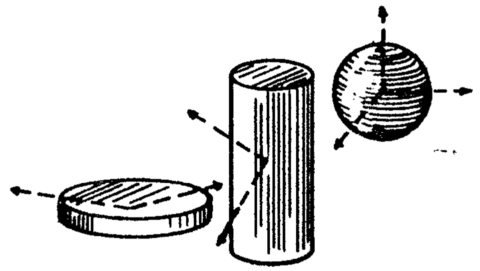

ISBN: 0-89448-119-3

CRITICALITY SAFETY IN THE STORAGE OF FISSILE MATERIAL

PROCEEDINGS OF A TOPICAL MEETING

Jackson, Wyoming
September 8-11, 1985

American Nuclear Society
Idaho Section
Nuclear Criticality Safety Division

ENRICHED URANIUM STORAGE IN STEEL TUBES EMBEDDED IN CONCRETE

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Neutron absorption in concrete and steel was utilized to develop an efficient storage medium for enriched uranium. Storage consolidations and improvements were needed due to cost and floor space required for air-spaced arrays that depend on neutron leakage. The KENO IV Monte Carlo criticality program with 16-energy-group cross sections was used in all calculations to finalize the storage module design. A test module was constructed for subcritical in situ loading experiments which confirmed the calculations.

INTRODUCTION

For many years, most storage of unirradiated highly enriched uranium was in air-spaced arrays whose safety was based on a few pertinent critical experiments. This situation was satisfactory until the amount of enriched material requiring storage greatly increased. This increase forced a refinement in storage efficiency in terms of cost and floor space occupied. Criticality safety for concentrated storage could no longer be obtained by neutron leakage from air-spaced arrays but must now be obtained by using low-cost, commercially available neutron absorbers.

CONCEPT

A conceptual design for spaced steel storage tubes embedded in a concrete monolith evolved from numerous discussions among operations, engineering, and criticality safety personnel. Neutron thermalization and absorption would be provided by commercially available concrete and steel, and each storage tube would accept a variety of shapes common to shipping containers. Since concrete dries with time, only that hydrogen which is chemically bound to the cement was considered in determining long-term safety. Concrete mixed using eight bags of cement per cubic yard--double that normally used-- was recommended to increase the bound hydrogen. Interspersed additives which might increase neutron absorption were rejected due to cost and quality-assurance considerations. Preliminary criticality safety calculations have shown that 30.48 cm (12 in.) of concrete will be an effective separator when enriched uranium materials are stored in 20.32-cm square by 366-cm long steel tubes with 0.635-cm thick walls (i.e., storage tubes are positioned on 50.8-cm centers). A conceptual design is shown in Figure 1.

CALCULATIONS

The calculations employed the KENO[1] computer program with 16-energy-group neutron cross sections. KENO is a multigroup Monte Carlo criticality program which allows K_{eff} calculations of complex three-dimensional systems. The code and cross sections were validated by the Oak Ridge Y-12 Plant for production criticality safety computations.[2, 3]

The KENO calculations utilized 53 batches of 600 neutrons each. The neutrons were started with a flat distribution in the enriched uranium, and the first three batches in each case were skipped to determine K_{eff}. The array of basic storage cells (i.e., steel tubes, fuel, and concrete) was reflected on all six faces with two feet of Tower Shielding concrete[4] by using differential current albedos.[5] Adjoint biasing was not employed.[6]

All calculations assumed a U-235 enrichment of 93.2%, the highest likely to be encountered for storage. The material atomic densities used in the calculations are given in Tables 1 and 2.

Calculational results are depicted in Figures 2 and 3 for uranium metal and in Figures 4 and 5 for UO_2.

RESULTS

Figures 2, 3, 4, and 5 depict the calculational results of U(93.2) fuel in various forms when the fuel is stored in 20.32-cm square by 366-cm long steel tubes with 0.635-cm walls. Each tube is surrounded by 30.48 cm of concrete and positioned in a 1 x 40 x 5 array fully reflected on all six faces by concrete. Uranium metal and UO_2 at various densities are chosen due to their general interest to the enriched uranium industry.

METAL

Figure 2 displays the results of a series of calculations for full density metal cylinders and full density metal slabs of constant 15.24-cm width, using wet and dry concrete as the absorbing medium. Two separate calculations for 20 percent uranium/80 percent aluminum alloy cylinders are also shown. The fuel is centered in the tubes. Dry concrete produces a greater neutron multiplication than wet concrete, thus indicating the effect of decreasing the hydrogen concentration in the concrete.

Figure 3 shows the results for varying density U(93.2) metal cylinders using only dry concrete. In these cases the cylinder mass was constant with density reduced by increasing the cylinder radius. As the metal density decreased from full density, neutron multiplication initially decreased and then rose to a K_{eff} slightly greater than that for full density metal when each tube contained the largest diameter cylinder possible. The effects of cylinder position within each tube are also indicated for full density metal.

OXIDE

Figure 4 depicts the results for $U(93.2)O_2$/water cylinders using only dry concrete as the absorbing medium. The fuel is closely surrounded by a 0.0254-cm polyethylene sleeve and is positioned in the corner of each tube. Neutron multiplication steadily increases as the amount of fuel increases.

Figure 5 displays the results for varying density $U(93.2)O_2$/water cylinders in doubled length (732 cm) tubes embedded in dry concrete. Fuel mass was constant for all calculations. In these cases, neutron multiplication gradually increased as the oxide density decreased. Two separate calculations indicate that polyethylene sleeving around each cylinder reduces neutron multiplication. Comparison of the 3.0 g/cm^3 point for 732-cm length tubes of Figure 5 with the analogous point for 0.4809-kg/cm loading in 366-cm length tubes of Figure 4 indicates that tube length has very little influence on neutron multiplication.

Since concentrated storage of uranium relying on neutron absorption was a departure from previous practices relying on neutron leakage, a subcritical in situ loading experiment was performed using the test module shown in Figure 6. The in situ experimental results were in good agreement (three significant figures in K_{eff}) with the calculations of wet concrete thus confirming the conclusions based on calculations.

DISCUSSION

Should storage of the type described herein be implemented, computations similar to those shown should be performed for the proposed material loading, shape, and position within each tube. Examples of potential problems which should be considered include: (1) improper concrete mixture, (2) voids in the concrete, and (3) double loading a single tube.

CONCLUSIONS

Criticality calculations and in situ measurements on a test module indicate that enriched uranium storage in spaced steel tubes embedded in concrete is possible, and some indication of the storage capacity attainable has been shown. The long-term safety of such storage is assured even if maximum concrete drying occurs.[7]

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Table 1. Material Atomic Densities (Non-Fissile Material)

Element	Atomic Densities $\left(\frac{\text{Atoms}}{\text{Barn - cm}}\right)$ Wet Concrete[a]	Dry Concrete[b]	Tower Shielding Concrete	Carbon Steel
H	1.3207-2	5.9299-3	8.5000-3	-
C	1.0869-2	1.0869-2	2.0200-2	3.9210-3
O	4.4426-2	4.0787-2	3.5500-2	-
Na	1.2899-5	1.2899-5	1.6300-5	-
Mg	2.1006-4	2.1006-4	1.8600-3	-
Al	3.2163-4	3.2163-4	5.5600-4	-
Si	9.6143-4	9.6143-4	1.7000-3	-
S	6.0281-5	6.0281-5	-	-
K	8.2232-6	8.2232-6	4.0300-5	-
Ca	1.3665-2	1.3665-2	1.1100-2	-
Fe	8.3678-5	8.3678-5	1.9300-4	8.3491-2

a A cubic yard of wet concrete nominally consists of 752 lbs. of cement, 333 lbs. of water, 1500 lbs. of fine aggregate, and 1470 lbs. of coarse aggregate. The cement weighs 94 lb/bag, and the relative weight percent of each element is 35.83% O, 0.11% Na, 1.90% Mg, 3.23% Al, 10.05% Si, 0.72% S, 0.12% K, 45.70% Ca, and 1.74% Fe.

b The mass of water in dry concrete is 20% of the cement mass. This water is chemically bound; therefore, the concrete will never be dryer than considered in this analysis.

Table 2. Material Atomic Densities (Fissile Material)

U(93.2) Metal			U(93.2) O_2/Water[a]					20% U(93.2)/80% AL		
Uranium Density (g/cm^3)	Atomic Densities ($\frac{Atoms}{Barn-cm}$)		Oxide Density (g/cm^3)	Atomic Densities ($\frac{Atoms}{Barn-cm}$)				Atomic Densities ($\frac{Atoms}{Barn-cm}$)		
	U-235	U-238		U-235	U-238	Hydrogen	Oxygen	U-235	U-238	AL
18.76	4.4796-2	3.2271-3	5.00	1.0507-2	7.5690-4	4.2024-3	2.4684-2	1.4965-3	1.0781-4	5.5951-2
11.21	2.6771-2	1.9286-3	4.00	8.4052-3	6.0551-4	3.3621-3	1.9748-2			
7.44	1.7776-2	1.2806-3	3.50	7.3546-3	5.2982-4	2.9415-3	1.7279-2			
5.30	1.2658-2	9.1188-4	3.00	6.3039-3	4.5413-4	2.5217-3	1.4811-2			
3.08	7.3503-3	5.2951-4	2.50	5.2533-3	3.7844-4	2.1012-3	1.2343-2			
2.40	5.7225-3	4.1225-4	2.00	4.2026-3	3.0276-4	1.6814-3	9.8740-3			

[a] Oxide is analyzed at relative weight percents of 88% U(93.2) and 12% O. H/U-235 = 0.4.

Figure 1. Tube Vault Conceptual Design

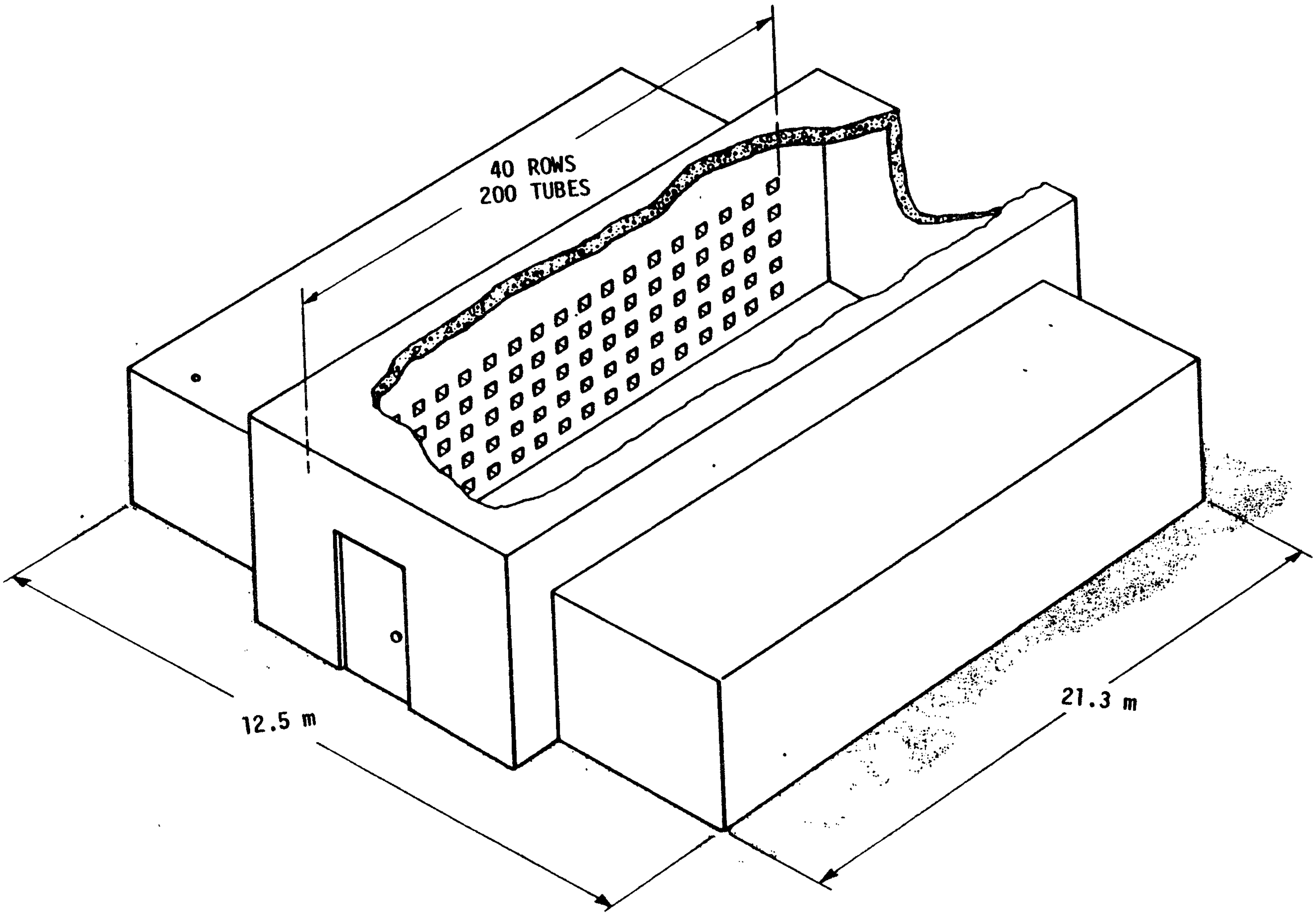

Fig. 2

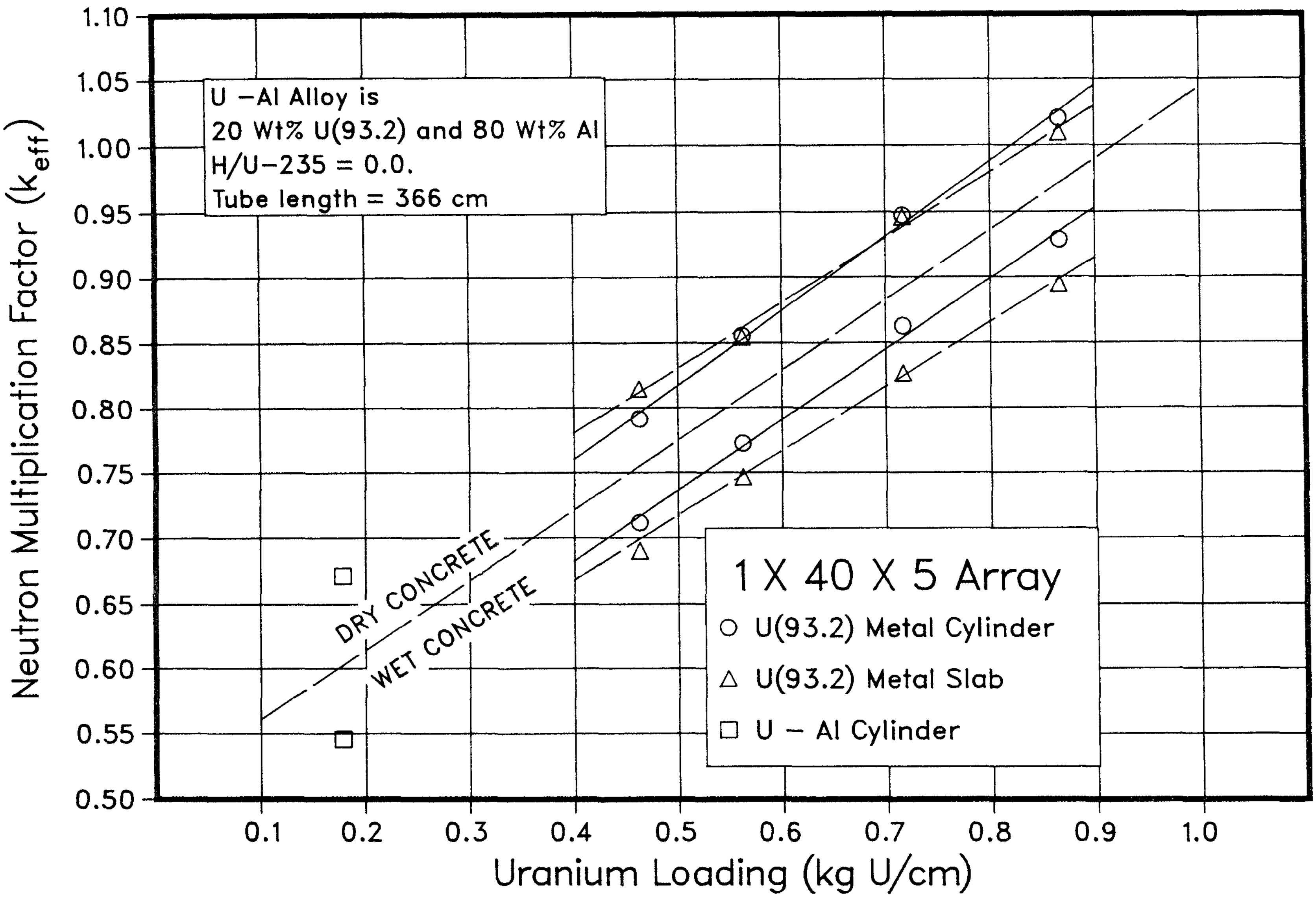
U –Al Alloy is
20 Wt% U(93.2) and 80 Wt% Al
H/U–235 = 0.0.
Tube length = 366 cm
DRY CONCRETE
WET CONCRETE
1 X 40 X 5 Array
U(93.2) Metal Cylinder
U(93.2) Metal Slab
U – Al Cylinder
Neutron Multiplication Factor (k_{eff})
Uranium Loading (kg U/cm)
1.10
1.05
1.00
0.95
0.90
0.85
0.80
0.75
0.70
0.65
0.60
0.55
0.50
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

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Fig. 3

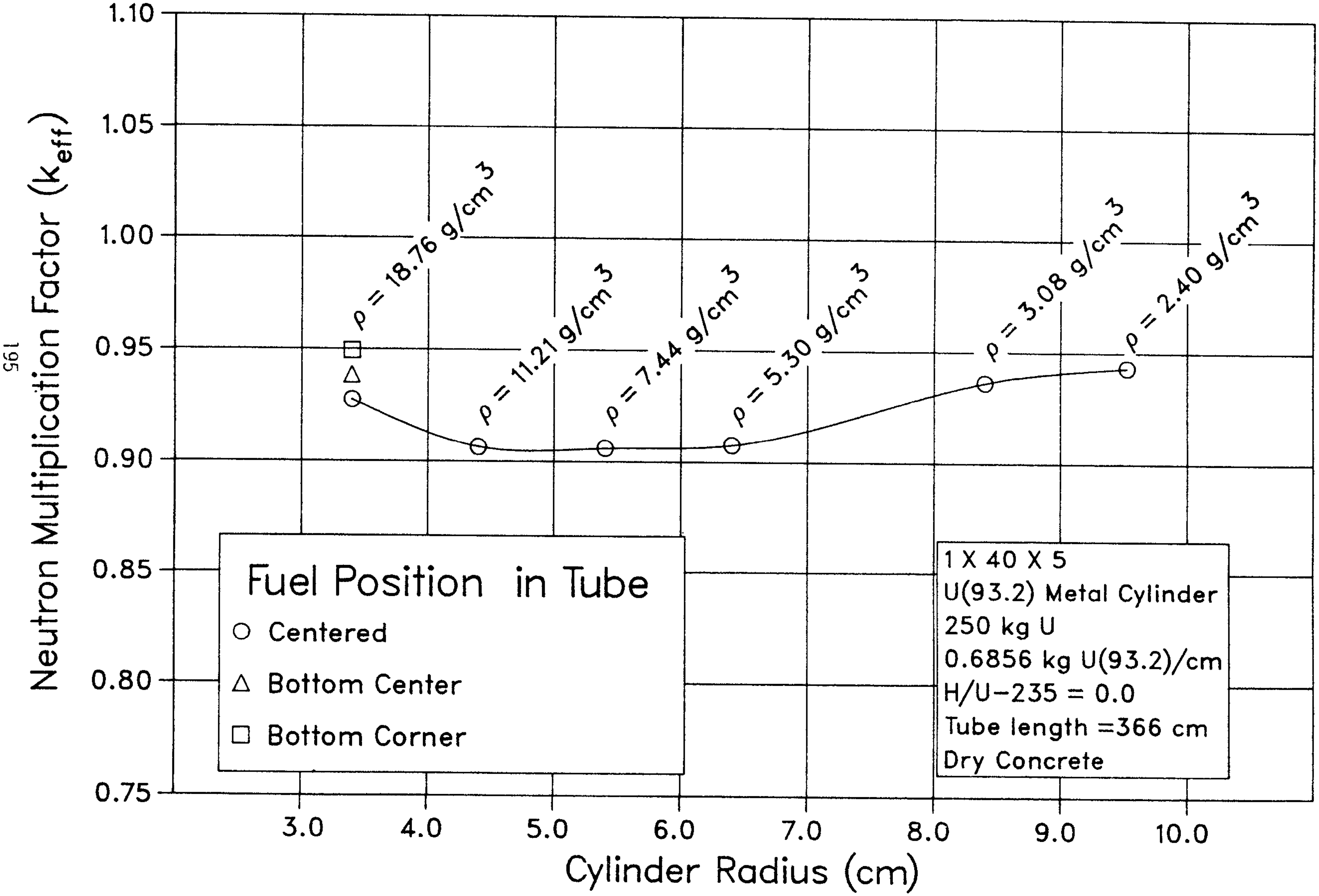
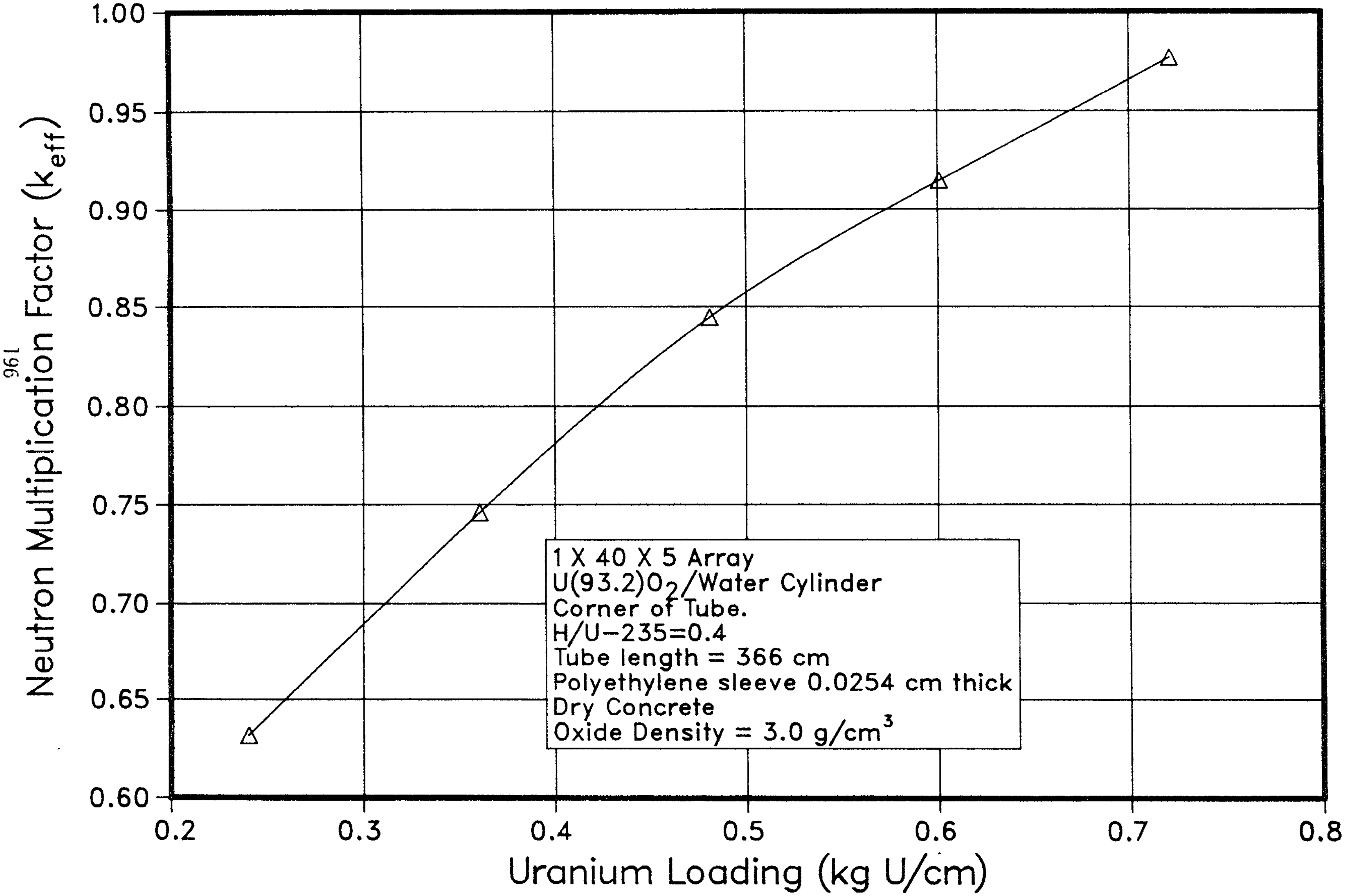

Neutron Multiplication Factor (k_{eff})
1.10
1.05
1.00
0.95
0.90
0.85
0.80
0.75
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
Cylinder Radius (cm)
ρ = 18.76 g/cm 3
ρ = 11.21 g/cm 3
ρ = 7.44 g/cm 3
ρ = 5.30 g/cm 3
ρ = 3.08 g/cm 3
ρ = 2.40 g/cm 3
Fuel Position in Tube
Centered
Bottom Center
Bottom Corner
1 X 40 X 5
U(93.2) Metal Cylinder
250 kg U
0.6856 kg U(93.2)/cm
H/U−235 = 0.0
Tube length =366 cm
Dry Concrete

Fig. 4



Neutron Multiplication Factor (k_{eff})
1.00
0.95
0.90
0.85
0.80
0.75
0.70
0.65
0.60
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Uranium Loading (kg U/cm)
1 X 40 X 5 Array
$U(93.2)O_2$/Water Cylinder
Corner of Tube.
H/U-235=0.4
Tube length = 366 cm
Polyethylene sleeve 0.0254 cm thick
Dry Concrete
Oxide Density = 3.0 g/cm^3

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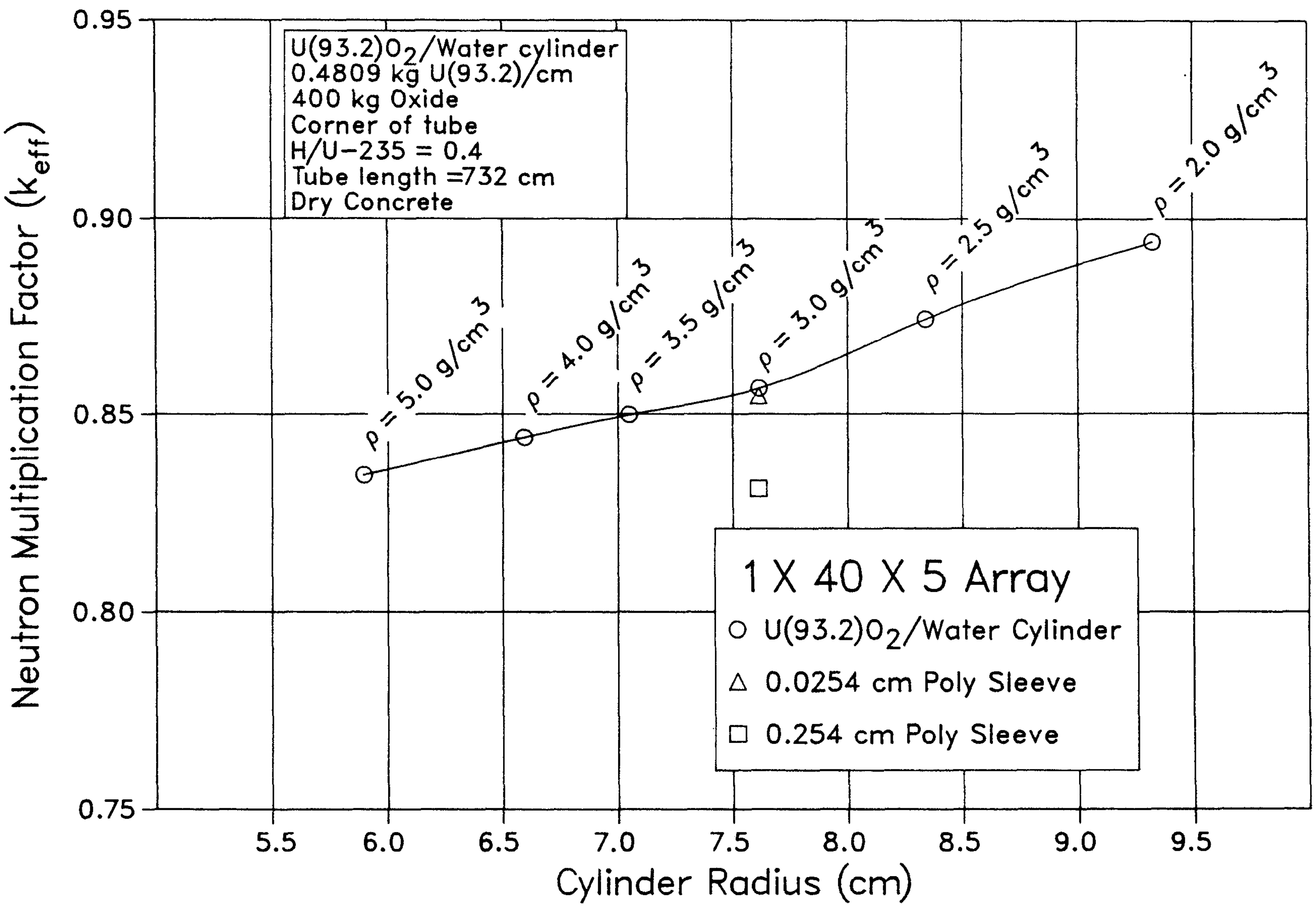
Fig. 5


U(93.2)O2/Water cylinder
0.4809 kg U(93.2)/cm
400 kg Oxide
Corner of tube
H/U-235 = 0.4
Tube length =732 cm
Dry Concrete
ρ = 5.0 g/cm 3
ρ = 4.0 g/cm 3
ρ = 3.5 g/cm 3
ρ = 3.0 g/cm 3
ρ = 2.5 g/cm 3
ρ = 2.0 g/cm 3
1 X 40 X 5 Array
U(93.2)O2/Water Cylinder
0.0254 cm Poly Sleeve
0.254 cm Poly Sleeve
Neutron Multiplication Factor (keff)
Cylinder Radius (cm)
0.95
0.90
0.85
0.80
0.75
5.5
6.0
6.5
7.0
7.5
8.0
8.5
9.0
9.5

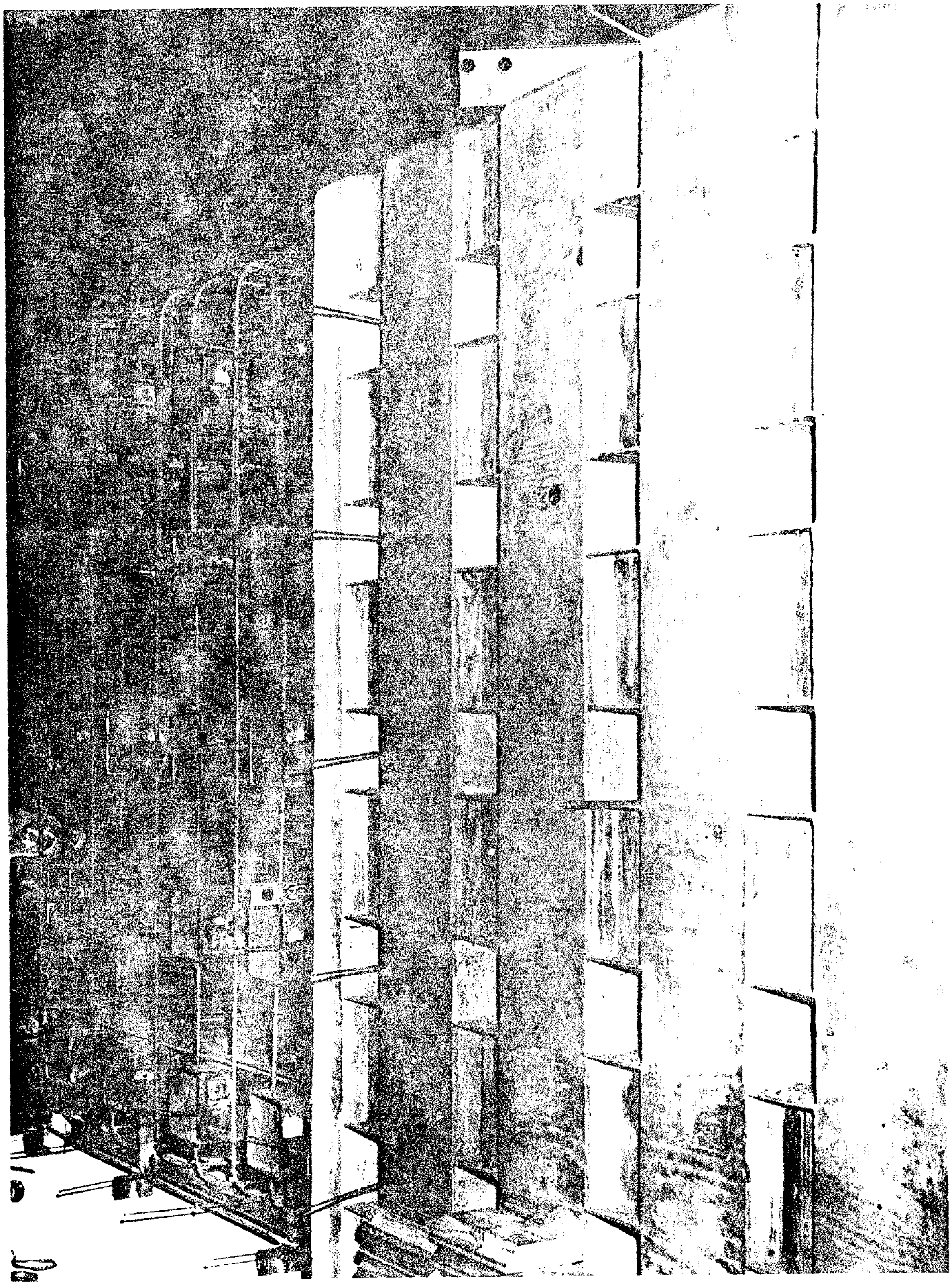


Figure 6. In Situ Module. Under construction.