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SHIELDING ANALYSIS FOR THE MDAS FACILITY

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ABSTRACT

A shielding analysis has been performed for the Multi-Detector Analysis System (MDAS) experiment being installed at the TREAT facility at Argonne National Laboratory - West. The MDAS experiment uses a linear accelerator to produce neutrons from accelerating deuterons (1.5 MeV) onto a beryllium target. The expected source output is 10^{11} neutrons/second.

A shielding configuration has been designed to protect personnel from the direct neutron radiation, and indirect neutron and gamma radiation from scattering within the experimental equipment and shielding structure. The shielding is based on a series of shields including steel and graphite shield rings, a primary shielding enclosure, a secondary shield made of concrete, and several other shielding components. The primary shielding enclosure is made of a custom material, known as caramel corn, that has been for shielding in other facilities at ANL. Details of this material are provided in the paper. Calculated dose rates for various positions within the facility are shown in the paper.

INTRODUCTION

The U.S. Department of Energy (DOE) has the responsibility to dispose of more than 200 fuel types that are under its control within the United States. These fuels have been irradiated as part of numerous experimental programs over the past five decades. As a result, the range of fuel types, sizes, shapes, and compositions is enormous, while the historical record is not always well documented. The DOE is looking at several non-destructive analysis (NDA) systems as a cost effective method to characterize the fuel for disposition in a mined geological repository.

One system under development is the Multi-Detector Analysis System (MDAS) being constructed at the TREAT facility at Argonne National Laboratory - West (ANL-W)[1,2]. The MDAS system uses accelerated deuterons (at 1.5 MeV) impinging on a target piece of beryllium to produce a neutron source. This neutron source is then used to interrogate the sample. The MDAS system integrates large detector arrays (both neutron and gamma), fast electronics, high-speed data acquisition, real-time analysis, and archival mass storage methods to characterize spent nuclear fuel.

However, to run this system effectively, without exposing personnel to excessive amounts or radiation, the facility has to be shielded for both neutrons and gamma rays. While the majority of the source neutrons will be generated as a result of accelerated deuterons impinging on a beryllium target, some will be generated from fission events in the sample being interrogated. Therefore, also included is an estimate of the relative ratio of accelerator-born and fission-born neutron sources, when the MDAS sample is a fresh EBR-II Mark-III driver assembly.

CALCULATIONAL MODEL

The MDAS experiment is located in one section of the TREAT reactor building at ANL-W. The beam tube of the linear accelerator is inserted into a steel shield ring and graphite reflector ring. The graphite ring is then surrounded with the neutron and gamma detectors. Surrounding the detectors is a primary shielding enclosure made of caramel corn shielding (described below). The entire experiment area is then enclosed with the secondary shielding structure. An overall view of the model building geometry is shown in Fig. 1. While this model does not include all portions of the TREAT building, it does include the rooms closest to the facility. The primary shielding is designed for neutron attenuation, whereas, the secondary shielding, also referred to as shadow shields, are effective for both neutrons and gammas. The shadow shield configuration has evolved from a relatively simple setup to the current design as a result

of several calculational iterations. For example, without shielding, the total dose rate just outside the south wall of the TREAT building is approximately 6000 millirem/hr, whereas with only shadow shielding, the corresponding dose rate is approximately 130 millirem/hr. Also shown in Figure 1 are the approximate locations for which neutron and gamma dose rates were determined.

An axial view of the basic MDAS primary shielding enclosure is shown in Figure 2. Sitting on top of the MDAS rings is a lead filled cask that is used to transfer assemblies within the TREAT facility. The transfer cask is mated to the MDAS shield ring. The transfer cask design has an outer diameter of 83.82 cm (33 inches), an inner diameter of 58.72 cm (23.12 inches), and a height of 370.84 cm (146 inches).

Figures 1 and 2 show the MDAS shield ring structure as a relatively simple figure. In actuality, it is a very complex structure composed of a steel cylinder surrounded by a graphite cylinder, each cylinder with numerous penetrations. The MDAS steel shield ring has an inner diameter of 66.04 cm (26 inches), an outer diameter of 96.52 cm (38 inches), and a height of 194.31 cm (76.5 inches); it is composed of cold rolled STL ASTM A36 steel. The graphite reflector has an inner diameter of 101.60 cm (40 inches), outer diameter of 154.94 cm (61 inches), and a height of 177.80 cm (70 inches). There is a 2.54 cm (1 inch) gap between the steel and graphite portions of the shield ring for fitting tolerances. The cylindrical graphite annulus is constructed using four axial sections.

In the model every penetration in the steel and graphite cylinders is included. There are a total of 164 holes in the steel and graphite sections; 82 in the steel and 82 in the graphite. In the steel ring there are: 48 stopped penetrations, and 34 through holes. In the graphite ring the 82 penetrations are through holes with three different diameters. The net amount of graphite in the graphite rings is reduced by 12.2 percent due to all of the penetrations.

Dose rate calculations were first performed with only the steel and graphite rings - no primary or secondary shielding. These calculations gave very high dose rates (on the order of several thousand millirem/hr) outside the experiment area. Additional calculations were then performed with a 2 foot thick polyethylene (poly) wall adjacent to the building wall, directly south of the MDAS ring (see Figure 1 for orientation). These calculations also gave unacceptable dose rates. Several attempts to reduce the dose rate by thickening the wall, raising the wall, or replacing the polyethylene by concrete only made minor differences. Additional calculations were performed with plugs inside the top of the shield rings in addition to a plug inside the transfer cask. The dose rates were still too high. It was determined that there was a significant fraction of neutrons radially escaping through the shield rings.

Calculations were then performed with a 30.48 cm (1 foot) thick cylindrical polyethylene (poly) cylinder surrounding the steel and graphite rings (including a "cap" on the whole structure). The "cap" included an additional donut arrangement around the lead cask. This arrangement reduced the neutron dose rates to nearly acceptable levels. Secondary, concrete shadow shields were then strategically placed inside the building. Calculations with lead gamma shields or "high-density" concrete secondary shields were also performed, but economic considerations dictated that plain concrete should be used for the secondary shields. While this configuration gave reasonable dose rates, the primary shielding material was changed to a combination of poly beads, borax, epoxy, and a curing agent. The dose rate results using this composite primary shield were significantly better, by factors of 2-5 depending on location, than those using a plain poly structure with the same thickness. In addition, this material is more cost effective (approximately $110 per cubic foot) and structurally better than poly.

This unconventional neutron shielding material, used for the composition of the primary shield in these calculations, is composed of a substance called "caramel corn". The name "caramel corn" results form the fact that it physically looks a lot like the candy caramel corn. This material, developed by the Intense Pulsed Neutron Source Division at Argonne, is 48.9% by weight polyethylene beads (CH_2), 12.6% borax ($Na_2B_4O_7$), 22.7% epoxy ($C_{15}H_{13}O_3Cl$), and 15.8% curing agent; the curing agent is composed of 90% polyamidamine (CON_2H_4) and 10% tetraethylenepentamine ($C_8H_{23}N_5$). Subsequent to performing the dose rate calculations the composition of the caramel corn was changed slightly. The epoxy and curing agent split changed from 22.7% and 15.8% to each at 19.25%. These relatively minor compositional changes do not significantly affect the dose rate results.

Although the initial calculations for the primary shield utilized a cylindrical shield geometry, engineering concerns involving moving the structure for detector maintenance and adjustment, dictated that the final form of the primary

shield be rectangular. The rectangular top and the back (East) section are stationary. The other three sides are a one-piece, movable section. The model includes a 2.54 cm (1 inch) gap between the stationary and movable sections of the primary shield.

The primary shield design is composed of a rectangular box with an outer dimension of 431.8 cm (14 feet 2 inches) and walls that are 30.48 cm (1 foot) thick. The top structure is 218.44 cm (7 feet 2 inches) above the floor. Like the walls, the top will be 1 foot thick. There is an additional foot-thick donut arrangement on the top that will surround the transfer cask. The box portion of the primary shield is made in sections, with the sections bolted together via rods that run through the sections. In the calculations, these rods were ignored. This model simplification does not significantly alter the calculated dose rates because the volume fraction of the connecting bolts is small.

Not shown in Figure 1, or included in the model, is the linear accelerator (Linac). The accelerator is directly east of the MDAS rings and a section of the surrounding primary shield enclosure had to be removed to accommodate it. This large opening was incorporated in the model. A one foot thick (6 foot long) paraffin shield block along with a 2 foot thick concrete shield is added in the backward direction. To further reduce backward leakage, a 15.24 cm (6 inch) wedge of primary shield material, running the full height of the graphite, is located adjacent to the graphite. The angular boundaries of the wedge were determined by the angle between detector stands. There is one other paraffin shield in the facility. The paraffin shield west of the rings is 60.96 cm (2 foot) square with a height of 144.78 cm (57 inches). This shield was added to help slow-down neutrons because of the forward peaked source. Paraffin was used because it was available on-site.

NEUTRON SOURCE SPECTRUM

The neutron source spectrum from the linear accelerator ranges up to 6 MeV, with a peak at 0.4 MeV and an angular dependence obtained from an experimental evaluation[3]. The source was modeled as a series of six discrete energy sources, one for each one MeV increment in the total spectrum (as shown in Table 1). Since there is a considerable amount of scattering in the graphite region, the energy dependence is not that sensitive to the input spectral shape. The lowest energy neutrons, modeled by the peak energy 0.4 MeV, were assumed to be anisotropic (forward peaked), whereas, all the higher energy neutrons (>1 MeV) were assumed to be isotropic. The total neutron source strength was assumed to be $1x10^{11}$ neutrons per second.

Table 1: Neutron Source Spectrum

Energy (MeV)	Source Fraction (%)
0.4	35.71
1.5	17.15
2.5	8.57
3.5	8.57
4.5	21.43
5.5	8.57

CODE, CROSS-SECTIONS, AND FLUX-TO-DOSE CONVERSION FACTORS

Particle (neutron and gamma) fluxes were determined using the MCNP-4A Monte Carlo code[4] using the initial neutron source. Cross-sections were standard ENDF/B Version V evaluations. However, a Los Alamos T-2 evaluation was used for iron and an Evaluated Nuclear Data Library (ENDL-85) evaluation was used for argon (a component of air).

Dose rates were determined for all calculations by multiplying calculated energy dependent particle fluxes by energy-dependent flux-to-dose conversion factors. Neutron dose rates were determined from energy-dependent particle fluxes

using ANSI/ANS standard (1991) flux to dose rate conversion factors[5]. However, gamma dose rates were determined using ANSI/ANS standard (1977) conversion factors[6]. It is believed that the older gamma conversion factors give more accurate results and definitely result in more conservative dose rate estimates.

RESULTS

Shown in Figure 1 are the approximate positions for which the dose rates were calculated. Key dose point locations are shown in Table 2. The X and Y coordinate values in the table are relative to the center of the MDAS shield ring. The axial height of each dose rate location was 104.8 cm above the floor of the TREAT building. This particular axial location was chosen because it is the point nearest the source elevation that has the maximum number of penetrations in the steel and graphite structure.

There are several locations that need further explanation. Dose point #1 is shown outside the building, it is actually inside the nearest (southeast) corner of the Health Physics room in the TREAT building. Dose point #2 is in the corner of the Instrument and Control room inside the TREAT building. The operators of the linear accelerator will be in the Instrument and Control room during facility operation. Dose point #3 is shown as being close to the south wall of TREAT. Dose point #3 is actually a series of dose points (3A-F) extending 90 feet out to the fence surrounding the TREAT facility.

The neutron, gamma, and total dose rates, with units of millirem (mrem) per hour, for the dose point locations described in Table 2 are shown in Table 3. In addition to neutron, gamma, and total dose rates, Table 3 contains the fractional standard deviation associated with each dose rate.

The actual measured dose rates should be less than the values presented in the tables since there was a considerable amount of material not accounted for in the model. For example, inside the primary shield there was no credit taken for the shielding effect of the detectors, detector stands, and structure used to support the top of the primary shield. In addition, the model did not include the accelerator structure or other components inside the TREAT building.

The MDAS experiment area, the area that will be off limits during operation, is defined by the outside TREAT building wall on the south and west sides, on the north by the secondary shielding, and on the east by the end of the PHP room (see Fig. 1). As seen from Table 3 all regions outside the experiment area have total dose rates less than 0.5 millirem/hr when the experiment is operating at the 1.0×10^{11} n/s level.

For planning purposes and accident scenarios, dose rate estimates were provided for the case where the accelerator was operated with only the secondary shielding in place. The results are shown in Table 4. From Tables 3 and 4 it is seen that there are considerable differences in dose rates, especially the neutron dose rate, with and without the rings and primary shielding. For example, consider the location one foot outside the south wall of the building (location 3A). The total dose rate under normal operating conditions is 0.36 mrem/hr (0.07 neutron and 0.28 gamma), whereas, without the primary shield and MDAS rings present, the dose rate is 127.6 mrem/hr (117.1 neutron and 10.6 gamma).

In all the calculational results presented in the above tables it has been assumed that there was no fuel sample inside the MDAS experiment. However, when there is an actual sample being interrogated inside MDAS, fissioning in the sample will introduce additional neutrons, with a completely different source spectrum.

A conservative estimate of the magnitude of this fission source was calculated for a fresh EBR-II MK-III driver assembly. In this estimate the fission neutron source was calculated using a neutron flux obtained from a transport theory flux, RZ geometry, deterministic flux solution. Furthermore, it was assumed that the fission source was entirely from fissioning in U-235. The neutron flux used in the estimate was obtained from an RZ model of the MDAS set-up. Radially this model included the MDAS steel and graphite rings, a cylinderized primary (caramel corn) shield, and a cylinderized concrete region (approximating the concrete secondary shield outside the building). The flux was determined using the TWODANT transport theory code[7] with a 28 energy group cross section set (ENDF Version 5) and a fixed neutron source (10^{11} n/s). The energy-dependent fixed source was put into the center node at the axial height that contained the actual source height (113.03 cm). The calculated flux averaged over the height of the enriched region of an EBR-II pin (34.29 cm), in the first radial interval, was 2.0×10^{8} n/cm^2-s.

A fresh MK-III assembly contains approximately 3050 grams of U-235. This translates into an atom density of 7.8×10^{24} atoms per assembly. Furthermore, in the center of the MDAS rings, the neutron spectrum will be very near the spectrum of the deuteron-induced source neutrons (i.e. greater than 0.1 MeV). From the cross section set used in the flux calculations, the average number of neutrons produced per fission times the fission cross section for U-235 ($\nu\sigma_{fission}$), over the energy range 0.1-6 MeV, is slowly-varying and equal to approximately 4.0. The resultant fission source from U-235 fission is approximately 6.3×10^{9} neutrons per second. This is about 6 percent of the deuteron-induced source. This estimate is conservative because samples will contain less U-235 than a fresh EBR-II driver assembly. Furthermore, the flux solution does not take into account any self-shielding of the assembly, which would also tend to decrease the fission source term.

SUMMARY

To conduct the MDAS experiment safely, without exposing personnel to excessive amounts or radiation, the facility must be shielded for both neutrons and gamma rays. Neutron, gamma, and total dose rates have been determined at various locations for the design of the facility. The dose rate results are presented in Table 3 for an operational facility and in Table 4 for accident scenarios where the primary shielding and the MDAS steel and graphite rings are absent. From the tables it is seen that the operational dose rates are less than 0.5 mrem/hr in regions that can be normally occupied while the linear accelerator is operating.

The results presented in the tables are conservative because there is a significant amount of shielding material that is not modeled in the analysis. In addition, the linear accelerator will be operated at outputs less than 10^{11} neutrons/second. However, all dose rates external to the MDAS experiment area are still expected to be less than 0.5 millirem/hr during full-power operation.

It was also shown that the contribution from fissioning within the samples will be much less than the source from the linear accelerator (less than 6% for a EBR-II fuel assembly and less than 0.1% for an individual fuel element). These are minor contributions and can be generally ignored.

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Table 2. Locations of Calculated Dose Rates (cm)			
Dose Point	X Coordinate	Y Coordinate	Location Description
1	-972.8	-710.6	Health Physics Room - SE corner
2	-1986.0	-549.0	Instrument & Control Room - SE corner
3A	422.0	0.0	Outside South wall - 1 foot from concrete
3B	482.9	0.0	Outside South wall - 3 foot from concrete
3C	696.3	0.0	Outside South wall - 10 foot from concrete
3D	1001.1	0.0	Outside South wall - 20 foot from concrete
3E	1915.5	0.0	Outside South wall - 50 foot from concrete
3F	3073.1	0.0	Outside South wall - 90 foot from concrete
5	422.0	874.1	Outside South Wall - beyond secondary shielding
8	0.0	-802.3	Outside West Wall
10	-311.2	740.0	Behind secondary shield - in PHP room
11	-311.2	313.4	Behind secondary shield - in PHP room
12	-646.4	282.8	Behind secondary shield - in PHP room
14	-504.2	133.0	Inside north access passageway
15	-504.2	-52.5	At north access gate
16	-504.2	-206.1	Behind secondary shield - in TREAT South High Bay
18	-301.0	-662.3	Closest personnel access to gap in secondary shield
19	-240.0	-669.8	At gap in secondary shield
20	0.0	2129.8	At east wall of TREAT
24	-1405.8	0.0	TREAT South High Bay
26	-1573.4	861.0	On second mezzanine (z=457.2 cm)
29	-249.0	1334.0	At east access gate
30	-249.0	1731.5	TREAT low-bay area
33	0.0	223.5	Inside linear accelerator
34	-33.0	226.1	At surface of linear accelerator
38	-308.0	0.0	Inside MDAS Experiment Area
41	0.0	-33.0	Inside MDAS Steel Shield Ring

Table 3: Dose Rates for Normal Operating Conditions						
dose point	dose rate (mrem/hr)			dose rate fractional standard deviation, %		
	neutron	gamma	total	neutron	gamma	total
1	0.053	0.031	0.084	38.32	7.76	24.42
2	0.040	0.017	0.057	32.37	8.00	23.05
3A	0.076	0.280	0.356	41.39	32.27	26.88
3B	0.116	0.240	0.356	37.23	20.60	18.43
3C	0.108	0.135	0.243	22.72	9.90	11.50
3D	0.094	0.098	0.192	19.22	20.1	13.92
3E	0.053	0.024	0.077	24.51	5.01	16.93
3F	0.014	0.010	0.024	13.86	4.16	8.41
5	0.110	0.034	0.144	14.39	17.26	11.74
8	0.055	0.033	0.088	65.18	14.92	41.25
10	0.052	0.048	0.100	25.14	32.24	20.27
11	0.057	0.090	0.147	40.35	35.66	26.86
12	0.052	0.048	0.100	25.61	5.89	13.67
14	0.598	1.411	2.009	28.31	5.75	9.35
15	0.059	0.228	0.287	33.52	14.18	13.20
16	0.174	0.130	0.304	76.13	15.32	44.02
18	0.062	0.152	0.214	46.27	26.20	22.93
19	0.200	0.694	0.894	57.26	13.08	16.35
20	0.094	0.041	0.135	17.18	6.11	12.13
24	0.039	0.034	0.073	32.13	19.71	19.42
26	0.038	0.037	0.075	14.71	5.92	8.03
29	0.210	0.214	0.424	16.03	3.21	8.09
30	0.180	0.086	0.267	30.37	7.72	20.69
33	11.7 R/hr	0.11 R/hr	11.8 R/hr	0.26	1.06	0.26
34	109.55	69.14	178.69	7.40	3.17	4.70
38	10.52	26.13	36.65	19.99	1.77	5.87
41	1198 R/hr	6.76 R/hr	1205 R/hr	1.61	15.14	1.60

Table 4: Dose Rates for Accident Scenario (only secondary shield in place)						
dose point	dose rate (mrem/hr)			dose rate fractional standard deviation, %		
	neutron	gamma	total	neutron	gamma	total
1	42.02	0.91	43.10	1.97	3.95	1.93
2	21.59	0.47	22.06	3.00	8.60	2.94
3A	117.07	10.55	127.62	9.78	15.03	9.06
3B	109.65	7.59	117.23	4.15	4.08	4.08
3C	83.04	3.45	86.49	1.94	2.58	1.87
3D	57.05	1.63	58.69	1.90	2.16	1.85
3E	24.92	0.47	25.39	3.02	3.08	2.96
3F	8.92	0.18	9.09	2.76	3.89	2.71
5	41.54	0.90	42.45	3.29	6.84	3.22
8	42.05	3.97	46.02	8.61	14.77	7.97
10	29.19	2.26	31.45	2.67	27.22	3.16
11	29.00	5.03	34.03	10.75	13.17	9.36
12	45.17	2.11	47.28	6.06	13.86	5.82
14	813.74	21.71	835.44	2.06	3.30	2.01
15	168.13	11.86	180.00	4.54	4.22	4.25
16	93.43	6.80	100.23	6.39	6.66	5.97
18	288.96	12.10	301.06	3.66	6.05	3.52
19	735.46	19.72	755.18	3.41	4.39	3.32
20	29.48	0.43	29.91	2.32	3.44	2.29
24	34.93	0.88	35.82	2.62	3.67	2.56
26	28.05	0.78	28.83	2.52	14.54	2.48
29	50.26	1.01	51.27	2.16	3.73	2.12
30	39.68	0.80	40.48	3.06	4.39	3.00
33	15.1 R/hr	42.13	15.2 R/hr	0.22	1.01	0.22
34	14.5 R/hr	42.17	14.6 R/hr	0.19	1.09	0.19
38	8.71 R/hr	50.84	8.76 R/hr	0.62	2.06	0.62
41	570 R/hr	71.34	570 R/hr	0.06	1.23	0.06

Fig. 1 MDAS Experiment Detector and Shield Location

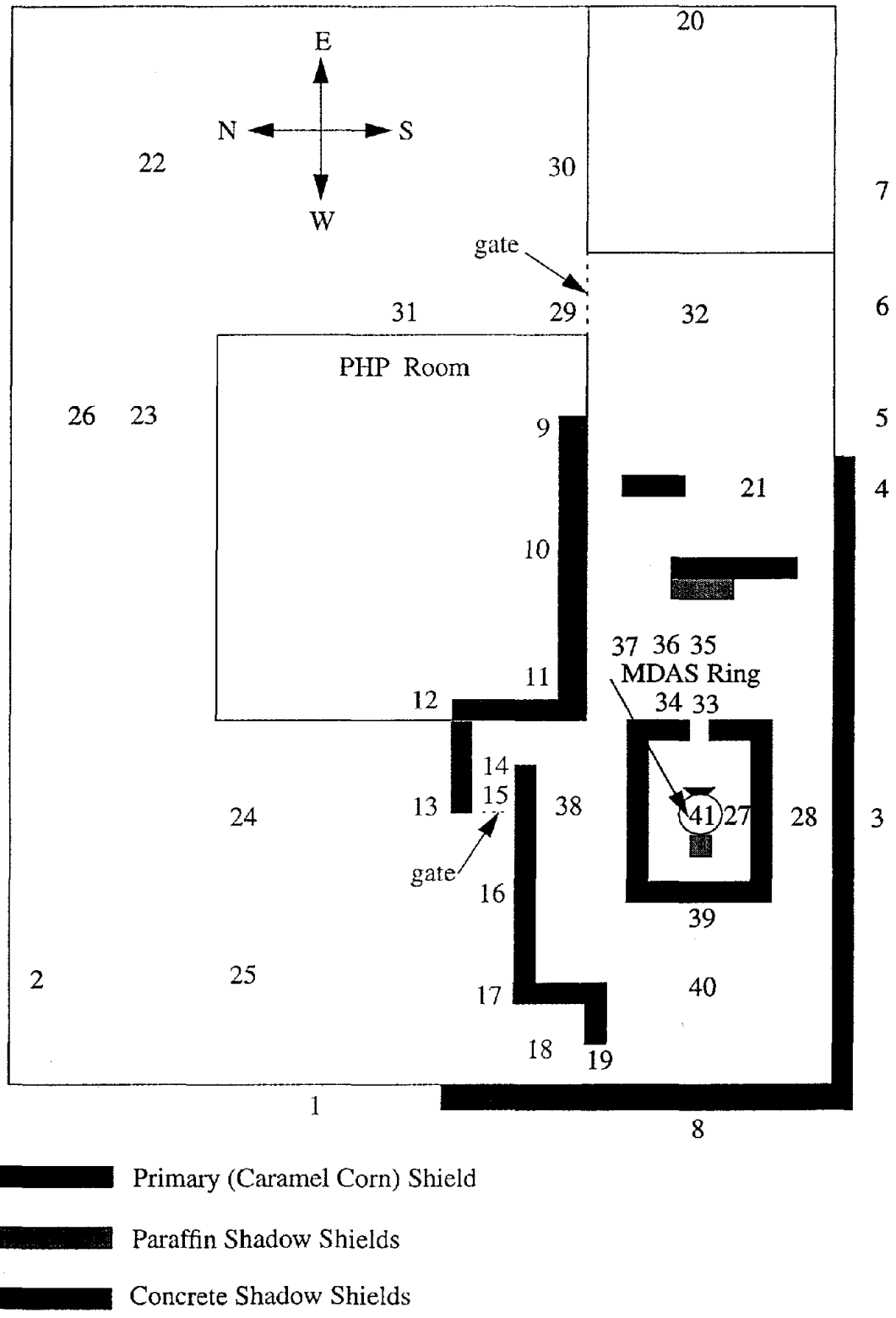


Fig. 2 MDAS Steel Ring plus Graphite Reflector, Primary Shielding, and Assembly Transfer Cask

