(Working Document)

Accelerator Driven Assembly

LA-SUB-95-2 3

J. Balderas, M. Cappiello, C. E. Cummings, R. Davidson, L. A. Dominguez, J. S. Elson,
J. Garcia, A. Gavron, M. Hall, S. Howe, P. W. Keaton, R. Kidman, C. F. Lebeda,
P. W. Lisowski, W. P. Lysenko, J. Martin, R. Nelson, J. Park, D. B. Pelowitz,
R. T. Perry, E. Pitcher, D. A. Poling, G. Russell, E. Schwegler, T. Stratton,
J. Teel, D. Trujillo, E. A. Wadlinger, R. B. Walton, W. B. Wilson

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FOREWORD

This report addresses a Los Alamos National Laboratory (LANL) proposal to build a pulsed neutron source for simulating nuclear-weapons effects. A point design for the pulsed neutron facility was initiated early in FY94 after hosting a Defense Nuclear Agency (DNA) panel review and after subsequently visiting several potential clients and users. The technical and facility designs contained herein fulfill the Statement of Work (SOW) agreed upon by LANL and DNA. However, our point designs and parametric studies identify a unique, cost-effective, above-ground capability for neutron nuclear-weapons-effects studies at threat levels. This capability builds on existing capital installations and infrastructure at LANL. We believe that it is appropriate for us, together with the DNA, to return to the user community and ask for their comments and critiques. We also realize that the requirements of last year have changed significantly. Therefore, the present report is a "working document" that may be revised where feasible as we learn more about the most recent Department of Defense (DoD) and Department of Energy (DOE) needs. We will file a finished report by December 31, 1994.

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ACKNOWLEDGMENTS

Before work on ADA was undertaken, the DNA tasked a number of individuals (John Bombardt, Cyrus Knowles, Robert Poll, and Clay Rogers, all from JAYCOR; John Okuma from White Sands Missile Range; and Theodore Wrobel from the Sandia Laboratories) to review the Accelerator Driven Assembly preproposal concepts. Their recommendations and guidance have been valuable to us.

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ACI	American Concrete Institute
ADA	Accelerator Driven Assembly
AISC	American Institute of Steel Construction
ALARA	as low as reasonably achievable
ANL	Argonne National Laboratory
ANSI	American National Standards Institute
APT	accelerator production of tritium
ASME	American Society of Mechanical Engineers
ASTM	American Standard for Testing and Materials
ATW	accelerator transmutation of waste
BPM	beam-position monitor
CCR	Central Control Room
DBE	design-basis event
DOE	Department of Energy
DNA	Defense Nuclear Agency
EDNA	externally driven nuclear assembly
F(E)	silicon damage (response) function
FMIT	Fusion Materials Irradiation Test Facility
FOM	figure of merit
FS	factor of safety
IPNS	Intense Pulsed Neutron Source
LAHET	Los Alamos high-energy transport system
LAMPF	Los Alamos Meson Physics Facility
LANL	Los Alamos National Laboratory
LANSC	Los Alamos Neutron Scattering Center
MCNP	Monte Carlo N-particle (transport code)
NEC	National Electrical Code
NM	nuclear material
PINS	Pulsed Intense Neutron Source
PSR	Proton Storage Ring
PSS	personnel safety system
RIF	reaction in flight
RMS	root mean square
RSS	radiation safety system
SES	single event safe
SMR	special military requirements (assembly)
SNM	special nuclear material
SOP	standard operating procedure
SOW	statement of work
TRANSX	cross-section processing code
TWODANT	two-dimensional, diffusion-accelerated, neutron-particle transport code
UBC	Uniform Building Code

WNR

Weapons Neutron Research Facility

SYMBOL TABLE

$\$$	unit of reactivity known as the dollar
β_{eff}	effective fraction of delayed neutrons
k	neutron multiplication factor
k_{eff}	effective multiplication or criticality eigenvalue
k_{pr}	prompt neutron criticality eigenvalue
M	neutron multiplication constant
m	fission only neutron multiplication constant
M_{pr}	prompt-neutron multiplication constant
ρ	reactivity

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ACCELERATOR DRIVEN ASSEMBLY

EXECUTIVE SUMMARY

Los Alamos National Laboratory

Los Alamos, New Mexico

October 1994

Defense Nuclear Agency Goals and Needs

The Defense Nuclear Agency (DNA) promotes the development and validation of the nuclear-radiation hardness of Department of Defense (DoD) systems. Military systems and components must be tested at nuclear and nonnuclear facilities that simulate nuclear-weapons effects. The DNA recognizes that facilities currently exist to meet many of today's testing requirements, but DNA also anticipates facility requirements for the future as dictated by the changing world conditions. At present, nuclear facilities at Aberdeen Proving Grounds, Sandia National Laboratories, and White Sands Missile Range have adequately satisfied many of DoD's testing requirements.

It is especially difficult to project future nuclear-weapons-effects defense-system requirements at this time because of rapid changes in the world and military situation. For example, the Army has recently reduced specific military requirements (SMR) for nuclear-weapons effects by 30%, and it is encouraging the consolidation of expensive testing and evaluation efforts. The reasons for these and broader changes throughout the DoD are many, including the completion of new facilities resulting from previously successful DoD planning strategies; the identification of military deficiencies in the recent Persian Gulf conflict; the dissolution of the Soviet Union, which created a multipolar world and changed the nature of potential conflicts; and substantive reductions in the defense budget of the U.S.

The DNA is responding to these uncertainties by exploring the advantages and disadvantages of alternative technologies for developing and validating nuclear hardness. DNA is interested in exploring alternatives to the existing burst-reactor facilities that could be used should funding or environmental constraints make the reactor facilities unavailable in the future. This study is valuable in helping to identify the most cost-effective option for meeting the requirements. In 1993, the DNA funded an initiative

by Los Alamos National Laboratory (LANL) to investigate the feasibility of using advanced accelerator technology to produce a pulsed source of fission neutrons for simulating nuclear-weapons effects. This report presents our results.

The Accelerator Driven Assembly Option for Meeting Nuclear-Effects-Testing Needs

We have designed an Accelerator Driven Assembly (ADA) facility that will produce high fluences of neutrons over large volumes in short pulses. The ADA facility can simulate neutrons from nuclear weapons, nuclear reactors, and cosmic rays. ADA will be safe and flexible, and it will incorporate simple controls. Our study philosophy was to make point designs that may or may not be optimum and then to initiate parametric studies to examine sensitivities to certain changes or alternative approaches.

The basic point design for ADA features a 50-cm x 50-cm slab target of 17% ^{235}U -enriched uranium. A pulsed beam of 800-MeV protons from the Los Alamos Meson Physics Facility (LAMPF) will bombard the target and interact with the nuclei to produce about 22 spallation neutrons for every incident proton. These neutrons are slowed by nuclear processes, and most are captured by ^{235}U nuclei that fission to produce neutrons. The multiplication in the slab-target design is adjusted so that every captured spallation neutron produces about 50 fission neutrons. Thus, for every incident proton delivered by the LAMPF accelerator, the ADA slab target will produce between 100 and 1,000 fission neutrons, depending on the physical arrangement and test requirements. Consequently, ADA can provide a fluence of 10^{13} n/cm² over a 50-cm x 50-cm area with a uniformity greater than 50%. In this way, reasonably large military components or electronic systems can be tested for neutron hardness near the slab target with a burst of neutrons lasting less than 1 ms and providing a predetermined radiation dose. We studied additional options for ADA that include

- a 50-cm-diam x 60-cm-high cylinder-target-cavity size with 10^{13} n/cm² fluence,

- a Pulsed Intense Neutron Source (PINS)* target with 10^{12} n/cm², and
- short (300-ns) pulses in a small cylinder.

Our detailed cost estimates show that the point design can be provided for \$23 million in two years from the time funds and permission to begin are obtained. The cost does not include that of the enriched uranium for the target. We estimate that the slab target can be built for about \$2 million. Our estimates for the annual operational costs of ADA are about \$4 million. We anticipate that in addition to serving the DoD, ADA can share operational costs by providing services to the Department of Energy (DOE), the National Aeronautics and Space Administration (NASA), and private industry.

Benefits to Nuclear-Effects-Testing Program

The ADA concept provides DNA with an answer to the question of whether an accelerator facility can provide a feasible alternative to nuclear reactors for weapons-effects testing. ADA benefits include the following:

- ADA produces a short-time-burst intense-neutron fluence generated over large areas.
- ADA may be perceived by the public as a safe alternative to a nuclear reactor.
- ADA generates minimal radioactive waste.
- ADA is a cheaper alternative to building a new reactor when old ones wear out.
- ADA has low operating costs. Infrastructure for operations comes from the LAMPF/Los Alamos Neutron Scattering Center (LANSCE) facility.
- ADA target security requires only locked storage in the "stand-by status" of no testing.

* In an attempt to limit confusion between the WNR and IPNS facilities, we will henceforth refer to the reference enriched uranium target for WNR Target-4 as the Pulsed Intense Neutron Source (PINS).

Los Alamos Experience

- LAMPF has operated since 1972, and since 1976, the facility has delivered 1-mA, 800-MeV proton beams to nuclear-physics users.
- The LANSCE and Weapons Neutron Research (WNR) infrastructure exists and has been active in neutron-effects studies for civilian and defense use.
- Los Alamos has built and operated nuclear reactors since the end of World War II. The LANL Pajarito site, where the ADA target would be pretested and calibrated, is licensed to test reactors and critical assemblies.
- LANL is one of three nuclear-weapons laboratories located in the U.S. We understand what nuclear-weapons-radiation effects must be studied.
- We recently tested, at WNR, the susceptibility of the electronics for the new Boeing 777 airplane to neutron-induced upsets.

1. INTRODUCTION AND OVERVIEW

1.1. Historical Perspective

Note to readers of this working document: the following comments will be expanded considerably in the final report.

In 1993, the DNA funded LANL to examine the feasibility of using LAMPF for defense applications. LAMPF is an 800-MeV proton accelerator that produces a 1-mA beam in short repetitive bursts. One of the tasks in the Statement of Work (SOW) between LAMPF and DNA was to explore the feasibility of building an ADA. The present report discusses the results of those exploratory studies.

The authors are indebted to Lee *et al.* (1990) at the Sandia National Laboratories who proposed an Externally Driven Nuclear Assembly (EDNA). The direction taken in our proposal was influenced by their work. EDNA proposed to build a 50-MeV electron accelerator. The electron beam would produce Bremsstrahlung gamma-rays in a high-Z target, and the gamma-rays would produce a short and intense burst of neutrons in a fissile target. ADA proposes to use the existing LAMPF accelerator and the Proton Storage Ring (PSR) to bombard fissile material directly and thereby produce a short and intense burst of neutrons. The ADA facility can be added to an existing neutron research and applications center, LANSCE, which also uses 800-MeV protons from LAMPF. Thus, ADA can take advantage of both the facilities and infrastructure that have been built to conduct neutron measurements at Los Alamos over the last decade.

The JAYCOR Report (Poll 1993) made four specific recommendations, each of which has been addressed below as part of our work:

- investigate the utility of a collimated neutron beam (see Sec. 2.2.3),
- evaluate the capability of producing short-pulse 14-MeV neutrons with ADA targets (see Sec. 2.6),
- investigate converting LAMPF protons to a few MeV for producing x-rays (see Sec. 2.5), and
- investigate long-term environment, safety, and health (ES&H) alternatives between fast-burst reactors and LAMPF (see Secs. 3.9 and 3.10).

1.2. Requirements

Significant changes have taken place in the last year for the ranking of SMRs in nuclear-weapons effects. For example, the total number of SMRs have been reduced by 30%, and the consolidation of expensive research, development, testing, and evaluation efforts are being encouraged. The change in emphasis on SMRs is due to several recent occurrences: the resolution of some nuclear-weapons-effects technology issues such as the construction of the Large Blast/Thermal Simulator at White Sands Missile Range, New Mexico; the identification of military deficiencies in the recent Persian Gulf conflict; and the dissolution of the Soviet Union and the associated reductions in military budgets. However, the fundamental criterion for ranking SMRs is still to protect real-mission critical systems, including both the military equipment and their human operators.

The slab target featured in the ADA point design will produce a neutron fluence of up to 10^{13} n/cm² in each burst of neutrons lasting about 1 ms. That fluence will irradiate an area of 50 cm x 50 cm with a uniformity of better than 50%. Thus, the hardness of military components to short neutron bursts can be tested over large areas.

1.3. Guide to the Accelerator Driven Assembly Proposal

The proposed ADA facility will be an incremental addition to the total LANSCE experimental facility at LANL (see Fig. I-1). LANSCE is a part of LAMPF with its 800-MeV, 1-mA proton beam (i.e., the highest-power accelerated beam in the world). The LAMPF linear accelerator provides a proton beam for defense research, applied nuclear technology, and basic science. LANSCE includes the PSR, which accumulates several LAMPF beam pulses to produce high-intensity short-pulsed proton beams; the LANSCE experimental facility to conduct neutron-scattering experiments; and the WNR facility. LANSCE provides the infrastructure for operating an ADA facility.

The PSR delivers 3.1×10^{13} protons per pulse, which has a total duration of 270 ns. If we need more protons, we can use more PSR pulses, which come once every 50 ms (20-Hz rate). Of course, multiple pulses are not desirable if a short pulse width is important. The direct LAMPF beam delivers 1.3×10^{14} protons per pulse, but this pulse has a much longer

duration of 1 ms. The duration of this pulse can be reduced if fewer protons are sufficient. If more protons are required, we can use additional pulses, which come once every 8.3 ms (120-Hz rate).

Thus, for submicrosecond times, we can use single pulses from the PSR, which contains 3.1×10^{13} protons. For more protons, we can use one or more direct LAMPF beam pulses for a total duration of less than one-tenth of a second.

The LAMPF linear accelerator provides proton beam for defense research, applied nuclear technology, and basic science.

Los Alamos

Fig. I-1. Overview of the LAMPF accelerator complex.

The ADA facility requires two new subsystems: (1) the ADA target and experimental building and (2) the beam line that delivers beam to the ADA facility. The ADA facility requires additions to the existing personnel safety system (PSS), which ensures that no beam can be delivered to the ADA facility while people are present in the facility, and the radiation safety system (RSS), which protects beam-line equipment (including the ADA target) from mis-steered or mis-focused beam.

1.3.1. Enhanced Neutron Production Targets

We investigated three different targets. A slab target and a cylinder target were designed for the ADA facility. The slab target will produce a unidirectional source of neutrons, and the cylinder target will simulate an omnidirectional source of neutrons. We also examined an enhanced radiation target to replace the WNR Target-4 as an inexpensive alternative to ADA. This target will not produce short, intense neutron bursts; however, it can be used for long exposures (greater than 30 minutes) to achieve a required integrated neutron flux.

1.3.1.1. Slab Target

The basic neutron-production slab-target concept consists of a rectangular, solid region of fissile material, which is interposed between the proton beam and an arbitrary test article. When the slab target is struck by the 800-MeV proton beam, spallation neutrons are created in the uranium through proton interactions. These spallation neutrons then induce the fissioning of ^{235}U atoms, and the resultant neutron multiplication produces the desired fast-neutron flux (see Fig. I-2). The slab-target arrangement is proposed to simulate a unidirectional source of neutrons and to alleviate test-article-size restrictions imposed by a cavity irradiation environment. The specific design requirements for the slab target are discussed in Sec. 2.2.1.1. The reference design is presented in Sec. 2.2.1.2. Physics and mechanical analyses in support of the reference design (including parametric studies) are addressed in Secs. 2.2.1.3 and 2.2.1.4.

The slab-target concept was designed to satisfy four key requirements: total fluence, uniformity, irradiation area, and fidelity. We require that the target system supply 1×10^{13} neutrons/cm² over a 50-cm x 50-cm irradiation area. [Larger slab geometries (3 m x 3 m) were considered early in the ADA program; the intention was to irradiate tank-size components. Although tank irradiation is no longer a specific design requirement, the 3-m x 3-m slab is highlighted in the physics parametric-analysis section (Sec. 2.2.1.3.3). Consideration of the test-article-envelope definition for tank-size components is presented in Appendix A.] We likewise require that the fluence uniformity be better than $\pm 50\%$ over the irradiation area. In terms of fidelity, we desire the incident neutron flux to have an energy-dependence characteristic of a fission spectrum. We assume the system is operated in a

pulsed mode but without any specific requirement on the neutron pulse width.

Fig. I-2. ADA combines spallation and fusion.

To achieve the desired neutron fission spectrum, we require a fissile target material (U-1.5%Mo). Selection of the specific target material is addressed in Sec. 2.2.1.2.3.1. We similarly require a stopping length of target material such that no incident protons impinge on the test article (i.e., a 24-cm slab thickness). In terms of criticality safety, we require a subcritical assembly ($k_{pr} = 0.98$, see Sec. 2.2.1.3) during operation with multiple/diverse methods of control and/or shutdown. With respect to materials access security, we limit the enrichment of the uranium to be at or below 19.9% (see Sec. 2.2.1.2.4) and assume that the target will be stored in a locked concrete vault when not in use. Operationally, we desire the capability to irradiate two to three test articles per day with acceptable thermal management.

In its operational configuration, the slab target is designed to provide a prompt-neutron multiplication factor of 50. A graphite reflector is placed on five sides of the uranium slab to obtain this multiplication with a reduced amount of fissionable material.

To adjust the multiplication of the assembly, we propose to use the two graphite control drums, as shown in Fig. II-2, and to change the separation distance between the lower and upper halves of the active slab target. Increased separation results in decreased multiplication (see Fig. II-3).

A neutron-absorber blade is incorporated into the target design. During operation of the target, the blade is held above the assembly, perpendicular to the beam, as shown in Fig. II-4. A signal from the control system or loss of power causes the blade to be released and fall via gravitational forces into position between the fuel (uranium) and the beam-face reflector region, thus greatly reducing the assembly reactivity. This blade is a third, independent, diverse system that ensures operational safety and deep subcritical storage.

The test articles are expected to be the largest source of environmental effects. We investigated the effect on reactivity of several potential test-article materials as a function of distance from the target. This investigation was done to estimate the magnitude of anticipated reactivity adjustments. Three materials were studied: (1) a 75- x 75- x 30-cm block of water, (2) a 75- x 75- x 30-cm block of stainless steel, and (3) a 14.45-cm cube of 93% enriched bare uranium. (This cube was chosen to be 90% of the critical cubical volume for this enrichment.) The criticality eigenvalue was evaluated for each of the three materials at distances between the target and the article of 1 to 100 cm. Results of this evaluation are presented in Fig. II-12. At a distance of 50 cm, the effect on reactivity of all three evaluated materials is less than 0.5% k_{eff} . For safety reasons, an ensured half of a meter separation between the target and the test article will be maintained to limit the environmental effect on reactivity induced by the test article. The reactivity safety margin will be confirmed with each operation. To control reactivity, all systems will return to their least reactive positions with loss of power or a signal from the control system.

One of the attractive features of the U-Mo alloy is its high-yield strength at room temperature. As will be discussed in Sec. 2.2.1.4.1, the thermal environment for the slab target is fairly benign for our reference target conditions. This environment provides a large margin between yield and the peak dynamic stresses discussed in Sec. 2.2.1.4.2.

For simplicity, we adopt a thermal-management strategy that uses no active components. The slab is merely cooled via its open face by natural convection to air. Passive cooling is completely adequate at the specified cycle rate for experiments (two to three irradiations per day) and the modest thermal conditions for the U-Mo.

To estimate the basic transient thermal response of the slab target to a single pulse or a series of pulses, we formulated a simple heat-transfer model representing the reference five-sided reflector configuration. Section 2.2.1.4.1.1 presents the basic analysis methodology, Sec. 2.2.1.4.1.2 discusses the results for the reference target, and Sec. 2.2.1.4.1.3 presents a limited set of parametric analyses. The maximum temperature rise at six irradiations per day is 30 K, which is minimal.

We calculated the effects of dynamic stress on the target that were due to temperature cycling. Based on current estimates for the energy deposition per pulse (360 J/kg) and the approximate pulse duration (2.6 ms), we can compute the peak dynamic stress induced within the slab-target material from the method described in Sec. 2.2.1.4.2. At present conditions, the recommended design stress (i.e., maximum stress multiplied by a safety factor of 2.0) is 1.3 MPa. This design stress is based on a characteristic dimension of 24 cm, or the thickness of the target material. Detail of the key analysis parameters is provided in Table II-6. If we examine strength versus temperature data for U-10%Mo (see Fig. II-14), we conclude that peak target temperatures of 900 to 1,000 K can be accommodated at this design stress. Because our maximum temperature will be 350 K, the dynamic stress is not important at the reference design conditions.

1.3.1.2. Cylinder Target

The cylinder-target concept consists of an annular, blind-hole region of fissile material with a central irradiation cavity. This arrangement is proposed to simulate an omnidirectional source of neutrons for components of nuclear weapons and other potential test articles. The specific design requirements for the cylinder target are discussed in Sec. 2.2.2.1. The reference design is presented in Sec. 2.2.2.2. Physics and mechanical analyses in support of the reference design (including parametric studies) are addressed in Secs. 2.2.2.3 and 2.2.2.4, respectively.

Like the slab, the cylinder-target concept was designed to satisfy the same key requirements for total fluence and fidelity. Specifically, we require that the target system supply 1×10^{13} neutrons/cm² in the central irradiation cavity, 50 cm in diameter and 60 cm high. In terms of fidelity, we desire the incident neutron flux to have an energy-dependence characteristic of a fission spectrum. Also, note that we assume the system is operated in a pulsed mode but without any specific requirement on the neutron pulse width.

To achieve the desired neutron fission spectrum, we require a fissile target material (U-1.5%Mo). Selection of the U-Mo target material was based on the same arguments as for the slab-target concept and is discussed in Sec. 2.2.1.2.3.1. The height and internal diameter of the fissile material were chosen to correspond to the dimensions of the irradiation cavity. In terms of safety, we specify a subcritical assembly ($k_{pr} = 0.98$) with multiple methods of control and shutdown. With respect to materials access security, we limit the enrichment of the uranium to be at or below 19.9% (see Sec. 2.2.2.2.4) and assume the target to be stored in a locked concrete vault when not in use. Operationally, we desire the capability to irradiate two to three test articles per day with acceptable thermal management. Graphite positioned beyond the fuel regions provides neutron reflection and thus enhances the neutron economy of the system.

Neutron multiplication in the annular target is induced by an 800-MeV proton beam. Like the slab target, the conceptual cylinder target is designed to provide a prompt-neutron multiplication factor of 50. To adjust the multiplication of the assembly, two methods are employed. First, the reflector annulus encompassing the target is segmented into six equal 60° segments. Three of the segments are stationary; multiplication-adjustment control of the assembly is achieved by the remote translation of the other three segments, as depicted in Fig. II-18. Each mobile reflector segment is controlled by an independent drive. Second, multiplication adjustment is accomplished by remotely adjusting the position of the lower fissile floor and its associated graphite relative to the target annulus. This translation is shown in Fig. II-20. As the drive system lowers the fissile floor away from the independently supported annulus, the reactivity of the assembly decreases. This drive system is similar to that described for the separated slab target. To raise the target floor, the lift must be energized.

Reactivity control is incorporated into both systems. First by actuators connected to a control system that automatically return the segments to their least-reactive ("out") position upon power loss or receipt of a signal from the control system. Second when de-energized via power loss or a signal received from the control system, the drive automatically returns the floor to its least-reactive (lowest) position.

Neutron-absorber blades also are provided to render the ADA cylinder target deeply subcritical. The blades are constructed of enriched B₄C,

which is clad in stainless steel. The blades reside above the target assembly during operation. A signal from the control system or loss of power causes the blades to be released and fall via gravitational forces into position between the stationary graphite and the fuel. Each blade is independently controlled.

In addition to the reference configuration, Monte Carlo Neutron and Photon (MCNP) models were created to estimate the reactivity worth of the mobile reflector segments and fissile floor as a function of distance and to evaluate the effectiveness of the control blades. Reactivity-feedback effects from the storage vault and from various test materials were also computed.

1.3.1.3. Weapons Neutron Research Facility Target-4

We investigated modifying the LAMPF WNR Target-4 to generate a neutron fluence that would be useful for simulating weapons neutron effects on test objects and components. The thrust of this approach is to provide a quick, convenient, and economical neutron source for weapons-effects testing.

1.3.1.3.1. Design Requirements

In this concept, the Target-4 environment is to remain unchanged. Therefore, the neutron flux and experimental location are constrained by the current Target-4 geometry, which is shown in Fig. II-28. The experimental location, which was arbitrarily set at 800 cm, is actually 175 cm beyond the concrete shielding of Target-4. This gives ample room for experiments and provides a conservative margin to our flux predictions. An additional geometric constraint is that the modified target and its cooling hoses will have to be constructed in place through a long access tunnel that is only 26.5 cm in diameter.

The target is struck by an uncollimated 800-MeV proton beam that is 5 cm in diameter, that has a Gaussian radial spatial distribution, and that has 90% of the protons within a 3-cm diameter. With this proton beam, the goal is to provide a 10^{12} n/cm² fluence in a 30-minute irradiation at 800 cm from the target.

1.3.1.3.2. Intense Pulsed Neutron Source Reference Concept

Argonne National Laboratory (ANL) has built and used an enriched-uranium booster target in their Intense Pulsed Neutron Source (IPNS) facility. This target is of interest to ADA for several reasons. It is small enough to fit into the Target-4 station. Neutrons reaching the experiment

originate from fission and therefore are basically a fission spectrum. The target exists, has been tested, and is relatively cheap.

We analyzed a PINS target for several operational modes, each responding to a perceived constraint. For a maximum practical proton current, what would be the heat-generation rate and how long would it take to reach the goal irradiation? For a heat-generation rate limited to the design of 63 kW, what proton current would be required and how long would it take to reach the goal irradiation? For an irradiation time limited to 30 minutes, what proton current would be required and what would be the heat generation rate? These questions are answered in Table II-9. The main result is that we can reach the irradiation goal with a PINS target without exceeding proton current limits and without redesigning the PINS cooling system. One can reach this goal a little faster using the maximum practical proton current, but that would require some redesign of the PINS cooling system.

1.3.2. The Accelerator Driven Assembly Beam-Delivery System

The beam transport line for the ADA facility (see Sec. 3 and Fig. III-1) is designed to handle either a direct LAMPF beam or a PSR beam to the ADA neutron multiplying target. The beam-transport line is designed to minimize cost, maximize reliability and maintainability, minimize the commissioning and tuning effort, and make operation of the facility safe. Personnel and target safety are critical items that are designed into this beam line. A pulsed "kicker" magnet is used to deflect the beam into the ADA transport channel. Only a fixed number (≤ 5) PSR or LAMPF macropulses can be accepted by this channel without manually rearming the kicker magnet (see Fig. III-2). This eliminates an accident scenario whereby many LAMPF or PSR beam pulses are directed onto and damage the ADA target.

The beam-pipe bore diameter was sized to minimize beam scraping and resulting beam-line component activation. Beam-position monitors (BPMs) and wire harps coupled with steering magnets and beam-phase-space-matching quadrupoles will be used to steer and focus the beam. Radiation monitors will be placed along the beam line to turn off the accelerator in case of beam spills. Three beam plugs in the beam line will ensure that beam cannot enter the ADA experimental building when personnel are present.

1.3.3. Accelerator Driven Assembly Site and Balance-of-Plant

The balance-of-plant includes site work, facilities, hardware, structures, utilities, and equipment required to support the ADA experiments

other than the principal target and beam-line hardware. When combined with the target and beam-line hardware the balance-of-plant completes a functional and operational project.

Site work consists of excavation, foundation preparation, drainage, road and walk construction, backfilling, and general site work to build the ADA target building and the beam-transport tunnel and supporting equipment. Three new structures are required: the ADA concrete building (Fig. IV-1), the concrete tunnel for the beam line, and a users' experiment-instrumentation trailer slab. For a detailed description of each see Secs. 4.3.2 - 4.3.4.

General requirements for the ADA experimental building include the experimental area and a side target vault made of concrete. This vault provides passive cooling for the target and security in the form of both personnel safety against radiation hazards and special handling of radioactive materials. The vault must have a lockable concrete or steel door to provide this security. The landscape is graded so that rain or snow water can never enter the building.

The experiment-instrumentation building will consist of a modular building or mobile trailer brought to the site to serve as a place where personnel can monitor experiments. This experiment-instrumentation building will be situated sufficiently far from the ADA building to allow personnel to be present during operations. The control of remote-handling operations and of the beam and tuning magnets will be from the existing LAMPF Central Control Room (CCR).

Mechanical work on this project involves cooling water, vacuum lines and pumps, piping and cooling towers for the beam-transport line, mechanical tracks and the remote handling of the target, structure for the targets and beam stop, and drainage for the floor of the ADA building. There will be no water allowed in the ADA experimental building.

Balance-of-plant electrical work can be broken into two areas: power supply and electricity (which includes lighting) and instrumentation. New power (480 V/208 V-3 phase, 40 KW) must be furnished for the beam transport and associated accessories, as well as for the new ADA experimental building and instrumentation trailer. Sensors, instrumentation, and signal wires must be installed, including the hardware and software needed to run and monitor the experiment.

Shielding will be required around the new beam-transport tunnel, the ADA experimental building, and in some areas inside the experimental building. Shielding is required to isolate the ADA target and beam stop from the rest of the experimental building to protect workers and experimenters from residual radiation when access to the building is required.

1.3.4. Safety and Security

1.3.4.1. Safety

We have addressed all applicable safety issues with respect to the neutron-multiplying target, the beam-delivery system, and beam interaction with the neutron-multiplying target. The beam-delivery system to the ADA target (slab or cylinder) is designed to be single-burst safe. In order for the beam to reach the ADA target, a pulsed 1.5° kicker magnet must be manually armed by charging a capacitor (see Fig. III-2). Once the kicker magnet is fired, it only maintains the correct field strength for bending the beam for a set number of beam pulses. The standard operating procedures (SOPs) control additional levels of safety. Prototype SOPs are given in Sec. 3.9.2.

The PSS controls an interlock entry system to the ADA experimental building that only allows entry by personnel to the facility when there is no possibility of beam entering the facility when the ADA target and californium k_{eff} calibration source (see Secs. 3.2.3 and 3.9) are properly secured in their storage vault and when the beam-dump shield covers the beam dump. Television cameras, placed inside the experimental building, will allow the operations crew to visually verify that the room is properly secured before allowing personnel entry.

The RSS protects equipment from beam spills. The RSS includes the PSS. The RSS uses radiation-spill monitors to shut off the beam if beam spills are excessive. The number of beam-spill monitors and neutron-flux monitors will be determined by the LAMPF radiation safety committee. This system will not allow beam unless magnets are properly turned on and dipole magnets are properly set.

As part of our ADA slab- and cylinder-target design efforts, we have adopted a conservative, well-accepted reactivity control philosophy known as the "Jezebel Control Philosophy" (Anderson 1994). The Jezebel philosophy incorporates four different safety methodologies. First, distance is used as the principal safety feature. As discussed above, measures are taken to ensure that no one is near the ADA experimental building when an irradiation

event occurs. Additionally, positioning and control of the target is done remotely, thereby limiting personnel exposure to doses that are as low as reasonably achievable (ALARA).

A second aspect of the Jezebel philosophy is the ability to separate the assembly into two or more large components. In the ADA slab target, this is accomplished by separating the two slab halves during nonoperational conditions. For the cylinder target, the bottom will be lowered.

The third safety methodology proposed by the Jezebel philosophy is to provide two or more ways to fine control the reactivity of the assembly. Each of these methods must provide at least 1\$ (see Sec. 2.2.1.3) of reactivity control. As designed, the ADA slab target provides three fine-control mechanisms. Each of the independently operated control drums has a reactivity worth slightly greater than 1\$. In addition, variation of the separation distance between the slab-target halves provides reactivity worth in excess of 11\$.

As an additional measure, a neutron-absorber blade can be inserted to substantially reduce the reactivity of the assembly for both the slab and cylinder targets.

The fourth safety measure presented in the Jezebel philosophy is the use of interlocks to limit the allowed operational sequences. Interlock design and philosophy will be addressed during the preliminary design phase of this project.

For the simplified ADA target model described and illustrated in Sec. 2.2.1.3.1, the temperature coefficient of reactivity was found to be small and negative with magnitude on the order of $-3 \times 10^{-6} \Delta k/^{\circ}\text{C}$. The temperature coefficient as a function of slab-target-assembly temperature is presented in Table II-2.

1.3.4.2. Security

One of our key design requirements for the slab and cylinder targets was to adopt a uranium enrichment of 19.9% or less. This decision was entirely dictated with respect to the special nuclear materials (SNM) categorizations cited in the *Nuclear Materials Control and Accountability Procedural Handbook* (Ostenak 1992) and DOE Order 5633.3. The material is thus placed in SNM category IV with an attractiveness level E. This category is the lowest SNM classification level and requires storage in a locked container or room when the target is unattended.

1.3.5. Cost and Time Schedules

Table I-1 summarizes all costs pertaining to the ADA proposal. Cost estimates for the components of the ADA are made based on actual costs incurred by other projects. The cost estimate covers hardware and personnel costs for the beam tunnel to house the beam-transport system, the ADA experimental hall, the experimental control trailer, the ADA beam-line system, the ADA target, and all required services. These costs cover design, procurement, checking, installation, and commissioning of the entire system.

We propose assembling the target at LANL's Pajarito site and bringing it to critical (i.e., this facility is designed for these activities) in order to verify design calculations and calibrate the target criticality controls. This cost is included in the estimate.

TABLE I-1. ADA COST SUMMARY

Item	Description	Cost-\$K
Balance-of-Plant Rough Cost Estimate		
Utilities	Power-480/3 phase, vacuum, cooling water, control conduits, communications, etc.	\$475
Structures, ADA	Complete building, 18" concrete w/ drains, doors, heating, etc., 1,000 sq ft, 6" boronated polyethylene shielding, 200-cu-yd concrete	\$1,350
Structures, beam tunnel	Complete enclosure, concrete, 219' long, heating, etc., 12'W x 10'H, exit and access, doors, heavy roof loading, special features	\$2,900
Equipment	All equipment for beam tunnel and target, remote target railcar, and stands, etc.	\$1,300
Shielding	8' Steel or 20' concrete for beam enclosure	\$320
Beam stop	Tungsten plates 18" diameter x total 1' thick, shutter door, etc.	\$450
Controls	Remote controls and sensors for target, controls for beam system	\$850
	Sum of construction costs for balance-of-plant	\$8,195
Design A&E		\$1,200
Design lab equipment		\$600
	ADA subcost for balance-of-plant	\$9,995
Subcritical assembly costs		
Fuel	U235 < 20% enriched fuel	\$0
Subcritical assembly stand	Graphite moderators and drums, etc.	\$1,600
Subcritical assembly	Support systems	\$1,500
Experiment data acquisition	Sensors, instrumentation for experiment	\$2,300
ES&H for subcritical assembly	Analyses and reports	\$2,400
Design of subcritical assembly		\$1,250
	Subcost for critical assembly (without fuel)	\$9,050
Beam-line cost	Total from Section 3.3	\$2,919
Target assembly and test at Parajito site		\$750
Total ADA project cost	Missing fuel	\$22,714

2. RESULTS OF DETAILED STUDIES

2.1. Accelerator Driven Assembly Concepts for Pulsed Neutrons

The ADA concept includes bombarding a heavy-element target with 800-MeV protons to produce tens of neutrons for each incident proton. The (p,n) reaction efficiency is large because protons strongly interact with nuclear forces. Neutrons produced in this way are called "spallation neutrons"; they impinge upon a uranium target enriched with ^{235}U . Fission reactions in the enriched target multiply the moderated spallation neutrons by factors of 10. Thus, the neutron-multiplying processes used in the ADA concept produce 100 to 1,000 neutrons for every incident 800-MeV proton. Subsequently, the multiplied neutrons bombard the test object placed in the ADA facility.

The ADA concept began with the intention of using a heavy-element target, such as tungsten, as a "booster" to produce spallation neutrons. An enriched uranium target placed nearby would further multiply the neutrons by fission reactions. However, our preliminary calculations showed no advantage to this booster concept over simply using the uranium target itself to stop the protons and produce spallation neutrons. In this way, the enriched uranium target serves as both a spallation target and a fission multiplying target.

We make a distinction here between the number of spallation neutrons N_s and fission neutrons N_f because they have quite different energy spectra. For our purposes, we are concerned with exposing test articles to neutrons with a fission spectrum. To continue the discussion of fission neutrons, we introduce the well-known multiplication factor. The multiplication factor, k , is defined as the ratio between the number of fission neutrons produced and the number of fission neutrons absorbed per unit time in an infinite medium (Segre 1977). If k is greater than 1, the first neutron initiates an unbounded chain reaction. Operations in the ADA concept will always keep k less than 1.

The multiplication factor is a convenient parameter because it has many different interpretations. For example, in noninfinite media, k is the solution to an eigenvalue problem and can be interpreted as the ratio between the number of neutrons in one generation and the number of neutrons in the next generation. For finite geometry, some of the neutrons escape from

the target and are, in the case of ADA, used to produce the neutron fluence that irradiates the test object. Thus, the total number of neutrons N_T produced after an infinite number of generations of fission neutrons take place is

$$N_T = N_f + kN_f + k^2N_f + k^3N_f + \dots = N_f \frac{1}{1-k}, \text{ and} \quad (II-1)$$

$$M = \frac{N_T}{N_f} = \frac{1}{1-k},$$

where M is called the multiplication constant. If the initial generation of neutrons is due to spallation neutrons, then

$$N_T = N_s + kN_f + k^2N_f + k^3N_f + \dots = N_s + N_f \frac{k}{1-k}, \text{ and} \quad (II-2)$$

$$m = \frac{N_T - N_s}{N_f} = \frac{k}{1-k},$$

where m is the fission only multiplication constant. The count rate in a neutron detector that is monitoring nearby fissioning material scales as either M or m , depending on whether it detects all neutrons or only neutrons predominantly in the fission spectrum or depending on whether the initial neutrons come from a fission source or a spallation source. For our purposes, the differences between M and m are not significant because both $1/M$ and $1/m$ go to 0 as k approaches 1. One can determine the nearness of k to unity by plotting $1/(\text{neutron count rate})$ while varying k .

The ADA concept consists of bombarding an enriched uranium target with a burst of 800-MeV protons to produce spallation neutrons, which, in turn, will provide a short pulse of neutrons by the fission process. Our calculations and our experience both at LAMPF and in reactor research show that this concept produces pulsed neutrons to a test article safely and efficiently.

2.2. Target Point Designs

2.2.1. Slab Target

The basic slab-target concept consists of a rectangular, solid region of fissile material, which is interposed between the proton beam and an arbitrary test article. The slab-target arrangement is proposed to simulate a unidirectional source of neutrons and to alleviate test-article size restrictions imposed by a cavity irradiation environment. The specific design requirements for the slab target are discussed in Sec. 2.2.1.1. The reference design is presented in Sec. 2.2.1.2. Physics and mechanical analyses in support of the reference design (including parametric studies) are addressed in Secs. 2.2.1.3 and 2.2.1.4.

2.2.1.1. Design Requirements

The slab-target concept was designed to satisfy four key requirements: total neutron fluence, fluence uniformity, experiment irradiation area, and neutron energy spectrum. We require that the target system supply 1×10^{13} neutrons/cm² over a 50-cm x 50-cm irradiation area. We likewise require that the fluence uniformity be no worse than $\pm 50\%$ over the irradiation area. Additionally, the incident neutron flux should have an energy-dependence characteristic of a fission spectrum. Finally, we assume the system is operated in a pulsed mode but without any specific requirement on the neutron-pulse time width.

Based on the fundamental design requirements specified above, we then adopted additional derived design requirements among the following categories: incident proton beam, slab geometry, slab material, safety, security, and operations. We designed the slab target to be compatible with the LAMPF-PSR supply of 800-MeV protons (3×10^{13} protons/pulse). To achieve the desired neutron fission spectrum, we require a fissile target material. Selection of the specific target material is addressed in Sec. 2.2.1.2.3.1. We similarly require a stopping length of target material so that the incident protons do not impinge on the test article (24-cm slab thickness). The height and width of the fissile material were both chosen to be 50 cm, which corresponds to the desired irradiation area. Larger slab geometries (3 m x 3 m) were considered early in the ADA program; the intention was to irradiate tank-size components. Although tank irradiation is no longer a specific design requirement, the 3-m x 3-m slab target is highlighted in Sec. 2.2.1.3.3,

"Physics Parameter Studies and Results." Consideration of the test-article envelope definition for tank-size components is presented in Appendix A. In terms of safety, we require a subcritical assembly ($k_{pr} = 0.98$)* with multiple and diverse methods of control and/or shutdown. With respect to materials-access security (see Sec. 2.2.1.2.4), we limit the enrichment of the uranium to be at or below 19.9% (i.e., the value for the slab is 16.42%) and assume that the target is stored in a locked concrete vault when not in use. Operationally, we desire the capability to irradiate two to three test articles per day with acceptable thermal management.

2.2.1.2. Reference Slab-Target Concept

2.2.1.2.1. Reference-Slab-Target-Concept Description

Figure II-1 illustrates the reference slab-target conceptual design. The fissile region of the target assembly is constructed of U-1.5%Mo interlocking bricks that are 16.42 atom% enriched in ^{235}U .** These bricks are stacked into two structural-framework baskets to form two halves of a single multiplying region. When the slab-target halves are contiguous, the total fissile region measures 50 cm high x 50 cm wide x 24 cm deep and is reflected on five of its six faces by 25-cm-thick graphite. The single unreflected surface of the slab-target faces the test article and measures 50 cm x 50 cm. In this configuration, when neutron multiplication is induced, the test article is exposed to an unmoderated neutron flux characterized by a fission energy spectrum.

In its operational configuration, the slab target is designed to provide a prompt-neutron multiplication of 50, or equivalently, a k_{pr} of 0.98. To adjust the reactivity of the assembly, two diverse methods of reactivity control are employed. First, graphite control drums, as shown in Fig. II-2, are placed on either side of the fissile slab. Each drum resides in a cavity that penetrates the full length of a side reflector region. The perimeter of each control drum incorporates a 120° segment of B_4C neutron-absorber material

* Note that k_{pr} , k_{eff} , β_{eff} , ρ , M , and M_{pr} are neutronic parameters that are defined in Section 2.2.1.3. We are interested in the prompt neutrons generated in the target; however, there are also delayed neutrons emitted during the decay of fission fragments that add to the reactivity. The fraction of delayed neutrons is given by the parameter β_{eff} , which for our assembly is estimated to be 0.0065. To keep the assembly subcritical, we must keep $k_{eff} < 1.0$.

** In other words, 16.42% of all uranium atoms in the slab material are ^{235}U .

(or neutron "poison") that is 80 atom% enriched in ^{10}B . The target assembly is most reactive when the drums are rotated "out" so that the poison is directed away from the fissile region. Similarly, the least-reactive configuration occurs when the drums are rotated "in" so that the absorber material resides near the active target. Stepper motors connected to a control system independently rotate each drum to any desired position. In the event of power loss or a signal received from the control system, the spring-loaded control drums automatically return to their least-reactive positions.

Fig. II-1. Reference slab-target concept. The proton beam enters the assembly on the side opposite to the exposed face shown in the figure.

(a) Control-drum and drive detail.

(b) Graphite-reflector detail.

Fig. II-2. Control-drum and drive detail and graphite-reflector detail.

Reactivity control will also be accomplished by adjusting the separation distance between the lower and upper halves of the active slab target. Increased separation results in decreased reactivity. In this slab-target conceptual design, the upper target region is stationary. The lower fissile region and its associated graphite can be raised and lowered remotely by a drive system that resides beneath the assembly. Please refer to Fig. II-3. Like the control-drum stepper motors, this lift system is connected to the reactivity control system. To raise the slab target, the lift must be energized. When de-energized via power loss or control-signal receipt, gravity automatically returns the lift and slab to its least-reactive position.

Although the control-drum and slab-separation mechanisms provide adequate means to adjust the reactivity of the ADA slab-target system, a third means of rendering the system deeply subcritical is prudent. Therefore, a neutron-absorber blade is incorporated into the target design. During operation of the target, the blade is held above the assembly, perpendicular to the beam, as shown in Fig. II-4. A signal from the control system or loss of power causes the blade to be released and slide via gravitational forces into position between the fuel and the beam-face reflector region, thus reducing the assembly reactivity. This blade is envisioned as a third, independent, passive system needed to ensure operational safety and deep subcritical storage ($k_{eff} < 0.90$).

When in its storage alcove, the ADA slab-target assembly will be in its least-reactive configuration—that is, both control drums will be rotated inward, the upper and lower active slab-target regions will be separated as far as mechanically possible (≈ 20 cm), and the absorber blade will occupy the slot between the fissile slab and the graphite reflector.

Fig. II-3. Target-separation control function and drive detail.

Fig. II-4. Neutron-absorber-blade control function and detailed view.

As seen in Fig. II-5, the ADA slab target is mounted upon a stainless-steel cart. When experimenters are prepared, a remotely operated drive system transports the target assembly along floor-mounted rails to its experimental position. Power, instrumentation, and any other required utilities are tethered to the cart and are transported from the storage alcove at the same time. After the irradiation is complete, the assembly and associated utilities are remotely returned to the shielded storage room.

Fig. II-5. Target-cart and drive detail.

Not illustrated is the framework attached to the cart that provides a mounting structure for instrumentation, drive systems, and so forth. This framework also imposes a 50-cm separation distance between the test article and the target. This required separation ensures that the flux uniformity requirement is met and also limits the reactivity influence of the test article (see Secs. 2.2.1.3.2 and 2.2.1.3.3.).

2.2.1.2.2. Control and Safety Functions and Philosophy

As part of our design efforts, we have adopted a conservative, well-accepted reactivity control philosophy known as the "Jezebel Control Philosophy" (Anderson 1994). The Jezebel philosophy incorporates four different safety methodologies. First, distance is used as the principal safety feature. As discussed elsewhere in this report, measures are taken to ensure that no one is near the ADA experimental facility when an irradiation event

occurs. Additionally, positioning and control of the target is done remotely, thereby limiting personnel exposure to doses that are ALARA.

A second aspect of the Jezebel philosophy is the ability to separate the assembly into two or more large components. In the ADA slab target, this is accomplished by separating the two slab halves during nonoperational conditions.

The third safety methodology proposed by the Jezebel philosophy is to provide two or more ways to fine control the reactivity of the assembly. Each of these methods must provide at least 1\$* of reactivity control. As designed, the ADA slab target provides three fine-control mechanisms. According to MCNP transport codes, each of the independently operated control drums has a reactivity worth slightly greater than 1\$. In addition, variations of the separation distance between the slab-target halves provides reactivity worth in excess of 11\$. [The specific Monte Carlo code used for neutronic analysis of the slab target is the MCNP transport code (Briesmeister 1993).]

As an additional measure, a neutron-absorber blade can be inserted to substantially reduce the reactivity of the assembly. Calculations indicate that the reactivity worth of the blade is about 9\$.

The fourth safety measure presented in the Jezebel philosophy is the use of interlocks to limit the allowed operational sequences. Interlock design and philosophy will be addressed during the preliminary design phase of this project.

2.2.1.2.3. Materials Issues

2.2.1.2.3.1. Fuel Selection

Enriched uranium alloy with 1.5% molybdenum by weight (U-1.5%Mo) has been used successfully in burst assemblies for decades. The Godiva IV (Wimett *et al.* 1969), Lady Godiva (Peterson 1953), and Skua (Orndoff 1980) critical assemblies at LANL all are composed of this material. The addition of 1.5%Mo increases the structural strength and ductility of the uranium. We would propose, as in Skua, that each fissile brick of the ADA target assembly be aluminum ion plated to minimize sources of contamination from fission-product decay.

*One dollar, 1\$, of reactivity is equal to β_{eff} , the fraction of delayed neutrons. For our assembly, β_{eff} is estimated to be 0.0065. See Section 2.2.1.3 for an explanation of neutronic parameters.

Another advantage of U-1.5%Mo is its high mass density ($> 18 \text{ g/cm}^3$). Stopping the 800-MeV proton beam requires approximately 480 g/cm^2 of mass. Consequently, the higher the target density, the less thick the target must be to stop the beam.

2.2.1.2.3.2. Graphite Irradiation

During our investigations, a concern over possible proton interaction with the graphite reflector was raised. The concern related specifically to any life-limiting phenomena or issues of mechanical integrity that may preclude the use of graphite directly in the proton beam path. Fortunately, there is some experience at LAMPF with pyrolytic graphite targets. Based on this experience at much higher proton fluxes, we concluded that there are no obvious phenomena that would preclude the use of a pyrolytic graphite reflector in the beam path. Note, however, that we have not specified the graphite material type (pyrolytic or otherwise) for the reference slab-target reflector. The actual graphite-type specification has been deferred until the preliminary design phase. As such, we recognize the need to revisit the issue of graphite irradiation once the material type is chosen.

2.2.1.2.4. Special Nuclear Materials Issues

One of our key derived-design requirements for the slab target was to adopt a uranium enrichment of 19.9% or less. This decision was entirely dictated with respect to the SNM categorizations cited in the *Nuclear Materials Control and Accountability Procedural Handbook* (Ostenak 1992) and DOE Order 5633.3. In general, special nuclear materials are classified two ways. The first, referred to as "attractiveness level," is defined as "a categorization of SNM material types and compositions that reflects the difficulty of processing and handling required to convert material to a nuclear explosive device" (Ostenak 1992). There are five divisions in attractiveness level: A, B, C, D, and E. Level A represents the most easily converted to a weapon. Sample material types and compositions for the five levels are cited below.

- Level A (weapons):
 - Assembled weapons
 - Test devices
- Level B (pure products):
 - Pits
 - Major components
 - Buttons
 - Ingots
 - Recastable metal
 - Directly convertible materials
- Level C (high-grade material):
 - Carbides
 - Oxides
 - Solutions (>25 gm/l nitrates, etc.)
 - Fuel elements and assemblies
 - Alloys and mixtures
 - UF₄ or UF₆ (≥50% enriched)
- Level D (low-grade material):
 - Solutions (1-25 gm/l)
 - Recyclable process residues
 - Moderately irradiated material
 - ²³⁸Pu (except waste)
 - UF₄ or UF₆ (≥20%, <50% enriched)
- Level E (all other material):
 - Highly irradiated forms
 - Solutions (<1 gm/l)
 - Waste
 - Enriched uranium (<20% enriched)

The second classification of material is referred to as "SNM category" and pertains to the level of effort required to safeguard the material. There are four SNM categories: I, II, III, and IV. At category IV, the material in question must be under the control of a designated nuclear materials (NM) custodian when in use, or it must be stored in an approved locked container or room when unattended. Above category IV, the access-control requirements become more stringent, and the material must reside in a security area. The material must be under continuous surveillance or stored in an alarmed and locked repository. Above category III, the SNM is subject to additional access control and material-surveillance requirements, including, but not limited to, restricted access via portals that are subject to material and personnel control (including searches, inspections, and

electronic monitoring and alarms); continuous two-person surveillance or storage in an approved vault; daily administrative checks; and waste-stream monitoring. In general, the higher the SNM category, the greater the operational security costs to the ADA program.

The attractiveness level is determined by the material type or composition, whereas the SNM category is defined by the amount of material present. A matrix showing the relationship between level, category, and quantity is presented in Table II-1 for ^{235}U .

TABLE II-1. SNM CATEGORIZATION FOR ^{235}U

Material Description	Attractiveness Level	SNM Categories for ^{235}U (All Quantities in Kilograms)			
		I	II	III	IV
Weapons	A	All quantities	N/A	N/A	N/A
Pure products	B	≥ 5	$\geq 1, < 5$	$\geq 0.4, < 1$	< 0.4
High-grade material	C	≥ 20	$\geq 6, < 20$	$\geq 2, < 6$	< 2
Low-grade material	D	N/A	≥ 50	$\geq 8, < 50$	< 8
All other materials	E	N/A	N/A	N/A	$>$ Reportable quantities

Now, assuming a 50- x 50- x 24-cm slab-target section of U-1.5%Mo, there is approximately 1,100 kg of uranium present. At an enrichment of 16.42%, the mass of ^{235}U is 181 kg. Based on Table II-1, this quantity of material would thrust the slab target into SNM category I or II for all but Level E attractiveness material types. Our intent is to keep the slab-target classification at IV-E, "reportable quantities," particularly with respect to the relative requirements for material access and surveillance, material inventory, and administrative controls. To do so requires one of the

following: (1) keeping the uranium enrichment below 20% or (2) irradiating the target sufficiently to provide greater than 15 rad/h dose at 1 m. At enrichments equal to, or above 20%, the U-Mo would presumably be "born" as I-C [high-grade material (alloys)]. After mild irradiation (<15 rad/h), the classification changes to II-D. Only after sufficient irradiation (>15 rad/h) would the classification fall to IV-E. Alternatively, below an enrichment of 20%, the U-Mo would remain IV-E regardless of operational history. Considering that low enrichment does not provide a significant impediment to meeting the goal fluence requirement, we felt it was the most prudent design course to follow.

Even at relatively low enrichment, transportation guidelines for materials control and accountability still provide some constraint as to the overall mechanical design. The guidelines in question (Ostenak 1992) require that during transportation, no more than 40 kg ^{235}U can be loaded per truck, no more than 18.5 kg of ^{235}U can be loaded per individual transportation container, and the maximum packing density per container must remain below 18.5 kg/ft³. As our current design requires approximately 181 kg of ^{235}U , the monolith must be assembled or disassembled into no fewer than 10 pieces. Transportation of the target material to and from the site (perhaps following U-Mo fabrication or decommissioning) would require no fewer than five truck loads.

2.2.1.3. Physics

When the slab target is struck by the 800-MeV proton beam, spallation neutrons are created in the uranium through proton interactions. These spallation neutrons then induce fissioning of ^{235}U atoms, and the resultant neutron multiplication produces the desired fast-neutron flux.

Several neutronic parameters influence the ADA target design. Four of the most significant parameters are k_{eff} , the effective multiplication eigenvalue or criticality eigenvalue; M , the neutron multiplication; ρ , reactivity; and β_{eff} , the effective fraction of delayed neutrons. From these parameters, we derived two more parameters: k_{pr} , the criticality eigenvalue when only prompt neutrons are considered; and M_{pr} , the prompt-neutron multiplication.

The effective multiplication eigenvalue, k_{eff} , is defined as the ratio of the number of fission neutrons in one generation to the number of fission neutrons in the preceding generation. When $k_{\text{eff}} \geq 1$, a self-sustaining chain

reaction results. The value of k_{eff} includes neutrons generated by prompt neutrons and also by delayed neutrons. Delayed neutrons are created during the decay of fission-daughter products and also include delayed photoneutrons created during photon interactions. Neutron multiplication, M , is the total number of neutrons (on average) appearing in the assembly per source neutron and is related to k_{eff} by the following equation:

$$M = \frac{1}{1 - k_{eff}} , \quad (II-3)$$

where $k_{eff} < 1$.

Because we are interested in the prompt neutrons generated in the target, we similarly define k_{pr} as the criticality eigenvalue calculated when contributions to the neutron population by delayed neutrons are neglected. Then the prompt-neutron multiplication factor, M_{pr} , becomes

$$M_{pr} = \frac{1}{1 - k_{pr}} , \quad (II-4)$$

where $k_{pr} < 1$.

Another definition of interest is reactivity, ρ . Reactivity is the deviation of the core multiplication eigenvalue from critical and is defined by

$$\rho = \frac{k_{eff} - 1}{k_{eff}} . \quad (II-5)$$

The change in reactivity, $\Delta\rho$, between two related assembly configurations with criticality eigenvalues of k_{eff1} and k_{eff2} , respectively, is therefore given by

$$\Delta\rho = \frac{k_{eff2} - k_{eff1}}{k_{eff2} * k_{eff1}} . \quad (II-6)$$

Reactivity effects such as control worths and room return are often presented as values of $\Delta\rho$.

Finally, for this fast-neutron spectrum ^{235}U system, we assume an estimated value for β_{eff} to be 0.0065 (Keepin 1965), where β_{eff} is the effective fraction of neutrons delayed by all processes. When $\rho = \beta_{\text{eff}}$, a fissile assembly sustains the chain reaction on prompt neutrons alone, and the assembly is called "prompt critical." Because of its importance in neutronic calculations, this amount of reactivity, namely $\rho = \beta_{\text{eff}}$, is used to define a unit of reactivity known as the dollar (\$)—that is, $\rho = \beta_{\text{eff}} = 1\$$ of reactivity.

Target-design decisions are influenced by understanding the physics that occurs in the target assembly, as well as any resultant safety implications. Through that understanding, operational requirements may be balanced by safety considerations. For example, because the neutron flux is proportional to the neutron multiplication, there are operational advantages to having a high neutron-multiplication factor. On the other hand, there are safety advantages in keeping the prompt neutron multiplication relatively low (<100). These advantages occur because safety concerns diminish as the reactivity of the assembly becomes more negative ($k_{\text{eff}} < 1$). By setting our goal-neutron-multiplication value at 50, we added safety conservatism to the design while achieving our neutron fluence goal of 1×10^{13} neutrons/cm² with an acceptable number (<5) of proton-beam pulses.

Another important design decision that was influenced by the neutronic characteristics of the assembly concerns the addition of graphite reflector regions. Although the proton beam is relatively unaffected by the graphite that it must penetrate to reach the fuel slab, the neutron reflector that envelopes five sides of the active target slab provides several design advantages. First, the fuel and reflector assembly is less influenced neutronically by surrounding structures, both in its operational mode and while in storage. Second, the added reflection reduces the enrichment of the U-1.5%Mo slab target required to give the desired neutron multiplication factor. Third, the graphite-reflector regions can be designed to incorporate uncomplicated control and safety mechanisms.

Physics considerations influence simple design decisions, as well as complex ones. For example, the slab thickness of 24 cm was chosen to provide adequate stopping mass for the 800-MeV proton beam. The ^{235}U enrichment was then decreased to provide the goal prompt-neutron multiplication of 50.

2.2.1.3.1. Analysis Model and Methodology

Neither Monte Carlo nor discrete-ordinates methodology alone provides the capability to characterize accurately all core physics parameters, including reactivity, reactivity control worths, temperature coefficients, and others. For these analyses, Monte Carlo was the primary calculational method used to determine the criticality eigenvalue (k_{eff}) of various geometric configurations, to transport the high-energy protons through the system, and to simulate the resulting neutron spallation process. Reactivity control worths are determined by comparing the calculated k_{eff} values for two related configurations and computing the resultant $\Delta\rho$ as described in Sec. 2.2.1.3. (Reactivity of the slab-target assembly will be experimentally verified before placing the target into the ADA facility.) The discrete ordinates method was used to estimate the temperature coefficient of reactivity for this multiplying slab-target design.

Monte Carlo codes randomly sample many histories to determine the average behavior of the particles. Because Monte Carlo is a statistical process, an uncertainty is associated with each calculated value. Running a sufficiently large number of histories generally keeps such uncertainties acceptably small.

The specific Monte Carlo code used for neutronic analysis of the slab target is the MCNP transport code (Briesmeister 1993). MCNP is a three-dimensional, general-purpose, coupled neutron-photon-electron transport code that can calculate k_{eff} eigenvalues for multiplying systems. Although MCNP includes delayed neutrons for determining k_{eff} , a code option allows delayed neutrons to be omitted from the computation. MCNP can model any geometry that can be described by quadratic surfaces and tori and provides easy geometry plotting that facilitates debugging. Because of its very powerful geometric capabilities, MCNP can model the ADA target assembly in great detail.

MCNP is run with a library of pointwise or continuous-energy cross sections based primarily on ENDF/B-V-evaluated data (Kinsy 1979). These data eliminate inaccuracies associated with multigroup-averaging techniques. For important scattering substances, such as graphite and water, thermal-scattering $S(\alpha,\beta)$ cross sections that account for chemical binding and crystalline structure are available. MCNP has been well benchmarked against analytical calculations and critical experiments (Wagner *et al.* 1992).

All MCNP calculations that are presented here were performed on SUN SPARC workstations. Eigenvalue calculations were started with a well-settled source, and each calculation followed about one million particle histories, resulting in a stated relative error of less than 0.1% in the value of k_{eff} .

Another Monte Carlo code, the Los Alamos high-energy transport system (LAHET) (Prael and Lichtenstein 1989), was used to estimate the response of the target assembly to the high-energy (800-MeV) proton beam. LAHET is a Monte Carlo code for the transport and interaction of nucleons, pions, muons, light ions, and antinucleons in complex, MCNP-compatible geometry. Low-energy (<20-MeV) neutrons that result from proton-beam interactions in the slab are subsequently transported using a version of MCNP.

Plan and elevation views of the three-dimensional MCNP reference model appear in Figs. II-6 and II-7, respectively. The U-1.5%Mo target region is represented by two material blocks, each enclosed in a stainless-steel angle-iron basket. Individual fissile blocks are not modeled; it is assumed that no significant error is introduced by this simplification.

Fig. II-6. Plan view through the midplane of the MCNP model used to analyze the ADA slab-target reference concept.

Graphite control drums on either side of the fissile target region are modeled explicitly. Each drum comprises regions that represent the cylindrical graphite drum, a 120° arc of enriched B_4C neutron-absorber material (1 cm thick) on the drum perimeter, stainless-steel cladding material,

and a stainless-steel center-support post. The clearance between the drum and side-reflector material is also modeled.

Similarly, the safety-blade region is represented in detail by the MCNP geometry. When the blade is retracted, the slot between the multiplying target and the reflector is void except for rails and shafts assumed to be mounted to the graphite. When inserted, blade-model details include the 1-cm-thick absorber region, its associated cladding material, two upper and lower aluminum pillow blocks, and stainless-steel bushings.

Fig. II-7. Elevation view cutaway of the MCNP model used to analyze the ADA slab-target reference concept.

The temperature coefficient of reactivity for the ADA slab-target conceptual design was estimated by using the two-dimensional, discrete-ordinates code, TWODANT (Alcouffe *et al.* 1984). For each investigation, a working cross-section set based on the 69 energy-group MATXS7 library (MacFarlane 1984) was created with the appropriate temperature dependence. Each data set was adjusted with the cross-section processing code TRANSX (MacFarlane 1984) to account for temperature dependence, neutron self-shielding, and scattering-kernal effects. The temperature range considered was from 300 to 700 K.

For the temperature-dependent transport calculations, the rectangular ADA target was transformed into the two-region r-z model pictured in Fig. II-8. Mass was conserved during this transformation. The resulting graphite cylinder has an inside radius of 29 cm, outside radius of 56.8 cm, and total height of 50 cm. Included in the graphite height is the 25-cm-thick graphite "floor." The cavity created by the graphite shell is filled with the uranium target material. This region has a radius of 29 cm and a height of 25 cm. ^{10}B was added uniformly to the graphite to adjust the k_{eff} of the described model to 0.98 at 300 K.

Fig. II-8. Schematic of TWODANT analysis model for temperature coefficient calculation.

2.2.1.3.2. Reference Slab-Target Results

For the reference configuration described in Sec. 2.2.1.2.1, LAHET coupled with MCNP computes that at a distance of 50 cm from the bare target face, the average prompt-neutron flux is approximately 2.1×10^{12} neutrons/cm²/pulse of 3×10^{13} protons. Recall that our goal neutron fluence is 1×10^{13} neutrons/cm². Therefore, the goal fluence is easily met by providing five beam pulses to the neutron-multiplying slab target. At this 50-cm separation distance, the relative uniformity of the flux is approximate $\pm 26\%$ where uniformity has been defined as

$$\text{Uniformity} = \frac{\text{Maximum Flux} - \text{Minimum Flux}}{\text{Average Flux}} \quad (\text{II-7})$$

Neutronic characteristics of the target-assembly design were evaluated using MCNP. In addition to the reference model used to calculate the nominal k_{eff} value, models were created to estimate the adequacy of the

control drums, the worth of the poison blade, and the effectiveness of splitting the slab monolith. Reactivity feedback effects from the storage vault and from potential test articles were also calculated using this model.

In summary, we find that a single control drum has a computed negative reactivity worth of $0.00736 \pm 11.69\% \Delta\rho$ (or about 1.13\$) while both control drums together provide a negative worth of $0.01526 \pm 6.18\% \Delta\rho$ (2.35\$). Next, the reactivity worth of the safety blade was investigated. A single safety blade residing between the fuel and reflector regions yields a negative reactivity worth of $0.06221 \pm 1.24\% \Delta\rho$ (9.57\$).

Conceptually, the fuel region of the slab target is split horizontally at its midplane. The top portion of the fissile region remains stationary. The bottom half with its associated graphite is supported by a drive system and can be lowered to adjust the reactivity of the system by providing a leakage path. Also, the drive is designed to return the lower half to its least-reactive position in emergency conditions and for storage of the assembly. Figure II-9 shows the effect on reactivity as the separation distance between the two fuel halves increases to an assumed maximum separation distance of 20 cm. At a separation of 20 cm, the drop in reactivity is computed to be $0.11573 \pm 0.73\% \Delta\rho$ (17.80\$).

Fig. II-9. Negative change in reactivity, shown with 2- σ error bars, as a function of separation distance between slab-target halves.

Finally, the effect of various materials positioned near or around the slab was investigated. Objects composed of stainless steel and water were positioned in the MCNP model 0.5 m (50 cm) from the slab-target face. The simulated test objects induce a reactivity increase of $<0.005 \Delta\rho$. Compensation for this feedback effect can be accomplished easily by the control drums or by the separated slab. Next, the slab-target model was enclosed in a small, ordinary concrete vault with 30-cm-thick walls. In the model, the distance from the slab-target assembly to the walls of the vault was 50 cm in all directions, the slab halves were closed, the drums were rotated out, and the poison blade was retracted. In other words, the assembly was in its most-reactive configuration. The resultant calculated increase in reactivity of the system was $0.01783 \pm 4.80\% \Delta\rho$ (2.74\$). Because of this relatively strong reactivity feedback from the vault walls, we will provide interlocks to ensure that the safety blade is inserted before the assembly can be moved into the vault region. The reactivity feedback from the vault can be reduced by lining the inside vault walls with borated polyethylene. This design feature will be investigated with MCNP calculations. Placement of the slab-target assembly (in its most-reactive configuration) in a concrete building representative of the proposed experimental area of the facility showed a small reactivity increase of $0.00351 \pm 25.56\% \Delta\rho$ (0.54\$).

Two calculations investigated the effect of water flooding and immersion of the ADA conceptual slab target. First, with the control drums positioned inward and rotated to their least-reactive position, the poison blade inserted, and the slab-target halves separated by 20 cm, the flooded and immersed assembly exhibited an estimated k_{eff} of 0.98. Second, isolating one slab-target half from the rest of the assembly (including the neutron-poison material) and immersing it in water resulted in an MCNP-estimated k_{eff} of 0.97. These criticality calculations predict that the assembly, when in its least-reactive configuration, will remain subcritical when flooded by water and immersed. These two analyses help to characterize the assembly's response to postulated severe environments and conditions. Other analyses will be necessary to complete the safety investigation for the target assembly.

The temperature coefficient of reactivity describes the extent to which the assembly is affected by changes in temperature. This coefficient is usually presented as the magnitude of change in k_{eff} per unit change in temperature. For the simplified ADA target model described and illustrated in Sec. 2.2.1.3.1,

the temperature coefficient of reactivity was found to be small and negative with a magnitude on the order of $-3 \times 10^{-6} \Delta k/^{\circ}\text{C}$. The temperature coefficient as a function of temperature is presented in Table II-2. Calculations indicate that the graphite temperature has no effect on the temperature coefficient. Only the target temperature appears to influence the result. Also recall that neutron-absorber material was added uniformly to the graphite of this simplified geometry to achieve the desired nominal k_{eff} value. When the absorber material is removed, the resultant temperature coefficient is more negative. Therefore, we conclude that the reference configuration yields a conservative estimate for the temperature coefficient of reactivity.

By extrapolating the results presented in Table II-2, we can estimate the reactivity increase of the assembly if the temperature were to drop from 300 K to 250 K. Using an extrapolated value of $-4.6 \times 10^{-6} \Delta k/^{\circ}\text{C}$ at 250 K, we calculate a reactivity increase of $0.00023 \Delta k$, or approximately 0.04\$. Conservatively, we therefore estimate the reactivity increase caused by a 50°C drop in temperature to be $< 0.10\%$, a value easily compensated for by the existing reactivity control mechanisms.

TABLE II-2. TEMPERATURE COEFFICIENT OF REACTIVITY AS A FUNCTION OF SLAB-TARGET-ASSEMBLY TEMPERATURE

Case	Graphite/Target Temperature (K)	Reactivity	Temperature Coefficient of Reactivity ($\Delta k/^{\circ}\text{C}$)
Base	300	0.98000	---
1	350	0.97981	-3.8×10^{-6}
2	400	0.97963	-3.6×10^{-6}
3	450	0.97947	-3.2×10^{-6}
4	500	0.97932	-3.0×10^{-6}
5	550	0.97919	-2.6×10^{-6}
6	600	0.97906	-2.6×10^{-6}
7	650	0.97895	-2.2×10^{-6}
8	700	0.97886	-1.8×10^{-6}

Plans for characterizing the criticality behavior of the ADA target at the LANL TA-18 assemblies facility (Pajarito facility) are presented in Sec. 2.3.

2.2.1.3.3. Physics Parameter Studies and Results

Several different parametric studies led to decisions that affected the development of the ADA slab-target conceptual design. Some of these are discussed below.

First of all, the thickness and enrichment of the target region had to be adjusted to provide both the desired nominal k_{pr} , as well as enough mass to stop the impinging proton beam. As can be seen in Fig. II-10, at an enrichment of 19.9 atom% ^{235}U , the slab must be at least 21 cm thick to provide the required neutron multiplication. In a separate study, it was determined that approximately 480 g/cm² of material is required to decrease the fractional proton transmission through the bare surface of the slab to a few tenths of a percent. To provide this minimal mass, the slab-target thickness was increased to 24 cm, and, consequently, its enrichment was decreased to 16.42 atom% to adjust the assembly reactivity. Figure II-11 shows the relationship between reactivity and slab enrichment for the 24-cm-thick target.

Fig. II-10. Reactivity versus slab thickness for 19.9%-enriched target material.

Fig. II-11. Reactivity versus slab enrichment for the 24-cm-thick target.

In another study, we investigated the effect on reactivity of several potential test-article materials as a function of distance from the target. This investigation was done to estimate the magnitude of anticipated reactivity adjustments. Three materials were studied: (1) a 75- x 75- x 30-cm block of water, (2) a 75- x 75- x 30-cm block of stainless steel, and (3) a 14.45-cm cube of 93%-enriched bare uranium. (This cube was chosen to be 90% of the critical cubical volume for this enrichment.) The criticality eigenvalue was evaluated for each of the three materials at distances between the target and the test article of 1 to 100 cm. Results of this evaluation are presented in Fig. II-12. The greatest positive effect to the system k_{eff} appears to be induced by the stainless-steel slab. However, note that at a distance of about 50 cm, the effect on reactivity of all three evaluated materials is less than $0.005 \Delta\rho$. In other words, an ensured 0.5-m separation between the target and test article adds to the safety of the system by limiting the reactivity increase induced by the test article.

Fig. II-12. Reactivity effect of potential test articles. The exclusion barrier will be placed at 50 cm.

Neutron flux decreases rapidly with separation distance. By placing the test article close to the target, the neutron flux delivered to the test article increases significantly. Moving the test-article position from a 100-cm to 50-cm separation increases the flux by a factor of 3. Figure II-13 illustrates the relationship between separation distance and flux. Although the values shown are for an earlier version of the slab-target design, the relative trends are still important. Table II-3 cites the flux values, as well as the flux uniformity. Although the flux increases with decreasing separation distance, the uniformity of the flux decreases. For example, the uniformity of the flux at 100 cm is about $\pm 8\%$, whereas the uniformity at 50 cm is about $\pm 20\%$ to $\pm 25\%$. Nonetheless, our specific requirement is not particularly demanding. The stated uniformity goal is $\pm 50\%$ across the 50-cm x 50-cm irradiation area. Therefore, we could adopt slab-target and test-article separations as small as 25 cm. Recall, however, that for separation distances less than 50 cm, the test article begins to have an important influence on the slab target k_{eff} . Therefore, we have adopted a baseline separation between the slab target and test article of 50 cm.

Fig. II-13. Variation of flux as a function of target-to-test article separation.

TABLE II-3. ADA SLAB-TARGET AVERAGE FLUX AND UNIFORMITY

Slab-Target/Test-Article Separation Distance (cm)	Average Flux (n/cm ² /pulse)	Flux Uniformity over 50-cm x 50-cm Irradiation Area
25	1.528×10^{13}	+43.9% to -36.8%
50	8.087×10^{12}	+23.2% to -20.2%
100	2.594×10^{12}	+7.5% to -7.5%
200	6.561×10^{11}	+1.7% to -2.0%

Early in the preconceptual phase of the ADA project, a very large (3-m x 3-m) irradiation test area was proposed. Preliminary parametric-scoping studies were done to calculate the effect of various parameters on the k_{eff} of a very large neutron-multiplying slab target. The initial goal k_{eff} for the 3-m x 3-m U-Mo slab was $1-\beta_{\text{eff}}$, or 0.9935. Simple parametric calculations were

completed to estimate the reactivity effect of slab-target material composition, ^{235}U enrichment, molybdenum fraction, iron fraction (to represent structural components), and the addition of boron. As a result of these studies, the preliminary large slab-target concept was selected to be a 3-m x 3-m monolith of U-10%Mo enriched to 20% ^{235}U with a thickness of 20.27 cm. We now know that this thickness does not provide sufficient mass to stop the proton beam. But because program requirements changed, no further design effort was expended for the large slab-target design.

2.2.1.4. Mechanical Design Issues

The two principal mechanical issues for the slab target are the thermal performance of the U-Mo alloy and the dynamic structural behavior of the material under periodic, pulsed conditions. These two issues are not decoupled. Both the thermal and dynamic stress conditions depend on the magnitude of the energy deposition. In addition, the U-Mo alloy exhibits the familiar inverse relationship of strength versus temperature. This inverse dependence is illustrated in Fig. II-14.

Fig. II-14. Strength versus temperature of UO_2 and U-10%Mo.

One of the attractive features of the U-Mo alloy is its high yield strength at room temperature. As will be discussed in Section 2.2.1.4.1, the thermal environment for the slab is fairly benign for our reference target conditions. This provides a large margin between yield and the peak dynamic stresses discussed in Sec. 2.2.1.4.2. Please note, however, that the data plotted in Fig. II-14 is for U-10%Mo, not U-1.5%Mo; and for comparison, data for sintered UO₂ fuel are also shown. Some caution must be exercised when extrapolating from the given data. We will, however, demonstrate that our operating conditions are far from the limiting material conditions and that this extrapolation does not cause significant concern. Nonetheless, for future studies, we will review the literature for data appropriate to U-1.5%Mo.

An alternative way of viewing the limiting design conditions is with respect to allowable temperature limits. Once again, the peak dynamic stresses for the slab are relatively minor at the given reference design conditions (Sec. 2.2.1.4.2). At these stress conditions, we could comfortably run the slab target to temperatures as high as 900 to 1,000 K. Note, however, that our projected peak temperature is < 330 K.

Finally, for simplicity, we adopt a thermal management strategy that uses no active components. The slab target is merely cooled via its open face by natural convection to air at ambient room temperature. We presently place no requirement on the balance-of-plant for conditioned (chilled) air. Passive cooling is completely adequate at relatively modest cycle times for experiments (two to three irradiations per day) and modest thermal conditions for the U-Mo. This assertion must be revisited should the requirements become more demanding.

2.2.1.4.1. Thermal Performance

To estimate the basic transient thermal response of the target slab to a single-pulse or a series of pulses, we formulated a simple heat-transfer model representing the reference five-sided reflector configuration. For conservatism (and simplicity), all interfaces between the graphite and target material were assumed to be adiabatic. The spatial distribution of the internal heat generation within the target was similarly assumed to be uniform. These assumptions yield a one-dimensional problem easily solved via closed-form expressions. Section 2.2.1.4.1.1 will present the basic analysis methodology, Sec. 2.2.1.4.1.2 will discuss the results for the reference target, and Sec. 2.2.1.4.1.3 will present a limited set of parametric analyses.

2.2.1.4.1.1. Analysis Methodology

The primary case of interest is one in which natural convection cooling to air is applied as the boundary condition on the open slab-target face. Relative to the long time scales associated with the surface heat transfer, the pulse events are practically instantaneous. For simplicity, we thus assume an instantaneous, adiabatic heating for each pulse, followed by the characteristic cooling transient. The adiabatic temperature rise for a single event or macropulse is defined by the expression

$$\Delta T_{\text{pulse}} = \frac{Q_{\text{sp}} \cdot N_{\text{pulse}}}{c_p}, \quad (\text{II-8})$$

where Q_{sp} is the specific energy (energy per unit mass) deposited per pulse, N_{pulse} is the number of pulses per single event or macropulse, and c_p is the specific heat of the U-Mo alloy. Because we assume that the pulse is instantaneous with a uniform spatial distribution of energy, this adiabatic temperature rise is applied instantaneously and uniformly to any differential element within the target material.

Based on the adiabatic temperature rise computed above, we can describe the time- and position-dependent temperature field for any single event occurring at time τ by the expression

$$T(x,t) = T_{\infty} + \Delta T_{\text{pulse}} \cdot F(x,t - \tau). \quad (\text{II-9})$$

The ambient room temperature is represented by T_{∞} . For convenience, we will assume that the x -axis is aligned with the beam axis with its origin at the "upstream" face of the target material and with the positive x -values extending into the bulk U-Mo material. Having done so, the function F can be derived as

$$F(x,t - \tau) = 0 \quad (\text{II-10})$$

for $t < \tau$, and

$$F(x, t - \tau) = \sum_{n=1}^{\infty} \frac{2 \cdot \frac{L \cdot h}{k} \cdot \cos(\alpha_n \cdot \frac{x}{L}) \cdot \sec(\alpha_n)}{\frac{L \cdot h}{k} \cdot (\frac{L \cdot h}{k} + 1) + \alpha_n^2} \cdot e^{-\alpha_n^2 \cdot \frac{k}{\rho \cdot c_p} \cdot \frac{(t - \tau)}{L^2}} \quad (\text{II-11})$$

for $t \geq \tau$, where α_n is defined by the positive roots of

$$\alpha_n \cdot \tan(\alpha_n) = \frac{L \cdot h}{k}. \quad (\text{II-12})$$

In the above functional relationship (Eq. II-12), L is the characteristic target dimension in the x direction, h is the heat-transfer coefficient at the open slab-target surface, k is the thermal conductivity, ρ is the target material density, and c_p is the specific heat of the slab-target material.

To quantify the effect of multiple events spaced over some arbitrary period of time (not necessarily uniform), we employ a simple superposition solution derived via Duhamel's Theorem (Carslaw 1984) such that

$$T(x, t) = T_{\infty} + \Delta T_{\text{pulse}} \cdot \sum_{i=1}^N F(x, t - \tau_i) \quad (\text{II-13})$$

for N events occurring at time τ_i ($i=1, N$).

For generality, we also replace the heat-transfer coefficient, h , with an effective heat transfer coefficient, h_{eff} . The effective heat-transfer coefficient is intended to accommodate the possible presence of a gas gap and a layer of structural material interposed between the open target face and the ultimate heat sink. Thus, we define h_{eff} such that the energy flow rate per unit area, q'' , is

$$q'' = h_{\text{eff}} (T_s - T_{\infty}), \quad (\text{II-14})$$

where T_s is the outer surface temperature of the slab material, and

$$h_{\text{eff}} = \frac{1}{\left(\frac{\Delta x_{\text{gap}}}{k_{\text{gap}}} \right) + \left(\frac{\Delta x_{\text{str}}}{k_{\text{str}}} \right) + \left(\frac{1}{h} \right)}. \quad (\text{II-15})$$

In Eq. II-15, Δx_{gap} and Δx_{str} represent the thickness of the gas gap and the structure, respectively. Similarly, k_{gap} and k_{str} are the thermal

conductivities. Note that in the limit, when both gas-gap and structural thicknesses are zero, the effective heat-transfer coefficient simply reduces to the convective heat-transfer coefficient, h , at the slab surface.

2.2.1.4.1.2. Reference Slab-Target Results

For our analysis of the reference slab target, we assume that the open face of the slab target is cooled via natural convection to the ambient facility air. We likewise assume a macropulse consisting of five individual proton pulses, which should yield an integrated test-article irradiation of 1.05×10^{13} neutrons per square centimeter. The energy deposition per unit mass (per pulse) is calculated from LAHET/MCNP as 360 J/kg. For each macropulse, the specific energy is thus 1,800 J/kg. Based on this value, the adiabatic temperature rise for a single-event or macropulse is approximately 15 K. A summary of key parameters is presented in Table II-4.

If we assume each event recurs at regular intervals (4-, 6-, or 8-h intervals), the transient temperature behavior of the slab target can be predicted using the method described in Sec. 2.2.1.4.1.1. Summing over the first 10 positive roots α_n , we present the transient-temperature results in Fig. II-15. Observe that even at 4-h intervals, the peak target temperature does not exceed 330 K. This result is based on an ambient air temperature of 300 K (80.3°F). To account for daily or seasonal temperature fluctuations, the resultant peak target temperature will merely vary by the same magnitude as the change in ambient temperature from 300 K. Even with substantial fluctuation in the ambient air temperature, the peak target temperature will remain well within our design limits for the U-1.5%Mo target material. Based on this analysis, we conclude that the slab target can easily accommodate two to three test article irradiations per day.

In comparison with the target material, heating rates in the graphite reflector (ranging from 3 to 10 J/kg) produce negligible temperature rises from the pulse itself. In reality, the high heat capacity of the graphite will serve as a sink for energy produced in the slab-target material. Nonetheless, the peak temperature estimates reported in Fig. II-15 should be conservative.

TABLE II-4. THERMAL SOLUTION PARAMETERS

Parameter	Value	Units
Ambient temperature	300	K
Specific energy per pulse	360	J/kg
Pulses per macropulse	5	
Specific energy per macropulse	1800	J/kg
Bulk adiabatic temperature rise per macropulse	15.13	K
Slab thickness	0.24	m
Slab material	U-1.5%Mo	
Thermal conductivity	30	W/m-K
Density	18661	kg/m ³
Specific heat	119	J/kg-K
Surface-heat-transfer coefficient—natural convection to air	30	W/m ² -K

Fig. II-15. Periodic peak-temperature profile as a function of macropulse interval (i.e., natural-convection-boundary condition).

2.2.1.4.1.3. Thermal Parameter Studies

Two cases examined were one in which either forced or natural convection cooling to air is present on the outer surface of the slab target and the other in which forced or natural convection cooling to air is present on the surface of some outer structure. This latter case was motivated by an early mechanical design in which the individual slab-target bricks were completely encapsulated by a "honeycomb" structure, complete with front and rear structural plates. The honeycomb-structure case thus introduces the additional resistance associated with a gas-gap and one-dimensional conduction through the structural material. In Fig. II-16, we present the nondimensionalized peak-target temperatures as a function of time for the various forced-convection and natural-convection cases. The results confirm our intuition in the sense that the heat transfer from the slab is degraded by the addition of a gap and outer structure. Note that this behavior is independent of the specific pulse magnitude.

Fig.

II-16. Nondimensional peak-target temperatures "Theta" following an instantaneous pulse as defined by time-dependent target temperature "T," initial target temperature "Tzero," and ambient air temperature "Tinf."

The temperature "decay times" for the nondimensionalized peak-target temperatures are presented in Table II-5. Again, this behavior is independent of the specific pulse magnitude. However, the conclusion here is not necessarily that we must wait up to a day between pulse events. This issue relates back to the peak temperature limit discussed in Sec. 2.2.1.4. The adiabatic temperature rise for a single event is approximately 15 K. Assuming a maximum temperature limit of 900 K would allow up to ~40 macropulses (200 individual proton pulses) to be fired in rapid succession before cooling is required. Of course, if the next event was to consist of another 40 macropulses, the time required between tests for natural convection on the target surface or an outer structure would be on the order of one to two days. For much smaller macropulses, however, the repetition rate can be substantially greater without violating the maximum temperature limit (as seen in the previous section).

TABLE II-5. CHARACTERISTIC DECAY TIMES FOR NONDIMENSIONAL PEAK-TARGET TEMPERATURES " $\theta(t)$ " AS DEFINED BY TIME-DEPENDENT TARGET TEMPERATURE " $T(t)$," INITIAL TARGET TEMPERATURE " T_0 ," AND AMBIENT AIR TEMPERATURE " T_∞ "

$$\theta(t) = (T(t) - T_\infty)/(T_0 - T_\infty)$$

		$\theta(t) = 0.05$	$\theta(t) = 0.01$
Surface-Cooled U-1.5%Mo	Forced Convection	4 hours	6 hours
	Natural Convection	15 hours	23 hours
Surface-Cooled Outer Structure	Forced Convection	21 hours	31 hours
	Natural Convection	31 hours	47 hours

2.2.1.4.2. Dynamic Stress

With each pulse of the proton beam, energy is deposited in the slab-target material over a fairly short period (2.6 ms for the slab target). This "thermal pulse," if sufficient in magnitude, can produce large dynamic

stresses and ultimately cause fracture in the U-Mo slab-target material. The potential for fracture raises both safety and operational concerns in the current slab-target configuration. With the stacked and interlocked nature of the target bricks, full credit is taken for the strength of the U-Mo alloy (i.e., the brick assembly is considered to be a solid piece). Fracture of one or more bricks could compromise the integrity of the slab-target halves, and ultimately compromise control and safety functions. There are ways to work around this situation, of course. One could consider enclosing the target bricks entirely within a "honeycomb" structure such that the U-Mo is not load bearing (somewhat obviating our concern about fracture). However, a significant quantity of absorbing material (structure) is introduced into the lattice, thus creating a performance penalty. For this reason, we adopt the philosophy that fracture of the target material must be avoided by design.

A first-order method is employed to assess the potential for target fracture. The goal of this work was to provide a simple tool to test various design alternatives in terms of target geometry and material. The analysis methodology is discussed in Sec. 2.2.1.4.2.1, and the reference results are discussed in Sec. 2.2.1.4.2.2.

2.2.1.4.2.1. Analysis Methodology

The maximum temperature of the target material can be estimated from

$$T_{\max} = T_{\text{initial}} + \Delta T_{\text{pulse}} , \quad (\text{II-16})$$

where ΔT_{pulse} represents the adiabatic temperature rise for a single-event, or

$$\Delta T_{\text{pulse}} = \frac{Q_{\text{sp}} \cdot N_{\text{pulse}}}{c_p} . \quad (\text{II-17})$$

In Eq. II-17, Q_{sp} is the specific energy (energy per unit mass) deposited per pulse, N_{pulse} is the number of pulses per single event or macropulse, and c_p is the specific heat of the U-Mo alloy. As discussed in Sec. 2.2.1.4.1, we have assumed that the energy deposition is uniform over the volume of the target element and that heating occurs so quickly that no significant cooling of the slab-target material takes place during the energy deposition.

The maximum pressure in the target is expressed by

$$P_{\max} = \Gamma \cdot \rho \cdot Q_{sp}, \quad (\text{II-18})$$

where Γ is the Gruneisen gamma (a material constant relating the increase in pressure to the increase in internal energy), and ρ is the material mass density.

If there are no relief waves reaching the center of the slab-target element during the heating phase, then the pressure in the central portion of the slab-target element will reach $P_{\max}$. However, if the slab-target element is small enough, relief waves from the outer surface will limit the pressure. This limit can be estimated from

$$P_{\max} = \left(\frac{t_c}{t_e} \right) \Gamma \cdot \rho \cdot Q_{sp}, \quad (\text{II-19})$$

where t_e is the time over which the energy is deposited into the slab-target element. The heating function is assumed to be a square wave—that is, instant on and instant off. The parameter t_c is the characteristic time for the target element. This represents the time required for a relief wave to travel from the free boundary to the center of the target element:

$$t_c = \frac{D_c}{2 \cdot C_o}. \quad (\text{II-20})$$

D_c is the characteristic dimension of the target element; in other words, it is the smallest external dimension of the target element. C_o is the bulk sound speed of the target material, which can be estimated from

$$C_o = \sqrt{\frac{K}{\rho}}, \quad (\text{II-21})$$

where K is the elastic bulk modulus of the material.

Equation II-19 is used for $P_{\max}$ if $t_c \leq t_e$. Otherwise, Eq. II-18 is used. Given $P_{\max}$ determined from either Eq. II-18 or II-19, the peak tensile stress in the target element can be estimated. A geometry parameter (G_p) is used to relate the maximum pressure to the maximum stress,

$$S_{\max} = G_p \cdot P_{\max}. \quad (\text{II-22})$$

This simplification is based on the fact that failure mode is tensile fracture (i.e., the material is at least as strong in compression as in tension) and that the boundaries of the target element are free (i.e., no restraint or pressure applied to the free surfaces of the target element).

If the temperature dependence of the strength of the material is known, the temperature calculated from Eq. II-16 can be used to determine the failure stress for the target element (S_u). The design factor of safety (FS) can then be determined from

$$FS = \frac{S_u}{S_{max}}. \quad (II-23)$$

For ductile materials, $FS \geq 2$ is suggested. For brittle materials, $FS \geq 3$ is recommended.

Finally, we must define the geometric parameter, G_p . After the slab-target element is heated, we assume that it has a uniform internal pressure. When the heating stops (in this case it stops instantly), a rarefaction wave starts into the slab-target element from the free boundary. This rarefaction wave is tensile and approximately equal to P_{max} . For this discussion, positive stress is compressive.

Assuming rectangular geometry, when the rarefaction waves from opposing surfaces collide at the center, they double in magnitude. This tension stress of about $-2P_{max}$ is added to the stress state present in the material at that moment. Earlier in the discussion, we assumed that the material was at a uniform stress state of P_{max} . Given this case, add the rarefaction of $-2P_{max}$ (the rarefaction is tensile), and we get a maximum tensile stress of $-P_{max}$.

However, the stress state in the slab-target element is not really a uniform P_{max} . Because of relief waves entering the slab-target element from the free boundaries during the heating phase, the stress at the center of the element is oscillating from $+P$ (compression) to $-P$ (tension). The rarefaction wave relieves pressure in the target element and subsequently combines with this oscillating stress. Because the oscillating stress is varying from $+P$ to $-P$ and the rarefaction wave is magnitude $-P$ (i.e., doubling on reflection at the center to $-2P$), the maximum tensile stress at the center of a plane

(rectangular) target element is $-3P$. The maximum stress occurs when the oscillating stress at the center of the target element is $-P$ (tensile) as the rarefaction wave arrives and doubles (adds $-2P$) for a total tensile stress of $-3P$. Therefore, the G_p for rectangular slab-target elements is 3. The maximum stress is thus evaluated such that

$$S_{\max} = 3 \cdot P_{\max} \quad (\text{II-24})$$

A difficulty arises in trying to define G_p for spherical and rod shapes. If the heating is turned off instantly, the rarefaction wave becomes a sharp discontinuity traveling from the free boundary toward the center. Conservation requires that the force on each succeeding spherical (or cylindrical) differential element be equal. The rarefaction wave must therefore increase in magnitude as it travels toward the center of the slab-target element. At the center of the element (for spheres and rods), the area is 0 and the stress is theoretically infinite, even for very small pressures. This case is not experienced in practice because the loading (heating) does not shut off instantly but decays over some finite period of time. For this simple model, however, the geometric parameter for spheres and rods is infinite. As such, this model is not sufficient for spherical and rod-shaped slab-target elements.

2.2.1.4.2.2. Reference Slab-Target Results

Based on current estimates for the energy deposition per pulse (360 J/kg) and the approximate pulse duration (2.6 ms), we can compute the peak dynamic stress induced within the slab-target material from the method described in the preceding section. At present conditions, the recommended design stress (maximum stress multiplied by a safety factor of 2.0) is 1.3 MPa. This design stress is based on a characteristic dimension of 24 cm, or the thickness of the target material. Detail of the key analysis parameters is provided in Table II-6. If we examine strength versus temperature data for U-10%Mo (see Fig. II-14), we conclude that peak target temperatures of 900 to 1,000 K can be accommodated at this design stress. A future action item is to review the literature for similar strength versus temperature data for U-1.5%Mo and ascertain the above peak-temperature limit. Nonetheless, we believe the dynamic stress issue is of relatively minor importance at the reference design conditions.

TABLE II-6. SLAB-TARGET-ELEMENT DYNAMIC STRESS
PARAMETERS

Parameter	Value
Γ , Gruneisen gamma	2.0
ρ , nominal density (kg/m ³)	18661
C_o , bulk sound speed (m/s)	2900
c_p , specific heat (J/kg-K)	119
FS, design factor of safety	2.0
D_c , characteristic dimension (m)	0.24
Q_{sp} , specific energy deposition (J/kg)	360
t_e , pulse duration (s)	2.60×10^3
t_c , characteristic time (s)	4.14×10^5
G_p , geometry parameter	3.0
P_{max} , maximum pressure (MPa)	0.214
S_{max} , maximum stress (MPa)	0.642
Design Stress, $FS \cdot S_{max}$ (MPa)	1.28
T_{max} , maximum temperature (K)	303.0

2.2.2. Cylinder Target

The cylinder-target concept consists of an annular, blind-hole region of fissile material with a central irradiation cavity. This arrangement is proposed to simulate an omnidirectional source of neutrons for pits and other potential test articles. The specific design requirements for the cylinder target are discussed in Sec. 2.2.2.1. The reference design is presented in Sec. 2.2.2.2. Physics and mechanical analyses in support of the reference design (including parametric studies) are addressed in Secs. 2.2.2.3 and 2.2.2.4, respectively.

The results presented in this section for the reference cylinder assembly with $k_{pr} = 0.98$ are extrapolated from calculations for a similar configuration with $k_{pr} = 0.9935$. Therefore, some parameters, such as the target-annulus thickness, are not exact values but are estimates based on the computed design. Because the described reference assembly differs only

slightly from the assembly that was calculated, the reported reactivity worths are not expected to differ significantly between the two configurations.

2.2.2.1. Design Requirements

Like the slab target, the cylinder-target concept was designed to satisfy the same key requirements for total fluence and neutron-spectrum fidelity. Specifically, we require that the target system supply 1×10^{13} neutrons/cm² in the central irradiation cavity, 50 cm in diameter and 60 cm high. In terms of fidelity, the incident neutron flux should have an energy-dependence characteristic of a fission spectrum. Also, note that we assume the system is operated in a pulsed mode but without any specific requirement on the neutron pulse width.

Based on the fundamental design requirements specified above, we devised additional design requirements among the following categories: incident proton beam, cylinder geometry, cylinder-target material, safety, security, and operations. Like the slab target, we designed the cylinder target to be compatible with the LAMPF supply of 800-MeV protons (3×10^{13} protons/pulse). To achieve the desired neutron fission spectrum, we require a fissile target material (U-1.5%Mo). Selection of the U-Mo target material was identical to the slab-target concept and is discussed in Sec. 2.2.1.2.3.1. The height and internal diameter of the fissile material were chosen to correspond to the dimensions of the irradiation cavity. In terms of safety, a subcritical assembly ($k_{pr} = 0.98$) with multiple/diverse methods of control and/or shutdown is needed. With respect to materials-access security, the enrichment of the uranium should be at or below 19.9% (see Sec. 2.2.2.2.4), and the target must be stored in a locked concrete vault when not in use. Operationally, we would like to be able to irradiate two to three test articles per day with acceptable thermal management.

2.2.2.2. Reference Cylinder-Target Concept

2.2.2.2.1. Reference-Cylinder-Target-Concept Description

The annular-target conceptual design proposed for the ADA project is illustrated in Fig. II-17. This concept provides a cylindrical irradiation cavity with a diameter of 50 cm and a height of 60 cm. The cavity is encompassed radially by a U-1.5%Mo multiplying annulus that is 19.9 atom% enriched in ²³⁵U. This annulus is constructed of curved interlocking bricks that have a radial thickness of about 6.5 cm. Additionally, a 5-cm-thick circular slab of uranium alloy closes the bottom end of the target cylinder. This target floor is

not attached to the annular region. Graphite positioned beyond the fuel regions provides neutron reflection and thus enhances the neutron economy of the system. Radially, an annular slot used to incorporate reactivity control features is positioned between the multiplying target and the graphite.

Fig. II-17. ADA cylinder-target concept in its operational configuration.

Neutron multiplication in the annular target is induced by an 800-MeV proton beam. Note that the axis of the cylinder target is oriented perpendicular to the beam path. Directing the beam through a peripheral region of the target ring, where the line-of-sight path through the dense multiplying material is maximized, provides adequate proton-beam stopping mass (refer to Sec. 2.2.1.3.3).

Like the slab target, the conceptual cylinder target is designed to provide a prompt-neutron multiplication factor of 50. To adjust the reactivity of the assembly, we employed two diverse methods of reactivity control.

First, the reflector annulus that encompasses the target is segmented into six equal 60° segments. Although three of the segments are stationary, reactivity control of the assembly is achieved by the remote translation of the other three segments, as depicted in Fig. II-18. Each mobile reflector segment is controlled by an independent drive. Actuators connected to a control system automatically return the segments to their least-reactive ("out") position upon power loss or by a signal received from the control system. Conceptually, this is accomplished, as illustrated in Fig. II-19, by sloping the reflector-segment support plate so that the actuators must be energized to position the segments near the target. When the actuators become de-energized, natural forces cause the outward translation of the reflector segments. Alternatively, springs or pneumatic actuators could be used to accomplish the outward translation.

Fig. II-18. Top cutaway view of the cylinder concept, showing two of three mobile reflector segments translated outward from the multiplying annulus. Three of the six reflector segments are stationary.

Fig. II-19. Mobile radial-reflector-actuator concept.

Reactivity control can also be accomplished by adjusting remotely the position of the lower fissile floor and its associated graphite relative to the target annulus. This translation is shown in Fig. II-20. As the drive system lowers the fissile floor away from the independently supported annulus, the reactivity of the assembly decreases. This drive system is similar to that described for the separated slab target. To raise the target floor, the lift must be energized. When de-energized via power loss or control-signal receipt, the drive automatically returns the floor to its least-reactive (lowest) position.

Fig. II-20. Cutaway views of the ADA cylinder concept, showing the floor in its raised operating configuration (a) and in its lowered position (b).

Neutron-absorber blades also provided render the ADA cylinder target deeply subcritical. An isolated poison blade is shown in Fig. II-21. The slot between the target and the stationary reflector regions incorporates three curved, neutron poison blades, each 60°, for safe storage of the target and for emergency shutdown of the assembly. The blades, which reside above the target assembly during operation, are constructed of enriched B₄C clad in stainless steel. A signal from the control system or loss of power causes the blades to be released and slide via gravitational forces into position between the stationary graphite and the fuel. Each blade is independently controlled. The safety blades in their inserted and retracted positions are illustrated in Fig. II-22.

Fig. II-21. Safety-blade design for the ADA cylinder-target concept.

When in its storage alcove, the ADA cylinder-target assembly will be in its least-reactive configuration—that is, the three mobile reflector segments and the target floor will all be positioned 20 cm from the target annulus, and the three absorber blades will occupy the slot between the target annulus and the stationary reflector segments.

Fig. II-22. Safety blades in their retracted (a) and inserted (b) positions.

Like the slab assembly, the ADA cylinder target is mounted on a stainless-steel cart. When experimenters are ready, a remotely operated drive system transports the target assembly along floor-mounted rails to its experimental position. Power, instrumentation, and any other necessary utilities are tethered to the cart. After the experiment is finished, the assembly and associated utilities are remotely returned to the shielded storage room.

2.2.2.2.2. Control Functions and Philosophy

The control philosophy that influenced the design of the ADA cylinder target is the same as that presented for the slab target (Sec. 2.2.1.2.2). As discussed previously, distance is used as the principal safety feature. And, like for the slab target, a combination of an exclusion region around the facility during operations and remote positioning and control of the target helps to provide a distance barrier between the test irradiation and personnel.

For the cylindrical design, separation of the assembly into several large components is accomplished in four ways. First, three large reflector segments can be independently translated away from the fissile target

annulus in the storage configuration. Also, the target floor is dropped down from the rest of the assembly for storage.

Fine reactivity control of the cylindrical assembly is provided through neutron leakage. Each of the three mobile reflector segments can be operated independently, thus providing three leakage/control mechanisms. Each segment is worth several dollars of reactivity. Another separate leakage mechanism is the translatable target floor/axial reflector. Lowering of the floor by 20 cm, its maximum distance, provides about 7\$ of negative reactivity worth.

Another safety feature incorporated into the ADA conceptual design is the three independently controlled safety blades. Each blade, when inserted, reduces the reactivity of the system by over 3\$.

Interlock design and philosophy will be addressed during the preliminary design phase of this project.

2.2.2.2.3. Materials Issues

The same materials are proposed for the cylinder target as for the slab target. Therefore, the material issues presented in Sec. 2.2.1.2.3 apply to the cylinder target as well.

2.2.2.2.4. Special Nuclear Material Issues

Like the slab-target concept, one of our key derived-design requirements for the cylinder target was to adopt a uranium enrichment of 19.9% or less. This decision was entirely dictated with respect to the SNM categorizations cited in the *Nuclear Materials Control and Accountability Procedural Handbook* (Ostenak 1992) and DOE Order 5633.3. Considering the size and enrichment of the cylinder target, approximately 290 kg of ^{235}U are present (not unlike the slab concept). For additional detail regarding the enrichment decision or SNM categorizations, please see Sec. 2.2.1.2.4.

2.2.2.3. Physics

Please refer to Sec. 2.2.1.3.

2.2.2.3.1. Analysis Model and Methodology

The MCNP and LAHET codes were the primary tools used for this analysis (see Sec. 2.2.1.3.1). For this cylindrical configuration, each eigenvalue calculation typically followed either 2 million or 4 million particle histories, depending on the desired precision of the estimated k_{eff} . For nearly all calculations, the stated 1- σ relative error was again less than 0.1%.

Figures II-23 and II-24 display plan and elevation views, respectively, of the three-dimensional MCNP model used to analyze the ADA cylinder target. The U-1.5%Mo active regions are modeled as an annular shell and a separate circular floor plate. For design purposes, the model of the cylinder target assumes that a fissile test article, which is inserted into the test cavity, contributes to the reactivity of the system.

Fig. II-23. Plan view of the MCNP model used to analyze the ADA cylinder target.

Radially encompassing the target annulus is the segmented graphite radial reflector. Through the use of transformation surfaces, three of the radial reflector segments can simulate any desired translated position. The lower axial reflector is also explicitly represented. When target floor movement is modeled, the associated graphite beneath the floor is also translated.

Fig. II-24. Elevation view of the MCNP model used to analyze the ADA cylinder target.

The three safety-blade regions are also represented by the MCNP geometry. When the blades are retracted, the slot between the target annulus and the reflector is void. When inserted, the three 1-cm-thick enriched B₄C absorber plates clad in stainless steel occupy the slot. In this model, the mechanical attachment features of the safety blades are not represented. However, this simplification is not expected to affect the results significantly.

2.2.2.3.2. Reference Cylinder-Target Results

According to the LAHET/MCNP extrapolated results for the cylinder-target configuration with a prompt multiplication of 50, the neutron flux at the midplane of the test cavity is about 5.5×10^{12} neutrons/cm²/pulse. Thus, the goal fluence of 1×10^{13} neutrons/cm² is met by providing two beam pulses to the neutron-multiplying cylinder target.

In addition to the reference configuration, MCNP models were created to estimate the reactivity worth of the mobile reflector segments and fissile floor as a function of distance and to evaluate the effectiveness of the control blades. Reactivity feedback effects from the storage vault and from various test materials were also computed.

Figure II-25 displays a graph of the reactivity decrease induced by the translation of one and three reflector segments simultaneously. At a

separation distance of 20 cm, the magnitude of the reactivity reduction caused by the translation of a single reflector segment is about $0.03523 \pm 2.19\% \Delta\rho$ (5.42\$), whereas that induced by all three segments is about $0.11579 \pm 0.23\% \Delta\rho$ (17.81\$). Similarly, the reactivity decreases as the fissile floor and the graphite reflector below it are lowered away from the annular target region. At a separation distance of 20 cm, the magnitude of this decrease is about $0.04894 \pm 1.50\% \Delta\rho$ (7.53\$). This relationship between reactivity decrease and floor position is also shown in Fig. II-25.

Fig. II-25. Negative reactivity worth as a function of separation distance for several cylinder-target control mechanisms.

Next, the reactivity worth of the safety blades was evaluated. A single 60° curved safety blade inserted between the fuel and a stationary reflector segment yields a negative worth of about $0.02177 \pm 3.04\% \Delta\rho$ (3.35\$). The insertion of all three blades causes a reactivity drop of approximately $0.07775 \pm 0.96\% \Delta\rho$ (11.96\$).

Next, the relative effect of various materials inside the test cavity was examined. Because all the test objects were selected to be 8-cm-diam spheres, these comparisons do not necessarily envelope those test-article configurations that cause the greatest change in reactivity. Instead, the evaluations provide us with the relative worth for test objects of the same size. Compared with an empty (void) test cavity, a beryllium sphere induces a reactivity increase of $0.00117 \pm 104\% \Delta\rho$ (0.18\$); a stainless steel sphere of $0.00045 \pm 225\% \Delta\rho$ (0.07\$); and a fissile sphere of $0.02830 \pm 3.73\% \Delta\rho$ (4.35\$). The reactivity must therefore be adjusted by at least $0.03 \Delta\rho$ ($\approx 5\%$) to maintain a prompt multiplication factor of 50 for any proposed test article.

Finally, the cylinder-target model was enclosed in a small, ordinary concrete vault with 30-cm-thick walls. The distance from the target assembly to the walls of the vault is 50 cm in all directions, the segments are closed, the floor is raised, and the poison blades are retracted. In other words, the assembly is in its most-reactive configuration. The calculated increase in reactivity of the system is about $0.03501 \pm 2.36\% \Delta\rho$ (5.38\$). According to previously discussed calculations, the safety blades should be able to counteract this feedback effect easily, and lining the walls of the vault with several inches of borated polyethylene will reduce the increase in reactivity of the system. Because of this relatively strong reactivity feedback from the vault walls, we will provide interlocks to ensure that the safety blades are inserted before the assembly can be moved into the vault region.

Although no temperature-coefficient calculation was explicitly calculated for this configuration, we expect the coefficient to be negative and of the same order ($\approx 3 \times 10^{-6} \Delta k / ^\circ\text{C}$) as the slab concept because the materials are nearly identical, the spectrum is similar, and the temperature range is comparable. The temperature coefficient of reactivity is governed primarily by neutron-interaction cross sections and by material properties (such as the thermal coefficient of expansion); therefore, we expect the geometric difference between the two assemblies to have little effect on the temperature coefficient.

Reactivity characterizations for the cylinder target, if selected, would be similar to those of the slab target described in Sec. 2.3.

2.2.2.3.3. Physics Parameter Studies and Results

Parametric studies add to our understanding of the cylinder-target conceptual design. A couple of these are discussed below.

First, Fig. II-26 shows the relationship between the reactivity and the 19.9%-enriched U-1.5%Mo thickness. The test cavity size, reflector thickness (6.648 cm), and fissile floor thickness (5 cm) are constant throughout this investigation. For a ^{235}U enrichment of 19.9%, the annular region of the target must be about 6.5 cm thick to provide the required neutron multiplication.

Fig. II-26. Reactivity (shown with 2- σ error bars) versus target-annulus thickness for the cylinder-target design.

Illustrated in Fig. II-27 is the relationship between ^{235}U enrichment and reactivity. For this study, the U-1.5%Mo uranium-alloy annulus was kept at a constant value of 6.648 cm.

Fig. II-27. Reactivity (shown with 2- σ error bars) as a function of ^{235}U enrichment for the cylinder-target concept.

2.2.2.4. Mechanical Design Issues

The two principal mechanical issues for the cylinder target are the thermal performance of the U-Mo alloy and the dynamic structural behavior of the material under periodic, pulsed conditions. Because these issues were discussed in Sec. 2.2.1.4 for the slab target, that discussion will not be repeated here. Like the slab target, we expect the thermal and dynamic stress characteristics of the cylinder target to be fairly benign.

In this regard, we have chosen a simple thermal-management strategy that uses no active components. The cylinder target is merely cooled via its open surfaces by natural convection to air at ambient room temperature. For modest cycle times for experiments (two to three irradiations per day), we expect passive cooling to be completely adequate. This assertion, however, has not yet been confirmed by direct calculation. Should passive cooling prove inadequate, we are free to consider either an

active cooling system or a reduction in the energy deposition per pulse (achieved via a reduction in the prompt neutron eigenvalue k_{pr}).

2.2.2.4.1. Thermal Performance

Simple adiabatic temperature rises per pulse were computed for the annular target material and the hypothetical spherical test article. Energy deposition rates and the adiabatic temperature rises are given in Table II-7. These estimates would imply that a single-pulse event that produces 1.7×10^{13} neutrons/cm² ($k_{pr} = 0.9935$) causes a benign thermal transient and poses no significant thermal challenge for a few irradiations per day. When k_{pr} is lowered to the reference value of 0.98, the thermal transient becomes even less significant.

TABLE II-7. ADIABATIC TEMPERATURE RISES BY REGION IN THE ANNULAR TARGET GEOMETRY

Region	Material	Heating Rate (per pulse)	Specific Heat (J/kg-K)	Adiabatic Temperature Rise (K)
Target sides (annular region)	U-1.5%Mo	360 J/kg	119	3.03
Target bottom	U-1.5%Mo	480 J/kg	119	4.03
Test article	Pu	4620 J/kg	132	35.0

2.2.2.4.2. Dynamic Stress

Because the temperature rise in the annular target is smaller than that of the slab target under similar irradiation, the dynamic stress of the annular target should also fall well within the acceptable performance regime. Explicit calculations for this geometry, however, have not been produced to date.

2.2.3. Weapons Neutron Research Facility Target-4: A Supplement to Accelerator Driven Assembly

As an alternative to the ADA facility and targets discussed above, we investigated the possible modification of the existing LAMPF WNR Target-4 to generate a neutron fluence that would enhance our ability to simulate

weapons neutron effects on various defense objects or components. Using an existing experimental facility may provide a quick, convenient, and relatively economical neutron source for weapons-effects testing. Our reference approach was to insert a duplicate of the 77.5%-enriched uranium target built for the IPNS facility at ANL. In an attempt to limit confusion between the WNR and IPNS facilities, we will henceforth refer to the reference enriched uranium target for WNR Target-4 as PINS. Design requirements and the reference concept description are presented in Secs. 2.2.3.1 and 2.2.3.2, respectively. Discussion of the physics performance of PINS is presented in Sec. 2.2.3.3. Note, however, that our investigation of the WNR facility did not end with the enriched uranium target alone. Alternative uranium-, tungsten-, and lead-target concepts were also investigated and appear attractive from the standpoint of simplicity. Detail of these parameter studies is discussed in Sec. 2.2.3.3.3. Finally, a brief discussion of those issues pertaining to the mechanical integration of the target concept with the existing WNR facility is presented in Sec. 2.2.3.4.

2.2.3.1. Design Requirements

It is assumed that the PINS target assembly will be placed in the pre-existing, unmodified, experimental Target-4 of the WNR. A schematic of Target-4 is provided in Fig. II-28. For this investigation, we assume that the test article is located 800 cm from the PINS target. This distance, which is 175 cm outside the concrete shielding region of Target-4, provides ample room for the positioning of the experiments. For test objects that can be placed closer than 800 cm to the target, the flux predictions presented here will be conservative (i.e., underestimated).

Design of the PINS target and its associated water-cooling hoses is constrained by the Target-4 geometry. Access to the crypt region where the target is irradiated is through one of two off-axis holes in the top of the target crypt (not shown in Fig. II-28). At its narrowest point, the diameter of this access hole is only 26.5 cm. Through this access porthole, the target must be placed into the crypt, connected to its cooling equipment, and correctly positioned in the beam path.

During irradiation, the target is struck by an untailed 800-MeV proton beam that has a diameter of 5 cm. The intensity of this beam exhibits a Gaussian radial spatial distribution with 90% of the protons appearing within a 3-cm diameter. Using the described proton beam, our goal is to deliver a

1-MeV silicon-damage-equivalent neutron fluence of 1×10^{12} neutrons/cm² during a total irradiation period of 30 minutes to a test article that is 800 cm from the target. The silicon-damage-equivalence relationship is discussed in more detail in Sec. 2.2.3.3.3.1. This response function, which relates an energy-dependent neutron flux to degradation of silicon transistors, was chosen because one projected use of the PINS is to determine irradiation effects on electronic components.

Fig. II-28. Model of the Target-4, the crypt, flight-path tubes, and the experimental location. All dimensions are in centimeters. Parameters r and l refer respectively to the radius and length of each piece of the target and flight path.

2.2.3.2. Reference Target-4-Concept Description

The PINS concept is directly related to an enriched uranium booster that was developed by ANL and used in their IPNS facility. When the enriched uranium booster was placed in the IPNS facility at ANL, fission and spallation in the target were produced by a 450-MeV proton beam.

The IPNS target is of interest to ADA for several reasons. First, it is small enough to fit into the Target-4 area. Second, because the target includes fissile multiplying material (enriched uranium), neutrons irradiating the experiment originate from fission and, consequently, are characterized by a fission energy spectrum. When the silicon-damage-equivalent response function is used, this fission flux can be related to the resultant damage in electronic components. Third, the IPNS target exists, has been tested, and is

relatively inexpensive to purchase. For these reasons, an IPNS-like target placed at Target-4 is our reference concept for enhancing the LAMPF WNR weapons-effects test facility.

The calculations described in this report were initiated to determine whether this water-cooled IPNS target, or a simple modification of the target, can produce our goal neutron flux from a LAMPF 800-MeV proton beam. If so, the IPNS is potentially a quick, convenient, and economical neutron source for the ADA.

2.2.3.3. Physics

2.2.3.3.1. Analysis Model

The IPNS target is described in the March 1991 revision of the *Final Safety Analysis Report (FSAR-II) for the Intense Pulsed Neutron Source Facility For Operation With The Enriched Uranium Booster Target* (Schulke 1991). Using information gathered from this document, we have modeled the uranium target, its cooling passages, and its elliptical housing. Cross-sectional and elevation views of the analysis model are shown in Figs. II-29 and II-30, respectively. Although based upon the enriched uranium target used in the ANL IPNS facility, the target proposed for use in Target-4 is referred to as PINS.

The material compositions and densities used to model the PINS target are presented in Table II-8. Some of the compositions are well documented in the reference IPNS document; others are estimates based on engineering practices.

Fig. II-29. End view of the model of the PINS target and housing.

Fig. II-30. Side view of the model of the PINS target and housing.

TABLE II-8. MATERIAL COMPOSITIONS USED IN THE PINS
MODEL

Material	Density (g/cm ³)	Isotope	Fractional Composition
Enriched uranium	18.77	C	0.045 wt%
		Si	0.035 wt%
		Fe	0.025 wt%
		²³⁴ U	0.589 wt%
		²³⁵ U	77.5 wt%
		²³⁸ U	21.806 wt%
Zircaloy-2	6.49	Cr	0.1 wt%
		Fe	0.15 wt%
		Ni	0.05 wt%
		Zr	98.2 wt%
		Sn	1.5 wt%
304 Stainless Steel	7.996	C	0.08 wt%
		Si	1.0 wt%
		³¹ P	0.045 wt%
		³² S	0.03 wt%
		Cr	19.0 wt%
		⁵⁵ Mn	2.0 wt%
		Fe	67.845 wt%
		Ni	10.0 wt%
Water	0.988	¹ H	66.657 atom%
		² H	0.01 atom%
		¹⁶ O	33.333 atom%
Water/304SS mix	3.0904	Water	70 vol%
		304SS	30 vol%
Tungsten	19.3	nat'l W	100%
Boron-copper	5.65	¹⁰ B	3.82 wt%
		¹¹ B	16.89 wt%
		Cu	79.29 wt%
Graphite	1.74	C	100%

2.2.3.3.2. Reference Pulsed Intense Neutron Source Results

To reach the experimental location, neutrons emanating from the PINS target must travel through a series of flight-path tubes (see Fig. II-28) that are embedded in the Target-4 shielding. This collimation influences the physical size and spatial distribution of the resultant neutron-irradiation field at the experimental location. To characterize these collimation effects, we computed the collimated and uncollimated 1-MeV silicon-damage-equivalent neutron flux in five circular zones (radii = 11, 22, 33, 44, and 55 cm) at the experimental location. The results are shown in Fig. II-31. For the geometric configuration pictured earlier in Fig. II-28, the PINS target assembly, when struck by an 800-MeV proton beam, produces a uniform, collimated neutron flux at the experimental location with a characteristic radius of approximately 25 cm. As evidenced by Fig. II-31, the magnitude of the collimated neutron flux falls rapidly beyond the 25-cm radius value.

Fig. II-31. The PINS uncollimated and collimated 1-MeV silicon-damage-equivalent neutron flux at the experimental location.

Neutrons from a fission nuclear-weapon explosion have a somewhat degraded fission energy spectrum. In Figs. II-32 and II-33, we compare a ^{235}U fission spectrum with the neutron spectrum that emanates from the PINS target when it is struck by the 800-MeV LAMPF proton beam. (These three graphs also include a curve labeled "tungsten PINS." This curve relates to an alternative concept that is discussed in Sec. 2.2.3.3.3.2.) To make this spectral comparison, we have normalized the ^{235}U fission spectrum and the neutron spectrum at the center of the experimental irradiation area so that each total-energy integrated flux is equal to 1. Figure II-32 compares the normalized spectra, and Fig. II-33 provides a magnified view of the upper energy range of the spectra where the silicon-damage-equivalent response function is most sensitive. (Please see Sec. 2.2.3.3.3.1.) Figure II-34 displays plots of the cumulative spectra. As evidenced by these graphs, neutrons that reach the experimental station exhibit a softer energy spectrum than newly born ^{235}U fission neutrons. This softening of the neutron spectrum occurs as the neutrons suffer collisions before escaping from the PINS target and as they travel to the experimental area.

Analyses indicate that the PINS target, placed in the WNR facility and struck by an 800-MeV proton beam, can produce our goal of 1×10^{12} neutrons/cm² of 1-MeV silicon-damage-equivalent neutrons at a distance of 800 cm from the target. A summary of the results is presented in Table II-9. Three operational modes, each responding to a different constraint, were examined. First, assuming a maximum practical proton current limit of 20.0 μA , we calculated the resultant heat-generation rate, as well as the irradiation time required to reach the goal fluence. Second, we constrained the heat generation rate to 63 kW (i.e., the existing target design value) and calculated the associated proton-beam current and required irradiation time. Third, the time to reach goal fluence was set at 30 minutes, and the required proton current and resultant heat generation were computed.

Fig. II-32. Normalized neutron spectra from ^{235}U fission and from an unreflected PINS (fissile) target at an orientation of 90° and distance of 800 cm from the target. Also shown is the normalized neutron spectrum from a nonfissile spallation target (i.e., unreflected PINS with tungsten substituted for uranium) at the same orientation and distance.

Fig. II-33. Upper-energy region of the normalized neutron spectra from ^{235}U fission and from an unreflected PINS (fissile) target at an orientation of 90° and distance of 800 cm from the target. Also shown is the upper-energy region of the normalized neutron spectrum from a nonfissile spallation target (i.e., unreflected PINS with tungsten substituted for uranium) at the same orientation and distance.

Fig. II-34. Cumulative, normalized neutron spectra from ^{235}U fission and from an unreflected PINS (fissile) target at an orientation of 90° and distance of 800 cm from the target. Also shown is the cumulative, normalized neutron spectrum from a nonfissile spallation target (i.e., unreflected PINS with tungsten substituted for uranium) at the same orientation and distance.

Examination of the results tabulated below shows the trade-off among the three constraints. By applying the maximum practical proton current (assumed to be $20.0\ \mu\text{A}$), the irradiation time required to reach the goal fluence is significantly lower than our self-imposed goal of 30 minutes. However, the resultant heat generation is 32% greater than the design value of 63 kW. This increase could require design changes to the existing target. We also find that the heat-generation design value for the existing target (63 kW) provides adequate cooling capacity for a $15.2\text{-}\mu\text{A}$ beam. Additionally, this combination of current and cooling capacity allows us to reach goal fluence well within our 30-minute time frame. Finally, by allowing ourselves 30 minutes to irradiate the target, the cooling requirements are reduced from the design value by 8 to 9%, and the required proton current decreases to $13.9\ \mu\text{A}$.

Therefore, we conclude that we can reach the irradiation goal with a PINS target without exceeding proton-current limits and without redesigning the PINS cooling. Although one can reach goal a little faster using the

maximum practical proton current, such a goal would require some redesign of the PINS cooling.

TABLE II-9. PREDICTED PINS TARGET PERFORMANCE

Feature	Proton Current (μA)	Heat Generation (kW)	Time to Goal (minutes)
Use maximum practical current	20.0	82.9	20.9
Use design heat removal of 63 kW	15.2	63.0	27.4
Use 30-minute irradiation time	13.9	57.6	30.0

2.2.3.3.3. Physics Parameter Studies and Results

2.2.3.3.3.1. Silicon-Damage Function

We have assumed that the neutron flux from the WNR Target-4 will be used to determine irradiation effects on electronic components. One common way to assess component damage is to measure the reduction in the current gain of silicon bipolar transistors. This current degradation is correlated with the volume displacement kerma in bulk silicon caused by neutron bombardment. Consequently, we decided to convert the computed neutron-fluence spectrum to a 1-MeV-equivalent neutron fluence for silicon using American Society for Testing and Materials (ASTM) Standard E 722 - 93 (ASTM 1993). The specific-silicon-damage (response) function, $F(E)$, that we used to weight the computed neutron spectra is shown in Fig. II-35. Note that, in general, high-energy neutrons cause more damage to the silicon than lower-energy neutrons and are therefore weighted more heavily. This 1-MeV-equivalent damage function provides a figure of merit (FOM) that facilitates comparison of irradiation from various target configurations. The 1-MeV equivalent neutron fluence for silicon is computed as

$$\Phi_{\text{equivalent}} = \frac{\int_0^{\infty} \Phi(E)F(E)dE}{95} , \quad (\text{II-25})$$

where $F(E)$ is the energy-dependent response function, and $\Phi(E)$ is the energy-dependent neutron flux.

Fig. II-35. Silicon-damage function.

2.2.3.3.2. Target Alternatives for Target-4

During our investigations, we compared the projected performance of the reference PINS target with that of several alternative Target-4 configurations. This comparison is presented in Table II-10. In the table, we refer to the reference concept as the bare PINS. Recall that it is designed to remove 63 kW of heat. The first alternative target listed in the table is a solid uranium cylinder. This cylinder target is composed of solid uranium (with the same enrichment as the PINS) and has the same uranium radius as the PINS; however, its length is increased to be comparable with that of the reference target to reduce exit-face proton leakage to below the side-surface leakage. The present-tungsten-target configuration is an accurate representation of the target currently being used at Target-4. Listed in Table II-10 as the third and fourth target alternatives, respectively, are the optimized-solid-W-cylinder and the optimized-solid-Pb-cylinder cases. These are simple cylinders with their lengths and radii optimized to produce a maximum uncollimated neutron flux at the experimental location. The W-for-U case substitutes tungsten for the uranium in the bare PINS. This case

also is referred to earlier in this document as the tungsten PINS (see Fig. II-34). The reflected-PINS case assumes that the reference target is imbedded in a 40-cm-radius sphere of graphite. The cone-void case assumes that a 22.5° cone-shaped void region penetrates the reflector of the reflected-PINS configuration. This void cone is oriented so that neutrons directed toward the experiment do not have to pass through the reflector region.

TABLE II-10. COMPARISON OF TARGET-4 ALTERNATIVES
IN A 20- μ A, 800-MeV PROTON BEAM

Target Description (diameter x length, cm)	k_{eff}	Heat Generation (kW)	Time to Goal ¹ (minutes)
Bare PINS (reference concept) (10 x 19)	0.730	82.9	20.9
Solid uranium cylinder (10 x 25)	N/A	105.6	17.6
Present tungsten target ² (3 x 7.5)	N/A	16.0	134.3
Optimized solid W cylinder (10 x 27.5)	N/A	16.0	74.9
Optimized solid Pb cylinder (17 x 40)	N/A	16.0	59.9
W-for-U in the bare PINS (10 x 19)	N/A	16.4	86.1
Graphite reflected PINS (10 x 19)	0.919	360.6	57.8
Cone void in the reflector of the PINS	0.906	312.9	25.4

¹ The goal is to provide a 1×10^{12} neutrons/cm² fluence of 1-MeV silicon-damage-equivalent neutrons at an orientation of 90° and a distance of 800 cm from the target.

² The 800-MeV proton beam on this target was 2.6 cm in diameter and exhibited a Gaussian radial spatial distribution. Ninety percent of the protons were within a diameter of 1.5 cm. The 800-MeV proton beam on all other targets was 5 cm in diameter with a Gaussian radial spatial distribution in which 90% of the protons were within a 3-cm diameter.

Assuming a 20- μ A, 800-MeV proton beam, the computed heat-generation rate and the time to reach the goal irradiation fluence for each target are tabulated in Table II-10. Several observations can be made by

reviewing these results. First, compared with the bare PINS, reflected versions of the PINS take longer to reach the goal fluence while generating three or four times more heat from fission than the reference PINS. Second, compared with nonfissile targets, fissile targets require shorter irradiation times to reach goal, but they generate much more heat that must be removed. In addition, fissile targets have higher costs, more safety concerns, increased operational complexity, tougher decommissioning problems, and so forth. The third observation concerns the beam stopping power of the PINS. The PINS was designed by ANL to accommodate 450-MeV protons. Compared with the bare PINS, the solid-uranium-cylinder results help to identify what dimensional and design changes might be needed if the PINS must be constructed to stop 800-MeV protons. Fourth, by comparing the present-tungsten-target case to the optimized-solid-W-cylinder case, we find that geometric optimization yields almost a factor of 2 improvement to the performance of the current Target-4 design. Fifth, a lead (Pb) target appears to offer a slight neutronic improvement over a tungsten (W) target. Sixth, comparison of the optimized-solid-W cylinder and the W-for-U PINS cases indicates that cooling a target may induce about a ~15% time-to-goal penalty to the target-performance parameters. Seventh, by comparing the bare-PINS reference case to the W-for-U case, we conclude that although the nonfissile target heat-generation rate is ~5 times less than that of a fissile target, the time-to-goal parameter for the nonfissile target is ~4 times longer than its fissile counterpart.

Comparing the performance of fissile and nonfissile targets, we naturally assumed that the neutron spectrum originating from a fissile target will more closely match a fission spectrum than the spectrum originating from a nonfissile target. We checked this assumption by plotting the neutron spectra (at the center of the experimental irradiation area) that resulted from the bare-PINS fissile target and from the W-for-U PINS nonfissile target and compared them with the ^{235}U fission spectrum. These plots appear in Figs. II-32, II-33, and II-34. Contrary to intuition, the neutron spectra from fissile and nonfissile targets are similar, and they appear to match the ^{235}U fission spectrum equally well.

From our alternative-targets study, we conclude that if the time-to-goal parameter is not crucial and/or if the proton current can be easily increased, then nonfissile targets seem to be the preferred choice. Conversely,

if the time-to-goal parameter is important and/or the proton current cannot be easily increased, then fissile targets may be the more desirable option.

2.2.3.3.3. Pulsed Intense Neutron Source Enrichment Variation

As the ^{235}U content of uranium increases, the associated operational, safety, and regulatory problems increase dramatically (see Sec. 2.2.1.2.4.) We therefore decided to characterize how the PINS performance varies with enrichment. With this information, designers and implementors can balance performance benefits versus operational complications.

The performance of several PINS targets with varying uranium enrichment values is summarized in Table II-11. These results were computed using a uniform 9-cm-diam proton beam and are based on an unweighted neutron flux tally. Consequently, these results are not precisely consistent with the previous reference concept calculations presented in this report. Nevertheless, the performance versus enrichment trend is clearly established. At lower enrichments, less heat is generated in the target and longer irradiation times are required to achieve the fluence goal. For example, if one were to use the more benign enrichment of 19.9 wt% rather than the reference concept value of 77.5 wt%, then the time to goal would nearly double, but the k_{eff} and cooling requirements would dramatically decrease.

TABLE II-11. VARYING THE BARE PINS ENRICHMENT
IN A 20- μA , 800-MeV PROTON BEAM

Enrichment	k_{eff}	Heat Generation (kW)	Time to Goal (minutes)
19.9 wt%	0.360	36.5	40.1
49.9 wt%	0.580	58.0	29.2
77.5 wt% (reference concept)	0.730	92.0	20.7
87.5 wt%	0.783	108.4	18.2
100 wt%	0.828	143.6	14.3

2.2.3.3.4. Flight-Path Booster Discs

Another optimization study was conducted to determine if the performance of the existing Target-4 tungsten target could be enhanced by placing uranium in the flight-path-tube region between the target and the experiment. Refer to the Target-4 geometry illustrated in Fig. II-36. Estimates of the relative 1-MeV silicon-damage-equivalent neutron flux at the experimental location were calculated for several configurations with varying uranium disk sizes placed at various locations within the flight-path tube. The results of these calculations are presented in Table II-12. All calculations assume that the uranium is 77.5 wt% enriched in ^{235}U and that the target is the current WNR Target-4 tungsten target.

Fig. II-36. Model of the Target-4 target, crypt, flight-path tubes, and experimental location, showing trial locations for possible uranium boosters. All dimensions are in centimeters.

For this configuration with a uranium disk between the target and the experimental area, neutrons that reach the experiment can come from three different pathways. First, neutrons produced in the target can strike the fissile disk and produce fission neutrons, which contribute to the experimental neutron flux. Second, because the uranium disk does not necessarily plug the flight-path tube, some neutrons from the target will miss the disk completely and directly contribute to the flux. Finally, some fraction of neutrons emanating from the target will pass through the uranium disk

without interacting and, hence, without causing fission. These neutrons will also contribute directly to the flux at the experimental location. One column in Table II-12 tabulates the relative contribution to the flux by neutrons that do not cause fission in the disk. This column is called "Relative Flux without Fission." The column entitled, "Relative Flux with Fission," lists the total relative flux at the experimental location. From the results, it appears that a disc-enhanced flux is only possible by placing a large, nearly critical uranium slab near the experiment. Because of cost, safety, and operational concerns, this approach is not considered feasible for the WNR Target-4.

TABLE II-12. URANIUM BOOSTERS WITH THE CURRENT W TARGET

Uranium Disc Dimensions (diam x length, cm)	Disc Location (cm from target)	k_{eff}	Relative Flux without Fission	Relative Flux with Fission
0	-	-	1.000	1.000
26.51 x 2.54	202	0.391	0.391	0.398
46.52 x 2.54	422	0.414	0.393	0.400
26.51 x 10	202	0.970	0.035	0.081
46.52 x 8.5	422	0.995	0.061	0.405
17 x 17	202	0.983	0.320	0.326
17 x 17	422	0.983	0.820	0.827
22 x 12	750	0.984	0.910	0.958
44 x 8	750	0.944	0.761	1.194
66 x 8	750	0.991	0.464	8.775

2.2.3.3.3.5. Collimation by the Flight-Path Tubes

Neutrons emanating from the Target-4 must travel through a series of flight-path tubes embedded in the WNR shielding before they reach the experimental location. Figure II-28 shows our model of the target, the crypt,

flight-path tubes, and experimental location. In order to characterize collimation effects, we computed the 1-MeV silicon-damage-equivalent neutron flux in five circular zones (radii = 11, 22, 33, 44, and 55 cm) at the experimental location. The collimated and uncollimated zonal fluxes are compared in Table II-13 for several alternative targets. These results quantitatively show how the neutron flux field is affected by collimation. With collimation, we introduce a size and spatial distribution to the irradiation field at the experimental location. We also noted that collimation affects the neutron flux from large targets more than it affects the neutron flux from small targets.

TABLE II-13. COLLIMATION EFFECTS ON ZONAL NEUTRON FLUXES
FOR COLLIMATED FLUX AND UNCOLLIMATED FLUX

	1st Zone	2nd Zone	3rd Zone	4th Zone	5th Zone	1 - 4 Zones
Outer radius, cm	11	22	33	44	55	44
3 x 7.5 Current W target	1.000	1.000	1.000	0.930	0.045	0.970
10 x 21 Bare PINS target	0.997	0.987	0.932	0.751	0.124	0.866
10 x 27.5 Optimum W target ¹	1.000	0.972	0.830	0.695	0.183	0.807
17 x 40 Optimum Pb target ²	0.641	0.720	0.668	0.564	0.218	0.629

¹ Looking from the center of the target, the flight-path-restricted field-of-view at 800 cm is a circle with a radius of 44 cm.

² These targets were geometrically optimized to produce maximum uncollimated neutron flux at the experimental location. Different dimensions will probably be required to produce maximum collimated flux at the experiment.

2.2.3.3.3.6. Proton-Beam Profile

The least-expensive proton beam to produce is an untailored circular beam with a truncated Gaussian shape. Within these guidelines, we have examined the effect of varying the size, or standard deviation, of the Gaussian beam distribution. The results are shown in Fig. II-37 for a bare PINS for which the experimental area is oriented at a 90° angle from the proton beam path. From this study, we concluded that the neutron flux from a bare PINS

is moderately enhanced by depositing the protons nearer the center of the uranium. In other words, there is a slight preference for a beam profile with relatively small standard deviation. For most of the calculations presented in this report, we have chosen a 2.5-cm-radius proton beam with a 0.91-cm standard deviation.

Fig. II-37. The effect of varying the size (standard deviation) of the proton-beam Gaussian shape. The beam was truncated at a radius of 4.508 cm, was composed of 800-MeV protons, and was directed at a bare PINS.

2.2.3.4. Mechanical Integration

2.2.3.4.1. Cooling Requirements

We assume that the cooling requirement is equal to the heat generated in a target. All heat-generation rates quoted in Sec. 2.2.3 of this report are computed using the following formula:

$$HG = (PE + FP \times FE) \times BC \text{ watts ,} \quad (\text{II-26})$$

where HG is the heat generation, PE is the proton energy in MeV, FP is the number of fissions per proton, FE is the energy per fission (assumed to be 200 MeV), and BC is the proton beam current in μA . FP is derived from a physics code calculation that models the entire system, whereas PE and BC are parameters that describe the proton beam.

The reference concept PINS target was designed to remove 63 kW of spallation and fission heat via forced light-water convection. Thus, 90 gpm ($5678 \text{ cm}^3/\text{s}$, 5610 g/s) of light water must enter the coolant housing at 120°F (48.9°C) and exit at 125°F (51.7°C). Actually, for a coolant specific heat of $4.1807 \text{ J/g/}^\circ\text{C}$, this flow rate and temperature rise could remove about 65.7 kW of heat. In our model of the PINS, the smallest coolant inlet area is 6.4 cm^2 . Hence, the coolant velocity in this area is 887 cm/s . Because the sum of the cross-sectional areas of flow across the uranium discs in the target was also designed to be $\sim 6.4 \text{ cm}^2$, we estimate the fluid velocity across the uranium discs to be 887 cm/s as well.

The above brief description of the PINS cooling design provides a mental ruler with which we can assess the meaning of other target heat-generation rates. For example, for any fissile or nonfissile target that generates heat greater than 63 kW, one can weigh the merits of meeting the increased cooling requirement with higher coolant velocities and/or with higher coolant volumes.

2.2.3.4.2. Target Insertion, Removal, and In Situ Support

Installation of the PINS with its required cooling services into the WNR Target-4 crypt is a recognized engineering challenge. As mentioned previously, the access tunnel into the Target-4 area is only 26.5 cm in diameter. The reference target and any of the described unreflected alternative designs can pass through this access tunnel. Likewise, in situ support of any of the alternative targets is not expected to pose any major problems. However, providing and installing adequate cooling capability to the selected target could require some insightful engineering. For example, flexible cooling lines attached to the PINS must accommodate a 13-cm radius of curvature. If this requirement is not met by the reference PINS design, some redesign of the cooling system may be required. Target alternatives with large heating rates and, consequently, large supply lines could be accommodated by connecting services to the target after the target is installed

in the crypt. These and other issues will be addressed after a target concept is selected for further development.

2.3. Criticality-Safety Aspects of Accelerator Driven Assembly Commissioning

2.3.1. Assembly and Characterization of the Accelerator Driven Assembly Target

Although the ADA is designed as a multiplying assembly, it will be operated in the regime of k_{eff} greater than 0.9 and, consequently, will be subject to the same scrutiny that is given to the operation of a critical assembly even if it is operated at a reactivity below delayed criticality. In fact, for safety overview, this assembly is classified as a category B reactor. Its operational design goal of 0.98 k_{pr} gives a multiplication of 50 for an accelerator-produced pulse of neutrons. Furthermore, the ADA target, as a unique assembly, will not have been tested, and calculations of its reactivity are expected to be no better than 1 or 2%.

Because the multiplication characteristics of the ADA target must be precisely defined, it will be assembled and tested at TA-18, the site of the Los Alamos critical facilities. Full oversight and collaboration of the site owner, NIS-6, will be an integral part of this initial phase of commissioning. Their extensive experience with critical assemblies and in personnel training for the operation of such will bring an extra measure of safety and efficiency during the commissioning phase. The time needed for this phase is estimated to be 18 months, based on the experience of NIS-6 on similar projects. The first full year must be devoted to formulating the experimental plan, reviewing the plan (i.e., by the Laboratory's Criticality Safety Committee and other authorities in the Laboratory and DOE), and obtaining the necessary approvals for starting the tests. With proper planning, all necessary characterizations should be completed in the remaining six months.

To cover the expenses and logistics efforts of NIS-6, \$750,000 has been designated in the proposed budget for ADA.

During the first phase of commissioning, an experimental plan for the subsequent commissioning of the ADA target assembly in the ADA facility will be written, and approvals will be sought early enough to permit the assembly to be moved without loss of time.

2.3.2. The Characterization of the Accelerator Driven Assembly

Target at TA-18

The plan for the assembly and characterization of the ADA target at TA-18 will be based on the standard procedures used by NIS-6 to commission a new, experimental critical assembly. We will begin with the installation of the mechanical assembly (without fuel) and the control system for moving the system components, as well as the neutron detectors and the safety-monitoring and control systems. Subsequently, the uranium will be loaded by hand into each half of the slab target in a configuration that has an overall system k_{eff} much less than 0.9.

The controlled elements for adjusting the system multiplication will be characterized by remotely increasing the reactivity of the assembly in small, carefully monitored increments until delayed criticality is reached. This design feature gives an absolute calibration of the reactivity worth of the control elements. The reactivity, ρ , is defined as $(k_{\text{eff}} - 1)/k_{\text{eff}} = \Delta k_{\text{eff}}/k_{\text{eff}}$, and a reactivity change of 1\$ is defined as a change in k_{eff} equivalent to the delayed neutron fraction (approximately 0.007). To achieve the design goal of multiplication, k_{eff} (delayed neutrons included) must be 0.987, which is very close to delayed criticality.

A small neutron source, 0.1 μg ^{252}Cf with a strength of approximately 2×10^5 neutrons/s, will be located inside the stationary half of the slab, near the center of the assembly when the slab-target halves are closed. The assembly, when closed, will have vernier control of at least 5\$ criticality worth, probably in the rotary drums that were envisioned in the conceptual design. The vernier will be designed to have a reproducibility equivalent to a reactivity change of a few tenths of one cent (one cent is equal to one hundredth of a dollar). Redundant detectors will be located at two or more distinctly different locations to minimize uncertainties caused by modal effects in neutron density.

The usual procedure for safe approach to delayed critical is called the reciprocal multiplication method, where multiplication M is proportional to the neutron counting rate. In the region of delayed critical, M is proportional to $1/(1-k_{\text{eff}})$. The reciprocal of the counting rate is plotted as a function of the parameter that is changed to increase reactivity, and this plot is extrapolated to 0 after each incremental increase in the reactivity parameter to project where criticality will occur. In this manner, conservative next steps can be

selected. In the case of our multiplier, the parameter of reactivity is first the closure distance between the two slab-target halves and then the rotary control rods. The ^{252}Cf source, which remains fixed in the assembly, ensures a baseline static neutron population throughout the approach to delayed criticality. As k_{eff} is increased, the amount of time required for the neutron count to reach a constant rate will also increase. This "settling" time is another important characterization parameter for the assembly. The reproducibility of the reactivity parameter changes will be tested to ensure that it is below one cent of reactivity. The effects of surrogate test objects on reactivity will also be determined as a function of distance from the assembly in order to test the calculations presented in this proposal. Temperature sensors within the assembly will be used to measure the thermal coefficient of reactivity in the projected range of operating temperatures.

2.3.3. Phase II: The Characterization of the Target Assembly at the Accelerator Driven Assembly Facility

Following the work done at TA-18, the performance of the target will be reviewed, and, if needed, physical and procedural adjustments will be made. When the necessary approvals are obtained, the dismantled target will be moved to the ADA facility, where it will be stored until the mechanical translation, control, and safety systems are tested and qualified for operation within the new site environment. Before this move, the proton-beam-translation system, together with its safety equipment, will have been thoroughly tested. All mechanical-, safety-, and beam-control systems will be integrated and tested before reassembly of the target. Next, the multiplication measurements with the ^{252}Cf will be repeated because small changes in the reactivity of the assembly may occur as a result of the move and of the different neutron reflection properties of the walls of the ADA facility. The time required to repeat the characterizations should be considerably less than time expended at TA-18. Stops can then be set on the reactivity verniers to ensure that subsequent operation with the proton beam is below delayed criticality. Measurements of multiplication, temperature rise, neutron fluence at irradiation positions, and other characterizations with the proton beam can then proceed. At the end of this commissioning, the facility should be ready to operate for customers.

2.4 Pulse-Width Studies

2.4.1. Small Cylinder with and without LiD

Using highly enriched uranium, we have attempted to design a small cylinder for irradiation in its inner cavity. The basic concept is that the smaller the cylinder is, the faster its flux will decay for a fixed value of k_{eff} . The cylinder is designed using a U-Mo alloy: 6% molybdenum and 94% uranium enriched to 92.55% ^{235}U . The uranium cylinder has a 11.86-cm outer diameter and 5-cm inner diameter. Its length is 21 cm, and the value of k_{eff} is determined to be 0.98. We have also considered the use of a LiD sleeve inside the cylinder. Its purpose is to enhance the 14-MeV neutron flux (see Sec. 2.6) and to attempt to shorten the pulse length by absorbing neutrons. The cylinder was lengthened to 22 cm to maintain a value of $k_{\text{eff}} = 0.98$. A comparison of the pulse time structure is presented in Fig. II-38.

Fig. II-38. Time structure of small cylinder ($k=0.98$).

In Fig. II-38, the diamonds represent the decay rate of the system with LiD, and the squares represent the decay rate of the pure U-Mo system. Evidently, there is no difference between the two decay curves. A least-squares fit to the data gave a half-life of 365 ns.

2.4.2. Pulse Width for Large Cylinder Sizes at $k_{\text{eff}} = 0.9935$

We now consider the pulse width of a much larger system: SNL3J, which is also significantly moderated. The time structure of the pulse is presented in Fig. II-39.

Fig. II-39. Time structure of the pulse of SNL3J.

Fitting the linear part of the logarithmic decay gives a half-life of 1.95 ms. The long time is due to the large size, the use of a moderator, and the high value of k_{eff} .

The final slab configuration that we have designed (see Sec. 2.2.1.2.1) has a k_{pr} of 0.98 and has a half-life of 550 μs . For comparison, a slab without any moderation, (50 x 50 x 35 cm^3 of uranium) has a half-life of 1.16 μs at $k_{\text{pr}} = 0.98$. Obviously, moderators exact a high price in terms of the much increased pulse width.

2.5. Simulation of X-rays

In a meeting with JAYCOR, it was suggested that the LAMPF 800-MeV proton beam could be used to generate a flux of secondary particles with an energy-loss spectrum matching that of soft x-rays, thus implying the emission of α particles with energies in the few MeV regime. We have

examined this possibility using two different configurations. The first uses a carbon slab whereby the protons almost range out. We had hoped that a high flux of low-energy protons would generate an even higher flux of heavier particles. The second possibility uses a carbon slab whereby the particles emitted backwards out of the slab (at 180° to the incoming beam) would have low energies necessary to simulate an x-ray spectrum. Both possibilities were tested using the LAHET code system. Neither are feasible! In hindsight, the reasons for this lack of feasibility are as follows:

- (1) The low-energy particles needed to simulate the x-ray spectrum have very short ranges (significantly less than 1 mm). The cross sections for production of these particles are very small (mb). Coupled with the very thin layer that can produce these particles, less than 1 in 10^4 protons produces a low-energy particle close enough to the surface to be ejected.
- (2) The initial high-energy protons produce a large flux of high-energy neutrons. In turn, these produce protons semi-uniformly through the entire slab volume via the (n,p) reaction. When emitted, these protons cause a constant energy loss through millimeter thicknesses of materials because of their high energy. A large number of these particles mask any variations in energy loss resulting from the small number of low-energy particles.

It may be possible to use a magnetic field to select outgoing particles with low energies. However, the very-low production cross section implies that we will not be able to attain the energy deposition rate needed for simulation of x-ray effects.

2.6. Fast Neutrons (14 MeV)

We investigated the possibility of simulating fusion weapons by enhancing the high-energy neutrons from an ADA target. A ${}^6\text{LiD}$ blanket placed next to the slab target will convert fission neutrons to 14-MeV neutrons by the two reactions ${}^6\text{Li}(n,t){}^4\text{He}$ and $\text{D}(t,n){}^4\text{He}$. Our study shows that this two-step conversion process produces only one high-energy neutron for 10,000 incident fission neutrons. We therefore conclude that the

simulation of fusion weapons will not be feasible for the ADA facility as presently planned.

This study involved four major components: (1) converting a classified Monte Carlo routine to handle a two-step fusion process in a cold unionized medium, (2) setting up a source-driven MCNP problem to mimic a proton-driven LAHET problem and thereby coupling to the classified routine, (3) conducting a series of calculations to verify that the modified code matches the existing experimental and analytic results of Miller *et al.* (1983), and (4) performing a series of parameter and design studies with the converter added to the basic slab-target ADA design.

The problems encountered in weapons usually involve fully ionized materials. The stopping mechanism in an ionized plasma for tritons is quite different from that in a cold material because in plasmas there are no atomic processes to compete with nuclear reactions. In a cold un-ionized material, a triton may interact with the converter atoms, causing atomic excitations or ionizations. The processes involved in slowing tritons in the cold material may be represented by stopping-power algorithms as developed by Anderson and Ziegler (1971). After implementing the stopping-power changes, we validated the code. We refer to the neutrons produced by these two-step processes as reaction-in-flight (RIF) neutrons.

We derived a basic Monte Carlo setup for the 24-cm slab-target design. We added to our model a slab target of ${}^6\text{LiD}$ and determined that the optimum thickness is 5 cm. We checked the spectrum at the interface between the uranium and the converter material. The spectrum matched well with the LAHET spectrum. During this process, we reduced the slab-target thickness to compensate for the increase in criticality introduced by the ${}^6\text{LiD}$. Finally, we compared our calculated results with the neutron experiment by Miller *et al.* (1983). Miller bombarded a ${}^6\text{LiD}$ target with low-energy neutrons to produce 14-MeV neutrons. Our results were consistent with the results of Miller *et al.* (1983) after we compensated for the differences in neutron energies. The resulting efficiencies for converting neutrons of a specific energy to 14-MeV neutrons are shown in Fig. II-40.

Fig. II-40. The efficiency for producing 14-MeV neutrons with ADA.

Folding the fission energy spectrum of the slab target into the cross sections for the two-step process in ${}^6\text{LiD}$, we calculated the resulting RIF neutrons as shown in Fig. II-41.

Fig. II-41. A semilog plot of the normal fission spectrum (dark dots) is shown along with the RIF neutrons (gray dots) produced in the ${}^6\text{LiD}$ blanket.

In Fig. II-41, we see that the RIF neutrons originating from the LiD blanket add only a small enhancement to the high-energy "tail" of the fission spectrum. In conclusion, the low-conversion efficiency and the isotropy of

the 14-MeV neutrons make this a difficult problem. It may still be possible to use a combination of altered composition of the converter material (perhaps a mixture of Li metal and LiD salt), reflectors, filters, and geometry to produce a cleaner 14-MeV source of strength 5 or 6 orders of magnitude below the peak-fission neutron source. However, we concluded that this technique will not be a practical way to produce 14-MeV neutrons in the present ADA design.

3. BEAM-LINE DESIGN AND THE ACCELERATOR DRIVEN ASSEMBLY SAFETY REVIEW

The proposed facility is an add-on to the existing LANSCE facility at Los Alamos. It consists of a new target area containing a neutron-multiplying target and a new beam line that will deliver the PSR or direct LAMPF beam to the target. The existing accelerator and storage ring do not need to be modified. Impact on other activities at LANSCE will be minimal as only a few pulses of beam per day will be used by the new ADA facility.

The PSR delivers 3.1×10^{13} protons per pulse, which has a total duration of 270 ns. If we need more protons, we can use more PSR pulses, which come once every 50 ms (20-Hz rate). Of course, multiple pulses are not desirable if a short pulse width is important. The direct LAMPF beam delivers 1.3×10^{14} protons per pulse, but this pulse has a much longer duration of 1 ms. The duration of this pulse can be reduced if fewer protons are sufficient. If more protons are required, we can use additional pulses, which come once every 8.3 ms (120-Hz rate).

Thus, for submicrosecond times, we can use single pulses from the PSR, which contains 3.1×10^{13} protons. For more protons, we can use one or more direct LAMPF beam pulses for a total duration of less than one-tenth of a second.

3.1. Beam-Line Description

The beam transport line for the ADA facility is designed to handle either a direct LAMPF beam or a PSR beam to the ADA neutron-multiplying target. The beam-line bore diameter is sized to accommodate the PSR beam with minimal beam losses so that no part of the beam line becomes activated enough to prevent hands-on maintenance (i.e., the direct LAMPF beam has much smaller emittance and resulting size). The beam line is designed to minimize magnet power consumption and the number of expensive magnets. We did not try to minimize the number of low-cost steering magnets and BPMs. Personnel and target safety are critical items that are designed into this beam line. A pulsed "kicker" magnet is used to deflect the beam into the ADA transport channel. Only a fixed number (≤ 5) of PSR or LAMPF macropulses can be accepted by this channel without the need for

manually rearming the kicker magnet. This design element eliminates an accident scenario whereby many LAMPF or PSR beam pulses are directed onto, and damage, the ADA target. In summary, the beam transport line is designed to minimize cost, maximize reliability and maintainability, minimize the commissioning and tuning effort, and provide safe operation of the facility.

3.2. Beam-Line Design Considerations

3.2.1. Targets and Fluences

The ADA beam line transports an 800-MeV proton beam from either the PSR or a direct LAMPF beam to the ADA target 100 m away with minimal beam loss in the transport. The only ADA target requirement on the ADA beam line is that the beam spot must be small enough so that all protons strike the target. Table III-1 lists the beam-parameter values on the ADA target for the PSR beam (i.e., the direct LAMPF beam-spot size will be smaller). These parameters meet the system requirements.

TABLE III-1. BEAM PARAMETER VALUES ON THE ADA NEUTRON-MULTIPLYING TARGET

Parameter	Values
Horizontal size (2σ)	31.2 mm
Horizontal divergence (2σ)	1.47 mrad
Vertical size (2σ)	33.0 mm
Vertical divergence (2σ)	1.24 mrad
Protons/burst	3×10^{13}

The ADA beam-optics design sets the requirements for beam diagnostics, controls, commissioning, tuning, magnets, interfaces, tolerances, and procurements. Tolerances for beam-line components are set by their effects on the beam at the beam stop and by their effects on beam-line aperture requirements. Tolerances are set for alignment and magnet currents.

3.2.2. Beam-Line Transport Systems

The ADA beam line transports the beam from line D downstream of the PSR to the ADA target and beam stop. Figure III-1 shows the beam-line conceptual layout, and Table III-2 lists the elements of the entire beam line.

Fig. III-1. Site layout.

We will use four of the existing line-D quadrupole magnets to match the beam from either LAMPF or the PSR to the ADA beam transport line. We will then use a 1.5° pulsed dipole magnet (for single-event safe operation, see Fig. III-2 for the pulsing-circuit concept) and a 2.5° direct-current dipole magnet to bend the beam toward the ADA target building and a periodic quadrupole-doublet transport channel to transport the beam to the ADA target.

A set of horizontal and vertical dipole steering magnets are placed after each quadrupole in the periodic channel to center the beam in the transport channel (i.e., because steering magnets are minor cost items, we placed one after each quadrupole). BPMs, placed after each quadrupole, measure the beam position and provide the information necessary to set the steering magnets.

TABLE III-2. ADA BEAM-LINE ELEMENTS*

Ele. No.	Element Name	Type	Bore Dia. (m)	Length (m)	Strength	Comment	Total Dist. (m)
1	BP1	plug		0.30			0.30
2		drift		0.70			1.00
3	WH1	harp		0.00			1.00
4		drift		5.00			6.00
5	Q1	quad	0.20	0.50	1.811 T/m		6.50
6		drift		2.02			8.52
7	WH2	harp		0.00			8.52
8	Q2	quad	0.20	0.50	(1.811) T/m		9.02
9		drift		10.98			20.00
10	WH3	harp		0.00			20.00
11	Q3	quad	0.20	0.50	1.811 T/m		20.50
12		drift		2.02			22.52
13	Q4	quad	0.20	0.50	(1.811) T/m		23.02
14		drift		10.98			34.00
15	Q5	quad	0.20	0.50	1.811 T/m		34.50
16		drift		2.02			36.52
17	Q6	quad	0.20	0.50	(1.811) T/m		37.02
18		drift		0.50			37.52
19	K	kicker	0.20	1.00	0.1275 T	1.5 Deg. Bend	38.52
20		drift		0.50			39.02
21	B	bend	0.20	0.50	0.4249 T	2.5 Deg. Bend	39.52
22		drift		8.48			48.00
23	WH4	harp		0.00			48.00
24	Q7	quad	0.20	0.50	1.811 T/m		48.50
25	BP2	plug		0.30			48.80
26		drift		1.42			50.22
27	BP3	plug		0.30			50.52
28	Q8	quad	0.20	0.50	(1.811) T/m		51.02
29		drift		10.98			62.00
30	Q9	quad	0.20	0.50	1.811 T/m		62.50
31		drift		2.02			64.52
32	Q10	quad	0.20	0.50	(1.811) T/m		65.02
33		drift		10.98			76.00
34	Q11	quad	0.20	0.50	1.673 T/m		76.50
35		drift		2.02			78.52
36	Q12	quad	0.20	0.50	(1.345) T/m		79.02
37		drift		15.50			94.52
38	WH5	harp		0.00			94.52
39		drift		5.00			99.52
40	FVV	valve		0.30			99.82
41	ADA	target		2.00			101.82
42		drift		9.00			110.82
43	WH6	harp		0.00			110.82
44	BD	dump		0.00			110.82

*Q designates a quadrupole magnet, K designates a "kicker" magnet, B designates a bend magnet, WH designates a wire harp, BP designates a beam plug, FVV designates a fast vacuum valve, and BD designates a beam dump. Negative values of quadrupole strengths (in parentheses) indicate defocusing in the horizontal direction.

Fig. III-2. Basic concept for "single-burst-safe" pulsed (kicker) dipole magnet.

There are three standard LAMPF beam plugs in the system. One plug is upstream of the kicker dipole magnet to protect beam-line components from "worst-case" accidents (which have never occurred at LAMPF), and two are downstream of the bending magnets for personnel protection for people working in the ADA experimental facility. It is important that no water be allowed into the ADA facility. There will be a wall between the ADA beam line and experimental facility; only the beam-line vacuum pipe will protrude between the two structures. This wall reduces the shielding required in the experimental facility for handling a "worst-case" beam accident (see Sec. 4.2). A fast-acting vacuum valve will be placed in the beam line at the downstream end of the ADA beam-line tunnel to protect the accelerator from any catastrophic vacuum loss resulting from a vacuum window rupture in the ADA experimental facility.

Four quadrupoles are required to match either the direct LAMPF beam (i.e., parameters are given in Table III-3) or the PSR beam (i.e., parameters are given in Table III-4) to the periodic transport system that

transports the beam to the ADA target. Calculations indicate that existing line-D quadrupoles will be able to do the beam matching. Two horizontal and vertical steering magnets will be added between the line-D quadrupoles to place the beam on axis in the periodic transport system and to offset the beam during commissioning and tuning operations. (Offsetting the beam is one technique for measuring the optical properties of the beam channel.)

TABLE III-3. DIRECT LAMPF BEAM PARAMETERS AT ENTRANCE OF QUADRUPOLE LDQD29 IN LINE D

Parameter	Value
Protons per macropulse	1.3×10^{14}
Macropulse bunch length	≤ 1 ms
Beam emittance	0.3 mm-mrad
Horizontal Twiss parameter α	-9.03
Horizontal Twiss parameter β	67.5 m/rad
Vertical Twiss parameter α	-7.52
Vertical Twiss parameter β	53.0 m/rad

TABLE III-4. PSR BEAM PARAMETERS AT ENTRANCE OF QUADRUPOLE LDQD29 IN LINE D

Parameter	Value
Protons per bunch	3×10^{13}
Macropulse bunch length	270 ns
Beam emittance	hor.: 6 mm-mrad, vert.: 8 mm-mrad
Horizontal Twiss parameter α	-1.41
Horizontal Twiss parameter β	12.8 m/rad
Vertical Twiss parameter α	-1.07
Vertical Twiss parameter β	2.82 m/rad

A periodic focusing channel transports the beam from the beam-matching section to the ADA experimental facility target. We analyzed several periodic transport systems. A conceptual design was determined by considering beam-line optical properties, cost, commissioning, operation, maintenance, tolerances, and complexity. A periodic channel consisting of

single-quadrupole magnetic-focusing elements spaced uniformly is the least expensive both in magnet and power-supply costs and power consumption. However, using asymmetric spacing (i.e., a quadrupole-doublet arrangement) allows more room for diagnostics and correction magnets with little penalty in cost and power. Our beam channel design requires 12 quadrupole magnets, a 2.5° direct-current dipole magnet, and a 1.5° kicker dipole magnet (for single event safe operation). The magnet specifications for the transport are given in Table III-2.

Our beam-line design achieves low cost by using a rather weak-focusing beam-transport lattice (long period). Such a design requires large magnet apertures to maintain a good acceptance-to-emittance ratio, but the magnets are not expensive because the required strength is low. Space charge is a potential concern in a weak-focusing lattice, but we have determined that space-charge tune depression is completely negligible in our beam line for both the PSR and the direct LAMPF beams. Magnet-alignment errors in our beam line are less harmful than in beam lines that use shorter periods. The effects of multipole errors in the quadrupoles have also been estimated. We found that sextupole errors of 1% and octupole errors of 9% have negligible effects. Smaller errors are routinely achieved in conventional magnet designs.

Normally, final-focusing quadrupole magnets would be required to obtain a desired beam-intensity distribution on a target. However, the neutron-flux distribution generated by the ADA target is only minimally influenced by the proton-beam distribution on that target, and an 800-MeV beam pulse with 3×10^{13} protons deposits only 900 calories into the ADA target. The size of the beam spot focused onto the ADA target, which is at the end of the periodic transport line and has no additional focusing magnets, is 31.2 x 33 mm. The beam distribution on a beam stop, placed at the end of the ADA experimental building and used for beam tuning purposes when the ADA target is safely removed, is 43.2 x 40.6 mm; LAMPF beam values are smaller. Because the proton beam size has minimal effect on the ADA target, the final quadrupoles in the periodic focusing channel will be adjusted to set the spot size on the final beam dump to minimize the beam-dump cost.

3.2.3. Commissioning, Tuning, and Standard Operational Procedures

The ADA beam transport system contains many different components for three systems that must be tested to ensure proper operation. There are components for the beam line that deliver beam to the ADA facility. There are components for the PSS that ensure that no beam can be delivered to the ADA facility while people are present in the facility. There are components for the RSS that protect beam-line equipment (including the ADA target) from mis-steered or mis-focused beams.

The LAMPF standard PSS system controls a Kirk-Key* interlock entry system to the ADA experimental facility that only allows entry by personnel when there is no possibility of beam entering the facility, when the ADA target and californium source (for k_{eff} measurements) are properly secured in their storage vault, and when the beam dump shield covers the beam dump. The system relies on limit switches to ensure that the three beam plugs are closed, that the ADA target is in its vault, that the vault door is closed, and that the beam-dump shield door is closed. TV cameras, placed inside the experimental facility, will allow visual verification by the operations crew that the room is properly secured before allowing personnel entry. A Kirk-Key release requires that the limit switches are properly set and that the operations crew is satisfied with their visual verification. Part of commissioning process is to check that this system is functioning.

The LAMPF standard RSS system protects equipment from beam spills. The RSS includes the PSS. The RSS uses radiation spill monitors to shut off the beam if beam spills are excessive. This system will not allow beam unless magnets are properly turned on and dipole magnets are properly

* A Kirk-Key system is controlled by interlock logic. When the interlock logic indicates that the experimental facility is safe for personnel entry, an operator releases a master key from a beam interlock switch, and the master key is then used to unlock a key bank. The key-bank keys are used to gain entry to the experimental facility. The master key, once used to release the Kirk-Key bank keys, cannot be removed from the key-bank lock until all the Kirk-Key bank keys are returned to the key bank. Personnel entering the experimental area are required to carry a key from the key bank. Once all keys are returned to the key bank, the master key can be removed and returned to the beam interlock switch that enables operation of the facility.

set. Part of commissioning process is to check that this system is properly functioning.

The ADA beam-line magnets consist of 12 electromagnetic quadrupoles for beam focusing, 16 vertical and horizontal steering dipoles to center the beam on the optic axis, a 2.5° bending magnet, and a 1.5° pulsed-kicker dipole magnet. All of these magnets will be mapped and their power supply current verses magnetic field strength calibrated. Once installed, the proper operation of the magnet power supplies and the magnetic polarity will be verified (i.e., this verification includes the testing of magnet cooling-water flow switches and over-temperature sensors).

The beam-line-commissioning effort checks the alignment of all beam-line elements (i.e., magnets and diagnostic devices), verifies the proper operation of the beam-line elements, and uses these elements to obtain the desired beam distribution on the beam stop. The optimum locations of the diagnostics remain to be determined; the diagnostic set will be complete so that all beam-line magnet elements can be set and the performance of the transport line verified. A step-by-step beam-line tuning procedure must be developed to efficiently tune the beam line.

3.2.4. Diagnostics

Diagnostics are required to commission, tune, and verify the performance of the beam line. The beam optical properties, commissioning plan, and tuning procedure of the ADA beam line set the requirements for beam-parameter measurements (including tolerances). The procedure for determining commissioning and tuning specifications is as follows: (1) identify the set of beam parameters that can be measured and that uniquely identify the proper beam-line tune, (2) determine the measurement accuracy required for the beam parameters, (3) produce a set of diagnostic requirements for tuning the system with built-in redundancy, and (4) produce a set of diagnostic requirements for monitoring the beam behavior. This section specifies the beam parameters to be measured and the required accuracy needed for operation. Diagnostics for the PSS and RSS safety systems are also covered in this section.

Table III-5 lists the beam parameters that can be measured and the beam-line elements that are sensitive to these measurements. Six wire harps will provide beam-profile measurements. Three harps placed before quadrupoles Q1, Q2, and Q3 will allow the beam phase-space distribution to be

characterized using tomographic reconstruction. A harp placed before quadrupole Q7 will provide a beam profile after the bend, and a harp placed at the entrance to the ADA experimental area plus a harp placed at the entrance to the beam stop at the end of the ADA experimental area will allow an extrapolation of the beam spot onto the ADA target. The last two harps will allow quadrupoles Q11 and Q12 to be tuned in an effort to set the beam spot size on the beam stop.

TABLE III-5. TYPES OF BEAM-LINE DIAGNOSTICS

Diagnostics	Measurements	Required Accuracy
Wire harp	Beam profile	1 mm
BPM	Beam centroid position	5 mm
Toroid	Proton-beam current	5%
Beam-spill monitor	Beam spill for the RSS via ionization chamber	¹ TBD
Neutron-flux monitor	Neutron flux for personnel protection	TBD

¹ TBD means "to be determined."

A total of 18 BPMs will be placed after each quadrupole, starting with the existing matching quadrupoles, and after each dipole in the beam channel. These monitors will be used to center the beam onto the beam channel axis using steering magnets. We will also be able to verify the beam-channel optical tune by offsetting the beam at the beginning of the channel and measuring the resulting offsets at the downstream BPMs.

Three toroids will be used to measure the beam current. One will be placed at the beginning of the channel, one will be placed in the middle, and the third will be placed after quadrupole Q13. All three toroids should read the same current; beam losses in the channel will be minimal. Having three current measurements provides redundancy and identifies the suspect measurement if the measurements do not agree.

The number of beam-spill monitors and neutron-flux monitors will be determined by the LAMPF radiation safety committee. We estimate that a minimum number of three of each type of monitor will be required for the

beginning of the transport channel, after the bends, and before the entrance to the ADA experimental facility. Additionally, at least two different types of neutron-flux monitors will be placed in the experimental facility to prevent common-mode problems.

3.2.5. Beam-Spill Considerations

The beam spill in the beam line must be below what is necessary for "hands-on" maintenance. This requirement, plus the beam size in the elements of the beam transport line, determines the aperture size of the beam-transport vacuum pipe. We chose a beam pipe size for the ADA beam-line channel that could transport all beam that might lie within the PSR acceptance multiplied by a 1.5-size safety factor. The activation levels in the PSR allow "hands-on" maintenance after a several-week cool-down period. Studies at LAMPF and for a number of programs, including the Fusion Materials Irradiation Test (FMIT), the Accelerator Production of Tritium (APT), and the Accelerator Transmutation of Waste (ATW) programs, have indicated that tube diameters for the beam bore should be about 7 times the root mean square (rms) beam radius for full-current LAMPF-type beam intensities. The direct LAMPF beam is substantially smaller than the PSR beam. We estimate that the ADA bore size is 68 times bigger than the LAMPF beam's rms radius. Therefore, beam-line activation for this beam line will be minimal. Moreover, the tuning effort required for this beam line will be minimized, and the beam-line operations will be substantially more efficient.

3.2.6. Recommendations for Design Trade-off Studies

We have designed a beam transport channel that will achieve the required performance for ADA. We have considered using only electromagnets. However, a conceptual design should look at the permanent-magnet option. From an operational standpoint, a permanent-magnet channel could be more cost effective. (Adjustable permanent magnets could also replace the electromagnets that currently exist for the matching section.) Steering in the periodic line could be accomplished by offsetting the permanent-magnet quadrupoles. However, using variable-field permanent-magnet quadrupoles to steer is complicated by the fact that changing the quadrupole field changes the steering coefficient for the magnet.

We used no additional final focusing magnets to adjust the beam distribution on the ADA target. For low k_{eff} targets or for other ADA-target

geometries where the proton beam distribution has a noticeable effect on the resulting neutron-flux distribution, final focusing magnets might be required and might be included in a final beam-transport design.

3.3. Beam-Line Cost Breakdown

Cost estimates for the components of the ADA are based on actual costs incurred by other projects. The cost estimate covers hardware and personnel costs for the quadrupole magnets, the direct-current-dipole and kicker-dipole magnets, steering magnets, magnet power supplies, the vacuum system, beam plugs, stands, water, and beam-line diagnostics. These costs cover engineering design, procurement, checking, installation, and commissioning of all of the beam-line hardware. The cost associated with controls is covered in the balance-of-plant. Table III-6 summarizes the cost breakdown. The total cost is \$2,919,000 plus contingency.

TABLE III-6. COST-BREAKDOWN SUMMARY FOR THE ADA BEAM-LINE COMPONENTS

Item	Staff	Graded	Hard-ware	Total
Magnets and power supplies	\$635,000	\$380,000	\$570,000	\$1,585,000
Vacuum, stands, water, and beam plugs	\$161,000	\$165,000	\$470,000	\$796,000
Diagnostics	\$142,000	\$136,000	\$260,000	\$538,000
Total	\$938,000	\$681,000	\$1,300,000	\$2,919,000

3.4. Beam-Line Engineering Issues

Beam-line engineering takes the conceptual design and produces drawings and specifications to manufacture hardware. The design is a standard beam line with minimal engineering challenges. However, beam-line engineering remains to be done. Some of the issues addressed in the engineering phase include the alignment method and specification, magnet specification, diagnostics specification, interface specification, and reliability/maintainability specification. We have recognized these issues in

our conceptual design and have ensured that these issues do not cause engineering difficulties. Beam-line engineering costs are included in our cost estimate.

The required alignment tolerance for all magnets and diagnostics was determined from the conceptual-design tolerance study (i.e., alignment plus the correction dipole magnets must achieve the required tolerance). The engineering study will define an alignment method capable of achieving these tolerances and will specify the appropriate alignment fiducial on all beam-line elements. The method for defining the reference trajectory will be determined.

The magnet specification requires the following input: (1) physical requirements (i.e., length, bore, pole-tip strength, and current and voltage ratings of available power supplies), (2) allowed harmonic content at a given radius, (3) calibration (i.e., integral field verses magnet current), (4) effects of temperature (i.e., ambient and cooling) on field strength and quality (i.e., this input is important for permanent magnets), and (5) power supplies (i.e., the availability and cost factor influence the design of the magnets, whereas conceptual-design tolerance studies set the requirements on power-supply set-point accuracy and stability).

The conceptual design specified the beam parameters to be measured and the required accuracy needed for operation. Specific diagnostics that can meet the physics-design requirement must be chosen and specified.

The beam line must interface with the following systems: (1) controls, including magnets, beam-line diagnostics, and fault protection; (2) facilities, including radiation, cooling, power, space, and support structures; (3) vacuum system, including vacuum, pumping port locations; and (4) support stands, including alignment.

We will engineer into the system sufficient reliability and maintainability to minimize operations cost and minimize the time required to activate the ADA facility from a dormant state. A failure is defined when a component does not meet its specification. Past experience with similar components will be used to engineer sufficient safety margin into the specified components to provide acceptable mean time between failures. Beam-loss specifications are set to minimize activation of components and permit hands-on maintenance. The components are engineered so that preventive maintenance can be performed and so that the components can be

fixed in the event of a failure. A specification must be written to address component engineering requirements for preventive maintenance and repairs.

Our labor estimate for engineering the beam line is 50 man-weeks of technical staff and 92 man-weeks of graded personnel support.

3.5. Beam-Line Procurement

The procurement cycle begins when a component specification (with relevant drawings) is approved and submitted to the buyer. The cycle ends when a component received meets the specification. Issues that remain to be addressed are the schedule, a vendor list, and quality assurance. Bidding criteria must be established for different components so that vendors can be ranked based on cost, delivery date, and past history on the quality of product and the honoring of commitments. A quality-assurance program for verification that specifications are met on deliverables must be established. Our in-house magnet and diagnostics laboratories are capable of providing the necessary quality assurance to the crucial beam-line components. Some items such as steering magnets and parts of beam diagnostics will be built in-house. Our in-house labor estimate for procurement and construction of magnets, diagnostics, vacuum, stands, and water is 65 man-weeks of staff and 18 man-weeks of graded personnel. The labor estimate for the check out of these components is 24 man-weeks of staff and 58 man-weeks of graded personnel.

3.6. Beam-Line Installation

Installation of the beam line in a finished beam tunnel will take about 3 months. Our labor estimate for installation of the beam-line components, including magnets, diagnostics, vacuum, stands, and water, is 10 man-weeks of staff and 40 man-weeks of graded personnel. The facility requirements for installation include access space, rigging systems, and support structures.

3.7. Beam-Line Commissioning

Commissioning of the beam line will take 1 month and will require 5 man-weeks of staff and 5 man-weeks of graded personnel. The

commissioning includes tuning, verifying the performance of the beam line, and verifying the proper performance of the RSS and the PSS. One major part of the commissioning exercise is to train the control-room operators to tune the ADA beam line during normal operation.

3.8. Beam-Line Maintenance

A preventive-maintenance schedule and procedures for fixing broken beam-line components will be included under maintenance. Beam losses in the beam transport channel will be minimized in order to decrease the radiation cool-down period required before personnel can work on radiation-exposed equipment. We will not require remote handling to fix equipment, but we will design the beam-line components to facilitate disassembly, assembly, and realignment of components to minimize all radiation exposure to personnel. Access space is required for preventive maintenance and for beam-line component removal and replacement when maintenance is required. A dolly system or an overhead-rail and chain-pull system will be required to handle some beam-line components during maintenance.

3.9. Beam-Line Safety Analysis

3.9.1. Hazard Evaluations

We have addressed a number of safety issues with respect to the beam-delivery system and the beam interaction with the neutron-multiplying target. The beam-delivery system to the ADA target is designed to be single-event safe. A pulsed 1.5° kicker magnet must be manually armed by charging a capacitor before the beam can reach the ADA target. Once the kicker magnet is fired, it only maintains the correct field strength needed to bend the beam for 1 ms (i.e., the maximum repetition rate for the LAMPF beam is 120 Hz, which corresponds to 8 ms between macropulses).

A worst-case-accident scenario whereby a full-intensity LAMPF beam is spilled must be addressed only upstream of the kicker magnet. We have designed in sufficient shielding to protect personnel from a spill of the entire

LAMPF beam upstream of the kicker magnet. Details of radiation safety requirements can be found in the LANL Radiation Control Manual, etc.*

There are several levels of safety that preclude sending more than one LAMPF macropulse or PSR pulse to the ADA target. The primary safety system is the 1.5° kicker magnet that steers the beam into a 2.5° direct-current-dipole magnet. This kicker magnet must be manually armed by the control-room operator before it can be pulsed to steer the beam into the direct-current-dipole magnet, and the kicker power-supply capacitor can only hold sufficient charge to maintain the field in the kicker magnet for a few PSR or LAMPF macropulses. The LAMPF injector has a computer-controlled electrostatic beam chopper that is used to control the macropulse structure of the beam to the PSR. This chopper can be set in single-pulse mode, which is synchronized to the manual dipole-kicker magnet for another level of safety. The SOPs control additional levels of safety. Prototype SOPs are given below.

3.9.2. Standard Operating Procedures

We give examples of two SOPs below: (1) quiescent state whereby personnel access to the experimental facility is permitted and (2) standard operations whereby personnel access to the experimental building is excluded, and beam is allowed into the experimental building.

3.9.2.1. Quiescent State

- ADA slab-target halves are separated by 20 cm, the control drums are rotated to minimize the k_{eff} , and the poison blades are inserted. The ADA target is located in the vault with the steel-shield door closed.
- Radiation from the tungsten beam stop in the facility is blocked by a steel shield door.

*Radiation safety at LAMPF is controlled primarily by the LANL Radiation Control Manual, LM 107-01, and by a number of other Laboratory procedures and standards, such as the three-series Safety Analysis Reports (SARs) and LP107-01 on accelerator-access-control systems. Also, DOE 5480.25, *Safety of Accelerator Facilities*, includes requirements and guidance on radiation protection at accelerator facilities.

- The experimental area remains empty in a closed building with no windows.
- A surrounding fence exists 20 m from the facility, where 1 mrad per event is possible.
- TV cameras and motion detectors are placed around the ADA facility, inside and outside.
- A control trailer is placed within 100 m of the facility where 0.1 mrad per event is possible. Remote operations of the target are controlled and monitored from here.
- Three beam plugs are placed in the beam tube.
- The single-event-safe (SES) kicker-magnet mechanism is locked in the unarmed position.
- No water is allowed in the facility at any time.
- The external terrain is graded so that no water can drain into the facility.
- The facility is earthquake safe.
- A 10^5 neutrons/s californium source, for k_{eff} measurements, is stored safely for remote operation.
- Electricity for lights and instruments is available.
- Interlocks permit no entrance to the facility unless the beam plugs are in and the SES is locked unarmed.

3.9.2.2. Standard Operations.

- The beam plugs and the ADA beam-stop shield are removed, and the beam is tuned with one pulse at a time every 10 s. This is achieved at the control room by manually arming the SES mechanism every 10 s. The SES cannot be by-passed, even for commissioning, because of the capacity of the charging power supply.
- After tuning, the beam plugs are inserted remotely, the SES mechanism is locked unarmed, and the shield is placed over the

beam stop. This sequence enables the PSS to permit people to enter the facility after an operator verifies a safe facility and gives a Kirk-Key release. Personnel place the experiment in position for irradiation. Then everyone leaves. One person does a sweep of the experimental area to verify that everyone is out. This person must push several buttons during the sweep to prove that the sweep was performed.

- The ADA slab target is remotely rolled into position, and the californium neutron source is brought near while the neutron count rate is monitored.
- ADA target halves are brought together remotely as the neutron-multiplication count rate is monitored. The target condition is brought from $k_{eff} = 0.85$ to $k_{eff} = 0.98$.
- The beam plugs are removed, the SES is unlocked and armed, and the single event is initiated. The 800-MeV protons impact the target making 22 neutrons/proton. The neutrons are multiplied about 50 times in the target creating 10^{16} to 10^{17} neutrons. The neutrons irradiate the experiment at 10^{13} neutrons/cm².
- The SES is locked unarmed, the beam plug is inserted, the slab-target halves are separated and the control drums are rotated and the poison blades installed, and the target is rolled back into the vault.
- After minutes, all radioactive buildup is dissipated, and people can safely enter the facility and remove the experiment.
- Experimental equipment removal is covered in an existing LAMPF SOP.

3.10. Safety Review of Accelerator Driven Assembly

A number of potential safety issues have been addressed throughout this report. Because the safety of this project is of the utmost importance, this section of the report summarizes the hazards that may be of concern in the design, implementation, and operation of ADA. A preliminary hazards evaluation that addresses individual systems previously described in this report has been conducted. In addition, other issues that shall be considered in the operation of ADA are addressed.

3.10.1. Preliminary Hazard Evaluation

Table III-7 provides a preliminary listing of the hazards associated with the operation of ADA. Potential accidents associated with each hazard are listed along with design features and administrative controls that shall be in place to mitigate each potential accident. The table also provides reference to specific descriptions and/or analyses developed to review each hazard.

3.10.2. Other Related Operational Issues

Table III-8 provides a listing of operational issues associated with ADA that shall be addressed before the completion of the design. The table provides a listing of operational issues and the associated regulatory drivers, as well as where the issues are addressed. Many of these issues are addressed under current LANL policy and procedures.

TABLE III-7. ADA HAZARD SUMMARY

Hazard	Potential Accidents	Mitigation Feature	Ref. Section
Critical Assembly	Nuclear criticality in - storage vault - beam-line setup - beam line as target	1. Computer modeled - verification of margin to criticality	2.2.1.3.1 2.2.2.3.1 2.3
		2. Engineered controls for loss of power/shutdown - control drums rotated to minimize k_{eff} - neutron-absorbing plates inserted - separation of target halves by 20 cm Note: Mitigation features listed are specific to the slab-target concept. Similar engineered controls are incorporated into the cylinder target and the modified WNR target-4.	2.2.1.2.1 2.2.2.2.1 2.2.1.2.1 2.2.2.2.1 2.2.1.2.1 2.2.2.2.1
Radiation	Contamination or personnel exposure	3. Environmental checks - fixed minimum distance from target to test article (50 cm)	2.2.1.2.1 2.2.2.2.1
		4. Jezebel philosophy incorporated	2.2.1.2.2 2.2.2.2.2
		5. No water allowed within the facility - design/procedures preclude water egress	3.2.2 and 3.9.2.1 3.9.2.1
		1. Engineered controls - PSS - RSS - TV cameras and motion detectors in ADA - tungsten beam stop shielded - facility layout - control trailer location - remote-operated drive transport system - californium neutron source stored before arming of kicker magnet	3.2.2 3.2.2 3.9.2.1 3.9.2.1 3.9.2.1 3.9.2.1 3.9.2.1
		2. Encapsulation of U-1.5%Mo target bricks (cladding)	2.2.1.2.3.1 2.2.1.2.2 2.2.1.2.2
		3. Health physics monitoring (management procedures) - administrative controls to limit access into facility - facility exclusion zone - calculation and measurement of gamma radiation build-up within targets - limit lifetime of targets based on dose rate - see prototype SOPs	4.2 3.9.2 3.9 2.2.1.2.2 3.9.2
		4. ALARA philosophy incorporated	2.2.1.2.2
		5. Structural design for facility	4.2 3.4

TABLE III-7 (continued)

Hazard	Potential Accidents	Mitigation Feature	Ref. Section
Beam-line failure in ADA beam-transport line (TL)	<ol style="list-style-type: none"> 1. Unanticipated pulse or continuous stream 2. Loss of beam control 3. Mechanical failure <ul style="list-style-type: none"> - vacuum loss 	<ol style="list-style-type: none"> 1. Engineered controls <ul style="list-style-type: none"> - kicker magnet - beam stops (3) - interlocks (PSS and RSS) 2. Engineered controls <ul style="list-style-type: none"> - BPMs - steering magnets - interlocks (PSS and RSS) - beam diagnostics 3. Engineered controls <ul style="list-style-type: none"> - vacuum valve - design - interlocks (PSS and RSS) 	3.1 3.2.2 3.2.3 3.2.2 3.2.2 3.2.3 3.2.2 3.2.2 3.2.2 3.2.3
Beam-line failure in ADA experimental facility	<ol style="list-style-type: none"> 1. Unanticipated pulse or continuous stream 2. Loss of beam control 3. Mechanical failure <ul style="list-style-type: none"> - vacuum loss 	<ol style="list-style-type: none"> 1. Engineered controls <ul style="list-style-type: none"> - kicker magnet (TL) - beam stops (TL) - interlocks (RSS and PSS) 2. Engineered controls <ul style="list-style-type: none"> - BPMs (TL) - steering magnets (TL) - beam diagnostics - interlocks (RSS and PSS) 3. Engineered controls <ul style="list-style-type: none"> - vacuum valve - design - interlocks (PSS and RSS) 	3.9.1 3.2.2 3.2.3 3.2.2 3.2.2 3.2.2 3.2.3 3.2.2 3.2.2 3.2.3
Beam-line failure in existing LAMPF facility	see LAMPF SAR		3.9.1
Natural Phenomena - flooding - fire - earthquake - tornado - volcano	Structural failure	Designed to withstand design-basis events (DBEs)	

TABLE III-8. ADA OPERATIONAL ISSUES LIST

Operational Issues	Driver	Where Addressed	Restrictions
Waste management	Regulatory/LANL DOE policy	LANL policies LAMPF SAR/SOPs	see LANL ES&H manual
Transportation	Regulatory/LANL DOE policy	LANL policies LAMPF SOPs	≤ 40 kg/truck ^{235}U ≤ 18.5 kg/container ^{235}U ≤ 18.5 kg/ft ³ ^{235}U
SNM -safeguards and security	DOE requirements	DOE Order 5633.3 LANL policy	$<20\%$ ^{235}U to be Class IV-E for security control requirements
Graphite irradiation	Fire safety	2.2.1.2.3.2.	None noted Analysis demonstrates that no hazard is present
Water	Nuclear criticality safety	3.2.2 and 3.9.2	None allowed Design precludes water entering facility
Thermal capacity	Safety (cooling)	2.2.1.4.1	900 K Analysis demonstrates that no hazard is present
High voltage	Safety (personnel)	LANL policies LAMPF SAR/SOPs	see LANL ES&H manual
Ventilation	Radiation safety	LANL policies LAMPF SAR/SOPs	10 CFR 835 DOE Order 5480.11 LANL policies
Dynamic stress - structural integrity of target	Safety (contamination)	2.2.1.4.2.2	1.3 MPa maximum design stress at 900-1000 K Analysis demonstrates that no hazard is present

4. ACCELERATOR DRIVEN ASSEMBLY BALANCE-OF-PLANT

4.1. Description

The balance-of-plant includes site work, facilities, hardware, structures, utilities, and equipment required to support the ADA experiments other than the principal target and beam-line hardware. When combined with the target and beam-line hardware, the balance-of-plant will complete a functional and operational project. The work will also include facilities design by an architect/engineer consultant and the hardware design of the experimental equipment done by Laboratory personnel.

4.1.1. Site Work

This site work includes excavation, foundation preparation, drainage, road and walk construction, backfilling, and general site work for the construction of the ADA target building and the beam-transport tunnel and supporting equipment. Additional fencing will be required.

4.1.2. Structures

There are two new structures and an experiment instrumentation trailer slab that will be required: the ADA concrete building and the concrete tunnel for the beam line. For a detailed description of each see Secs. 4.3.2 - 4.3.4.

4.1.3. Mechanical

Mechanical work includes cooling water, vacuum lines and pumps, piping, and water connection to existing cooling towers for the beam-line components. Mechanical tracks and remote handling for the target, structure for the targets and beam stop, and drainage for the floor of the ADA building must be provided. There is no need for water in the ADA building; therefore, it will not be delivered to the building because it may reflect neutrons and increase the neutronic reactivity of the target.

4.1.4. Electrical

Balance-of-plant electrical work can be broken into two areas: power supply and electricity (which includes lighting) and instrumentation. New power (480 V/208 V-3 phase, 40 kW) must be furnished for the beam transport and associated accessories, as well as for the new ADA building and for the experiment-instrumentation trailer. (The beam line and ADA target are controlled from the LAMPF CCR.) Sensors, instrumentation, signal

wires, and the hardware and software needed to run and monitor the experiment must be installed.

4.1.5. Shielding

Shielding will be required around the new beam-transport tunnel and in some areas of the target-storage room. Shielding will also be required around the beam stop, including a shutter that will protect workers and experimenters from radiation produced by the beam stop. In the event of beam spillage, the shielding in the beam-transport tunnel will protect the area beyond the walls of the beam tunnel in adjacent and close structures and outside in the open from radiation doses exceeding the maximum limits for personnel.

4.2. Accelerator Driven Assembly Balance-of-Plant Design Requirements

The following is a list of requirements for the conceptual design of the balance-of-plant for the ADA project.

- The slab or cylinder targets and experiment must be housed in a heated concrete building and protected from the weather.
- At least two floor drains must be provided in the building to collect water that may enter the building inadvertently. This water will be drained via a closed loop to a holding tank. The site will be graded and drained to prevent rain water and melted snow from entering the building.
- For general shielding, the building must be made of reinforced concrete 18 in. thick (including the roof) with a concrete slab, 4-ft steel-wall shielding (free shielding blocks are available), and 4 in. of borated polyethylene on the roof.
- A side-target vault made of concrete (also 18 in. thick) is required. This vault provides passive cooling for the target, security in the form of both personnel safety against radiation hazards, and special handling of radioactive materials. The vault must have a lockable concrete or steel door to provide this security.
- The building must be adequately lighted, and proper warning lights and signs must be furnished for radiation safety.
- No windows are required in the building.

- A large (about 10- to 12-ft-wide and 8-ft-high) roll-up door is required for access to the building by a fork lift or vehicle, which delivers target and experiment materials. The opening of the door will be shielded on the inside with a large, steel rolling door. In addition, an exit for people should be furnished.
- A beam stop downstream from the target on the south wall of the structure is required. It should be passively cooled and serve as the target stop when the beam is being tuned.
- There is no requirement for an overhead crane at this time; however, because the building is made of 18-in.-thick reinforced concrete walls, provisions in the design should be made for placement of a 10-ton bridge crane with no additional remodeling of the walls necessary (i.e., design the supports for a bridge crane into the walls.)
- No additional shielding is required in the facility during an experiment (i.e., when there may be high bursts of radiation). Instead, the facility will be fenced, and personnel will be kept away during those periods and not let back in until the radiation levels are safe, as determined by radiation control technicians and based on the PSS.
- In addition to the building, a 218-ft beam tunnel for the beam-transport line from the PSR and line D to the new facility is required. Utilities required are water for cooling, power, vacuum lines, communications, and controls.
- Shielding will be required for this 218-ft tunnel. The shielding must be above and on both sides of the structure. It must be made of at least 8 ft of steel, 20 ft of concrete, or an equivalent combination of both. (A wall between the beam tunnel and the ADA experimental facility, plus beam plugs, sufficiently isolates the experimental facility from the beam tunnel to permit reduced shielding of the experimental facility to protect against worst-case accidents.)
- The experiment-instrumentation trailer slab must be designed to support a trailer that will house the experiment-instrumentation electronics. The only utilities required are electrical power for heating, experiment instrumentation, and lighting of the target. Communication utilities and instrumentation lines will be required for control, safety, and communication.

- Approximately 900 ft of new security chain-link fencing will be required.
- Improvements and additions to the existing road will be needed.
- All work must conform to DOE and Laboratory standards, including the Uniform Building Code (UBC), American Concrete Institute (ACI), American Institute of Steel Construction (AISC), American Society of Mechanical Engineers (ASME), National Electrical Code (NEC), and good engineering practice. In addition, the building must be designed to American National Standards Institute (ANSI) earthquake and wind-loading conditions as required by Laboratory and DOE regulations.
- Quality assurance with respect to conformance to specifications and inspection must be done as required by Laboratory and DOE requirements. Documentation of conformance is also required.
- DOE and Laboratory requirements for operating procedures, permits, and reviews must be met.

4.3. Conceptual Design

4.3.1. Site

Construction for this project will begin with site preparation. Excavation will be required for the beam-transport tunnel and for the ADA building and the new road and experiment-instrumentation building. Some old pipelines and concrete structures will need to be removed and will be identified in the detailed design. Penetration and connection into the existing beam-transport tunnel and shielding will be required. Excavation for the new water lines and cooling towers, the installation of new pipelines, and the compaction of soil over the new lines will be required. The site for the experiment-instrumentation building will be developed with power and control conduits ready for the experiment control wire. A concrete slab will be furnished for the experiment-instrumentation trailer (see Fig. IV-1.).

Fig. IV-1. Site plan.

4.3.2. Beam Tunnel

Construction of the beam tunnel will include a reinforced concrete foundation, concrete walls, a concrete water-proof roof, and utility ports. Shielding of either 8 ft of steel, 20 ft of concrete, or 24 ft of soil (or a combination of two or three of these materials) will be added for safety on the outside of the beam tunnel. Water for cooling, as well as the lines and connections to existing cooling towers, will be added. A vacuum system (with pumps, lines, etc.) will be furnished for the beam tube. Access doors and shafts for equipment and personnel evacuation are required and will be shielded using steel and concrete shielding formed into a maze and spaced no further than 44 ft. A monorail and a 2-ton hoist capable of hoisting beam-line equipment are required for the entire length of the tunnel. Electrical power sufficient for the operation of the quadrupole magnets and supporting equipment and for lighting will be brought in from the closest transformer. The tunnel must be heated and properly ventilated for personnel. Control, instrumentation, communication, and alarm services will be added as required for safe operation.

4.3.3. Accelerator Driven Assembly Building

This building (see Fig. IV-2) will have a reinforced-concrete-slab foundation with 18-in. reinforced concrete walls and an 18-in. reinforced concrete roof that is topped with water-proof roofing material. Floor loading will be set at 500 psf to allow for fork lifts and heavy equipment. Below the slab will be two drains that will transport any water that may inadvertently enter the building to a set of holding tanks via a closed pipe loop. The beam enclosure is connected to the ADA building via a beam entrance window. The first two rails that support the target cart and the target will be located 1 m immediately inside the building from the entrance window. The target will be transported into and out of the target area by remote control and by an electrical motorized cart. When the target is in the storage location on the west side of the building, it enters an attached storage vault. This vault is designed to store the target, allow the target to passively cool, keep the target secure, and provide a storage place for the radioactive target while the experiments are being set up. See Fig. IV-3 for the floor plan of the target in its storage position.

Fig. IV-2. ADA building floor plan with the target ready for beam.

The experiments will take place in an experimental area beyond the target area. At the opposite end of the room (south side), there will be a beam stop that consists of a set of 18-in.-diam tungsten disks for a total thickness of 1 ft. This beam stop will have an electrically actuated steel door or shutter that allows personnel to be shielded from the beam stop during experiment set up. A large door sufficient in size to allow a truck or fork lift to enter will be located at the east side of the building.

Fig. IV-3. ADA building floor plan with the target in storage position.

4.3.3.1. Support Equipment

Support equipment consists of structural stands for the experiment and the target; equipment that will provide for the transport of the target, including rails and motorized cart; and all the functional hardware needed for the operation. Also, equipment needed to close shielding doors or shutters for target storage or for the beam stop will be installed.

4.3.3.2. Controls

Controls and monitors are required for the experiment and for the remote operation of the cart and the storage door. We propose that all the controls for the experiment will be run from a PC computer using Lab View or an equivalent software program that can handle several operations and monitoring signals at the same time. Temperature will be monitored for the target and beam stop. Video cameras will view the experiment and the movement of the remote cart that carries the target. These video images will appear on monitors in the LAMPF control room and the ADA experiment-instrumentation trailer. Gamma, neutron, and other radiation monitors will be placed in key locations to monitor the radiation. Alarm and shut-off signals, both automatic and manual, will be monitored at the LAMPF CCR.

4.3.3.3. Remote Handling

Hardware, motors, switches, and stops are required for the dynamic motion of the target on the cart and for the positioning of the target, the target storage door, and the beam-stop shutter. Safety-hardware backup and diagnostics to ensure that the operation proceeds as planned are also required.

4.3.3.4. Beam Stop

The beam stop will be designed to place a 30.5-cm-thick (1-ft) tungsten target in 5-cm (2-in.) plates (each plate is 46 cm in diameter) for maximum passive cooling behind a personnel protection shutter on the south side of the building. See Fig. IV-4 for a conceptual layout of the beam stop. The tungsten target stops the beam while the beam is being tuned.

Fig. IV-4. Conceptual plan view of tungsten beam stop.

4.3.4. Experiment-Instrumentation Building

The ADA experiment-instrumentation building will consist of a modular building or mobile trailer brought to the site to serve as a place where personnel can monitor experiments. The control of the remote handling and of the beam and tuning magnets will be from the existing LAMPF CCR. This experiment-instrumentation building will be situated sufficiently far from the ADA building (100 m) to allow personnel to be present during operations. A permanent slab with stubouts for power and instrumentation conduits will be the base for this building.

4.4 Cost Estimate

The cost estimate is given in Sec. 1.3.5.

APPENDIX A. TEST ARTICLE ENVELOPE DEFINITION FOR A LARGE SLAB TARGET

Early in the design process for the ADA slab target, some consideration was given to facility issues as they relate to potential test articles. One of the first questions addressed pertained to what types of test articles, components, and/or systems are of potential interest. Our baseline assumption was to provide the capability to irradiate tank-size components. Thus, to first order, we are interested in the maximum envelope (overall dimensions), which must be accommodated for tank-size test articles, including main battle tanks, medium tanks, light tanks, and armored vehicles. A second question relates to our ability to simulate a "sky-shine" burst of neutrons. Assuming horizontal beam insertion, provisions for a sky-shine capability would require either moving the target assembly or rotating the test article. Thus, the gross weight and size of the test article is again of interest. Although tank irradiation is no longer an ADA requirement, this appendix serves to document our findings for future reference.

Based on information presented in *Jane's Armour and Artillery* (12th ed., 1991-92), statistics for weight and size were compiled for a variety of tanks and armored personnel carriers within the U.S. arsenal. A summary of the maximum parameter values and corresponding vehicle types is presented in Table A-1. A complete breakdown of weight and envelope parameters for each vehicle type is presented in Table A-2. From the summary table, we see that the M1A1 Abrams Main Battle Tank presents the most limiting constraints in all but one category. To accommodate the M1A1, the facility must be designed for a 57-tonne test article with maximum dimensions of 9.8 m in length, 3.7 m in width, and 3.4 m in height.

In spite of the large size and weight of the "maximum" test article, our thinking was to actually rotate the test article (on a single axis) to provide a sky-shine capability. In this case, the target system would remain fixed in place (horizontal beam insertion). This is in contrast to a system in which the test article is positioned below the target system with the multiplying slab reoriented for a vertical irradiation. Operationally, we feel that rotating the test article is preferable to moving the target. As the baseline, we assumed that single-axis rotation of the test article can be accommodated by some type

of rig, similar in form to those devices currently employed for single-axis rotation of standard railcars.

TABLE A-1. MAXIMUM PARAMETER VALUES FOR SELECTED TANKS
AND ARMORED VEHICLES

	Parameter Maximum	Vehicle
Combat weight (kg)	57154	M1A1
Ground pressure (kg/cm ²)	0.96	M1A1
Envelope:		
Length (m) (w/gun)	9.828	M1A1
Hull length (m)	7.918	M1A1
Width (m)	3.657	M1A1
Height (m) (overall)	3.397	M47

TABLE A-2. SPECIFICATIONS SUMMARY FOR SELECTED TANKS AND ARMORED VEHICLES

Vehicle Type	Vehicle Weight			Envelope					
	Unloaded Weight (kg)	Combat Weight (kg)	Ground Pressure (kg/cm ²)	Length- (w/gun) (m)		Hull Length (m)	Width (m)	Height Turret roof (m)	Height Overall (m)
				front	rear				
Main battle tanks									
M1 Abrams		54545	0.96	9.766	8.971	7.918	3.653	2.375	2.885
M1A1		57154	0.96	9.828	9.033	7.918	3.657	2.438	2.886
M60	45631	49714	0.8	9.309		6.946	3.631		3.213
M60A1	48684	52617	0.87	9.436		6.946	3.631		3.27
M60A3	48684	52617	0.87	9.436		6.946	3.631		3.27
M48	42240	44906	0.78	8.444		6.705	3.631		3.241
M48A1	43999	47173	0.83	8.729		6.87	3.631		3.13
M48A2	43999	47173	0.83	8.686		6.87	3.631		3.089
M48A3	44452	47173	0.83	8.686		6.882	3.631		3.124
M48A5	46287	48987	0.88	9.306		6.419	3.631		3.086
Medium tanks									
M47	42130	46170	0.935	8.508	7.09	6.307	3.51	2.954	3.352
M47M	42130	46814	0.935	8.553	7.09	6.267	3.39	2.954	3.397
Light tanks									
M41	18457	23495	0.72	8.212		5.819	3.198		3.075
Stingray	19387	21205	0.72	9.3		6.448	2.71		2.55
FMC CCV L	17509	19414	0.69	9.37		6.197	2.692	2.349	2.781
TCM DFSV		19051	0.696	7.49		6.273	2.692		2.54
M551 Sheridan	13589	15830	0.49	6.299		6.299	2.819	2.272	2.946
RDF/LT	12247	13426	0.49	8.235		5.569	2.54		2.286
RDF/LT (13.2 ton)	11800	13200	0.48	7.34		5.569	2.54		2.235
Armored personnel carriers									
M3 Bradley	19005	22590	0.54			6.453	3.2	2.565	2.972
M2 Bradley	18824	22443	0.53			6.453	3.2	2.565	2.972

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