 1095^\circ\text{F/hr}; \end{aligned}$$

for 20 minutes of operation:

$$T = 1/3 (1095) + 68 = 433^\circ\text{F}$$

b) For explosive:

$$\Delta T = (0.0445 + 0.0785) \frac{\text{watt}}{\text{gm}} \times \frac{1\text{b}^{\circ}\text{F}}{0.165 \text{ BTU}} \times \frac{3.412 \text{ BTU}}{\text{hr watt}} \times \frac{453.6 \text{ gm}}{1\text{b}}$$
$$= 1153^{\circ}\text{F/hr}$$

The specific heat for carbon which was used in this calculation is somewhat lower than the specific heat for most organic compounds.

- 12) To calculate the equilibrium temperature for infinite operation, taking into account losses due to radiation, the following equation was used.

$$\frac{q}{A} = 0.171 \epsilon \left(\frac{T}{100} \right)^4$$

where:

T is expressed in $^{\circ}\text{R}$

q is in BTU per hour

A is square feet of surface area

ϵ = emissivity

Using a heating rate of 0.0892 watt/gm for titanium and a heating rate of 0.1230 watt/gm for the explosive, the total rate of energy absorption was calculated to be 9478 watts in the 55-inch long projectile and in the container. Using an emissivity of 0.5, the equilibrium temperature is 962°F . Assuming the projectile to be a black-body with an emissivity of 1.0, the equilibrium temperature is 736°F .