Conf-780506--22

MASTER

REVIEW OF CRITERIA FOR NUCLEAR CRITICALITY SAFETY CONTROL IN TRANSPORTATION*

J. T. Thomas
Computer Sciences Division at Oak Ridge National Laboratory
Union Carbide Nuclear Division, Oak Ridge, TN 37830

D. R. Smith
Los Alamos Scientific Laboratory, University of California
Los Alamos, New Mexico

*Research sponsored by the Office of Energy Technology, Waste Management Division, U. S. Department of Energy under contract W-7405-eng-26 with the Union Carbide Corporation.

DISCLAIMER

REVIEW OF CRITERIA FOR NUCLEAR CRITICALITY SAFETY CONTROL IN TRANSPORTATION

J. T. Thomas, ORNL
D. R. Smith, LASL

SUMMARY

Basic elements in the review of criteria for nuclear criticality safety in transportation are the magnitudes of reactivity changes that may occur to a shipment of packages and those inherent in the regulatory procedure of assessment. The generic representation of criticality of reflected arrays of uncontained fissionable materials is used as a basis for comparison of packaged fissionable materials. The reactivities associated with array changes and perturbations representative of credible conditions that may occur in storage or transportation are summarized for air-spaced units of fissionable materials. Calculations of packaged fissionable material determined reactivities associated with similar changes to arrays of packages. Typical thermal insulating materials being studied are Celotex, wood, Foamglas, and a bonded vermiculite. The effect on the array neutron multiplication of these, with and without steel as an inner and outer container material, is examined. The present stage of the study has produced results illustrating the variable margin of subcriticality manifested by the criteria. Depending upon the packaging, mass loading and array reflector condition, the margin of subcriticality can be of the order of 1% in k_{eff}.

REVIEW OF CRITERIA FOR NUCLEAR CRITICALITY SAFETY CONTROL IN TRANSPORTATION

J. T. Thomas, ORNL
D. R. Smith, LASL

Early safety assessments of the potential for nuclear criticality in the transportation of fissionable materials were accomplished by comparison with experimental data and conservative extrapolation to the environment of commerce. Evaluations have since grown to rely more extensively on calculational methods. The reliable domonstration of subcriticality by calculation must consider credible normal and abnormal conditions that may be met in transit. Control of criticality for type B packages in class II shipments is primarily by managing the number of packages allowed in a vehicle or temporary storage area. This is accomplished by the assignment of a transport index (TI) to each package. The index for a package is determined by multiplying the reciprocal of the allowable number, N_A, by 50. Thus, if carriers limit the aggregate TI to 50, no vehicle or area should have more than the allowable number of packages.

The condition establishing the number of allowed undamaged packages is that five times N_A in any arrangement closely reflected by water shall be subcritical. For packages damaged to the extent defined by approved tests, twice N_A in any arrangement closely reflected by water and with homogeneous hydrogenous moderation between and within packages consistent with the tests in that amount which results in the greatest increase in reactivity shall be subcritical.

A basic assumption in the regulations is that full reflection by water defines a more reactive condition for an array of packages than will be encountered in transportation. The demonstration of subcriticality is not specific. The requirement calls for a neutron multiplication factor less than unity. Adequacy of the margin of subcriticality inherent in 1/5 the number of undamaged packages, or 2/5 in the case of damaged packages is assumed by the nuclear community. Characterization of the magnitude of reactivity changes associated with different packaging materials, with encountering reflectors other than water, with the presence or absence of hydrogenous moderation, and with the variation of density of fissionable materials is necessary to judgments of adequacy.

Each package configuration can present a unique evaluation. Therefore, expression of the criticality characteristics in a generic manner is needed to effect meaningful comparisons. A well-documented bases that can be used for this purpose is the criticality data of air-spaced units of fissile materials. The effect of water and concrete as reflectors surrounding arrays has been characterized. The influence of changing the shape of the unit, the shape of the array, and the shape of the cell, singly or in combination, on the neutron multiplication factor can be reliably estimated. Further, the equivalence of fissionable material masses in critical arrays is defined and enables evaluations performed with a particular material to be related to other materials. This data base has been in use for approximately ten years and is consistent with the ANSI Standard N 16.5 (1975) Guide for Nuclear Criticality Safety in the Storage of Fissile Materials.

The following presents these bases in terms of array reactivity changes typical for air-spaced units in water and concrete reflected arrays. Similar characteristics thus far studied for packaged fissionable materials are presented and comparisons made.

Calculational Method and Validation

The magnitude of changes in array neutron multiplication factors associated with changes in array conditions is determined by calculational techniques validated by critical experiments with material of interest. The KENO Monte Carlo code[1] in combination with the Hansen-Roach[2] sixteen group neutron cross section sets was used in this study. The reliability of the code and cross section sets to compute the complex geometries of reflected arrays of air-spaced subcritical components of fissionable materials has been documented.[3,4] Validation of calculations performed on packaging materials surrounding fissionable material is by applicable experiments from a series conducted[5] at the Oak Ridge Critical Experiments Facility in 1972. These experiments utilized eight U(93.2) metal cylinders at a height-to-diameter ratio of 0.94, each having a mass of 20.96 kg, spaced in various insulating materials, and the arrays reflected by a minimum of 16 cm thickness of polyethylene ($(CH_2)_x$ at 0.92 g/cc). The experimental k_{eff} determined with four typical insulating materials are presented in Table 1. Comparison of the calculation and experimental results is made. The agreement is within 1% ± 2σ. A conservative application of calculated data would be to assign a -2% bias to the calculations with Foamglas insulation and -1% to the Celotex and wood insulation.

Results with Air-Spaced Units

Calculated critical water-reflected cubic arrays of spherical U(93.2) metal units were subjected to changes to determine the reactivity change of the resulting array. The array reflector condition was examined by noting the change in neutron multiplication factor caused by replacing the thick water reflector with concrete of several thicknesses and representing the result analytically.[3,4]

TABLE 1

Experimental Neutron Multiplication Factor of Eight-Unit Polyethylene Reflected Arrays of 20.96 kg U(93.2) Metal Cylinders with Various Interstitial Materials and KENO Monte Carlo Calculated k_{eff}

Material	Density (g/cc)	Neutron Multiplication Factor: Exps.	Neutron Multiplication Factor: KENO
Vermiculite	0.34	1.0005	1.0082 ± 0.0036
Plywood	0.529	1.0005	1.002 ± 0.005
			0.989 ± 0.004
Celotex	0.215	0.9979	0.999 ± 0.004
Foamglas	0.148	1.0004	1.017 ± 0.004

TABLE 2

Change in Array Reactivity Associated in Replacing 20-cm-thick Water Reflector on Six Sides of an Array by 20.3- and 40.6-cm-thick Concrete

Mass for Criticality Water Reflector kg U(93.2)	Concrete Reflector on 6 sides: 20.3 cm	Concrete Reflector on 6 sides: 40.6 cm	Reflector on 3 sides: Water, 20.3 cm	Reflector on 3 sides: Concrete, 40.6 cm
45.0	+0.018	+0.027	-0.048	-0.032
35.0	+0.044	+0.064	-0.074	-0.051
26.0	+0.066	+0.095	-0.099	-0.068
13.0	+0.096	+0.137	-0.138	-0.095
7.5	+0.108	+0.153	-0.156	-0.106
3.6	+0.117	+0.165	-0.169	-0.115
1.0	+0.122	+0.173	-0.178	-0.120

Table 2 presents typical results for 20.3- and 40.6-cm thick concrete ($\rho \sim 2.3$ g/cc). The gain in reactivity is dependent on the mass of the unit, increasing as the mass decreases. The effect is independent of the number of units. Also shown in Table 2 is the effect of partial array reflection. The loss in array reactivity relative to the totally water reflected critical array by water and by concrete is given. The magnitude of loss increases for decreasing mass of units in the arrays. Under the constraint of criticality, these larger effects at smaller mass per cell are indicative of arrays with strongly neutron-coupled units.

Reducing Number of Units in an Array

The loss in array reactivity as a result of reducing the number of units in a critical reflected array is dependent on the mass of the unit per cell and to a lesser extent on the number of units in the array. Typical results for spherical units of U(93.2) metal units are presented in Table 3 for the factors of 1/5 and 2/5 appearing in the regulations. These results for spherical units are maximum values that may be expected. For units having the same reactivity as the spherical units but of different shape, the loss in array reactivity will be less than for the spherical units.

Shape of Unit and Cell

The effect of varying the unit shape and the cell shape on the array neutron multiplication factor was explored by calculation. Cylindrical units of U(93.2) metal were centered in cubic cells in arrays with an equal number of cells along each array edge, and the arrays reflected by water. The shape of the cylinder was varied by changing its height-to-diameter ratio, h/d, while the mass was constant.

TABLE 3

Loss in Array Reactivity ($\Delta k_{eff}/k_{eff}$) Due to Reducing the Number of Units in a Reflected Critical Array of N-Air-Spaced Units

Mass of U(93.2)/cell (kg)	N'/N = 2/5			N'/N = 1/5		
	N=8000	512	64	8000	512	64
45.0	0.012	0.013	0.015	0.019	0.021	0.024
35.0	0.030	0.032	0.037	0.048	0.052	0.060
26.0	0.047	0.049	0.057	0.076	0.082	0.095
13.0	0.072	0.077	0.089	0.120	0.128	0.151
7.5	0.083	0.089	0.103	0.139	0.150	0.177
3.6	0.091	0.097	0.113	0.159	0.166	0.196

TABLE 4

Loss in Array Reactivity to a Critical Water Reflected Array of U(93.2) Metal Cylinders When Unit and/or Cell Shape is Varied

Unit Shape	Cell Shape				
	9.5 kg, 512 units	20.9 kg, 27 units	26.2 kg, 216 units		
h/d	cubic[a]	cubic[a]	cubic[a]	cell=unit[a]	cell=2 x unit[a]
4.0	0.046	0.058	0.082	0.109	0.102
3.0	0.031	0.041	0.069	0.074	0.085
2.0	0.018	0.012	0.033	0.037	0.048
0.7-1.0	--	--	--	--	--
0.5	0.008	0.008	0.009	0.022	0.014
0.3	0.025	0.041	0.048	0.068	0.058
0.2	0.034	0.064	0.095	0.120	0.097
0.1	0.066	0.113	0.137	0.166	0.179

[a]Cell shape defined as ratio of cell height to an edge of its square base. Cell volume is constant.

The h/d ratio varied from 0.1 to 4. Typical results are shown in Table 4 for these different critical arrays. There is not a significant change in the array k_{eff} for h/d variation in the range 0.7 to 1 independent of the mass, number of units or cell shape. In general, deviation of unit shape from the optimum, i.e., near equilateral, maintaining the mass results in a decrease in the array neutron multiplication factor. Similar effects are observed when the cell and unit shapes are changed simultaneously and have about the same shape factors. In contrast, variation of the cell shape from 0.1 to 8 while the unit is near equilateral results in a negligible change in the array k_{eff}, provided unit surfaces remain separated at least 15 cm.

Array Shape

A calculational study of the response of reflected array k_{eff} to changes in array shape was made where the cubic cells of the top tiers of a cubic array were removed and placed at the boundaries of the array to produce a nearly equal number of cells along the base edges of the array. Characterizing the array shape as the ratio of the number of cells in the vertical direction to the number along the base edge, it was observed that less than 5% in k_{eff} is associated with changing the array shape from 1 to 0.5. Further reduction in the shape ratio results in greater reactivity loss. In the limit, arrangement of the cells of a cubic array into a planner array, reflected by water, can result in as much as 30% reduction in k_{eff}. The reactivity response is dependent on the mass of the unit in the cells, the reactivity loss increasing with decreasing mass of units.

Density of Fissionable Material

Reflected arrays of air-spaced units with fissile materials at maximum theoretical densities are, in general, more reactive than arrays with same mass of unit per cell at reduced densities. The magnitude of array reacitivity loss on reducing the density of fissile material in a critical array increases with increasing mass of units. This effect may not occur when the space between units is occupied by neutron energy moderating materials.

Reduction in Cell Volume

Uniform decreases in cell volumes result in an increase in the array k_{eff}. Decreasing the cell dimensions in an array by about 3% causing a decrease in cell volume of approximately 5% result in the array reactivities shown in Table 5 as a function of mass of a spherical unit in the cell. Doubling the volume change results in a doubling of the reactivities shown.

TABLE 5

Reactivity Increase to a Critical Water Reflected Array
Due to a 10% Decrease in Cell Volume

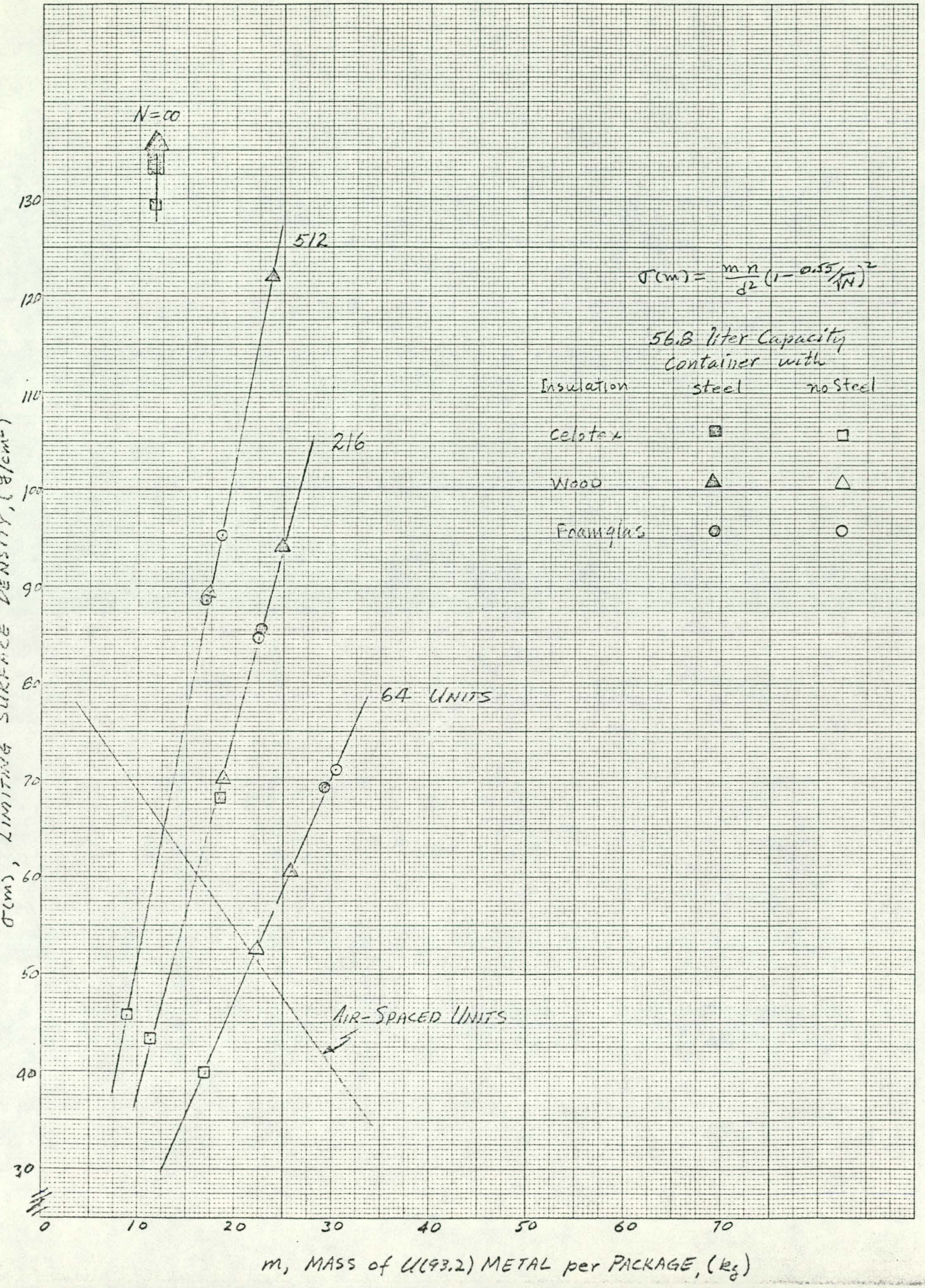
Mass of Unit in Cell, kg	$\Delta k_{eff}/k_{eff}$
45.0	0.003
35.0	0.007
26.0	0.011
13.0	0.016
7.6	0.018
3.6	0.020
1.0	0.021

Arrays with Packaging Materials

The introduction of packaging materials into arrays of air-spaced units affects the neutron coupling among the units, increases the unit self multiplication within the array and diminishes the effects of reflector materials on the array k_{eff}. In an effort to minimize geometric differences and allow direct comparison to the data base, cubic cells arranged in cubic arrays are used in the calculation. The arrangement and location of the packaging materials is similar to the Type B, specification 6M container.[6] The 2R inner container is centered in the cell and the insulation and outer container are located adjacent to the cell boundary. A majority of the calculations were performed with three container capacities. These volumes were 56.8 liters (15 gal.), 113.6 liters (30 gal.) and 208.2 liters (55 gal.)

The effect on the array k_{eff} caused by introducing only the Celotex insulating material at a thickness of 8.9 cm into arrays of air-spaced units is to increase the k_{eff}. By contrast, the introduction of wood or Foamglas at the same thickness causes a decrease in the array k_{eff}. These effects are summarized in Fig. 1 for the 56.8 liter volume. The data show the limiting surface density[3,4] in g/cm^2 as a function of mass loading per package. The calculations are with right cylinders of U(93.2) metal. A mass loading per cell less than the reference line for air-spaced units is indicative of an increase in array reactivity while a larger mass loading corresponds to a loss in reactivity. The introduction of the inner and outer containers of steel at the minimum thickness given in Ref. 6 is to cause a negative reactivity effect in the case of Celotex and wood and a slight increase in reactivity for the Foamglas. The Celotex and wood are hydrogen bearing materials and result in a lower mean energy for fission than Foamglas which has no hydrogenous components. The neutron moderation enhances neutron absorption in the steel.

Fig 1. Critical water-reflected cubic arrays of 56.8 liter containers with different thermal insulating materials.



The wood with the inner and outer containers results in the largest mass loadings and shows little variation in loading with the number of units in the array. The presence of package materials does allow definition of loadings that would satisfy the criteria for Class I shipments. This is demonstrated in Fig. 1 by the k_∞ calculation for the Celotex package, which occurs for a mass loading of 11.6 kg U(93.2) as a cylinder. Similar results are given in Fig. 2 for the 113.2 liter and in Fig. 3 for the 208.2 liter volumes. In general, larger volumes result in larger mass loadings for the same number of packages.

The effect of concrete as a reflector surrounding arrays of packages was explored with the Celotex as the insulating material. These data for critical arrays are presented in Fig. 4. Mass loadings for criticality in a 216 unit array were calculated. These are compared to the water reflected array data from Figs. 1 through 3. The effectiveness of the concrete reflector is less than occurs in the air-spaced arrays by about a factor of 3 in reactivity.

The maximum difference in reactivity is about 0.03 while for the same arrays of air-spaced units the maximum would occur with the smallest cell volume and is approximately 0.11. These results are consistent with those of a study with a 72 liter container reported in Ref. 4. It may be expected that the effect of a concrete reflector will be less for wood and larger for Foamglas than for the Celotex.

Variation of the thickness of Celotex in a container was examined by calculating the mass loadings for a 7.6- and 10.2-cm thickness in the three cell volumes. The maximum loadings were observed for the 10.2-cm-thick insulation. However, the total reactivity difference is only about 3% in k_{eff}. These different thicknesses are interpretable as a density variation in the Celotex corresponding to about a 20% change in density.

Fig. 2 Critical water-reflected cubic arrays of 113.6 liter containers with different thermal insulating materials.

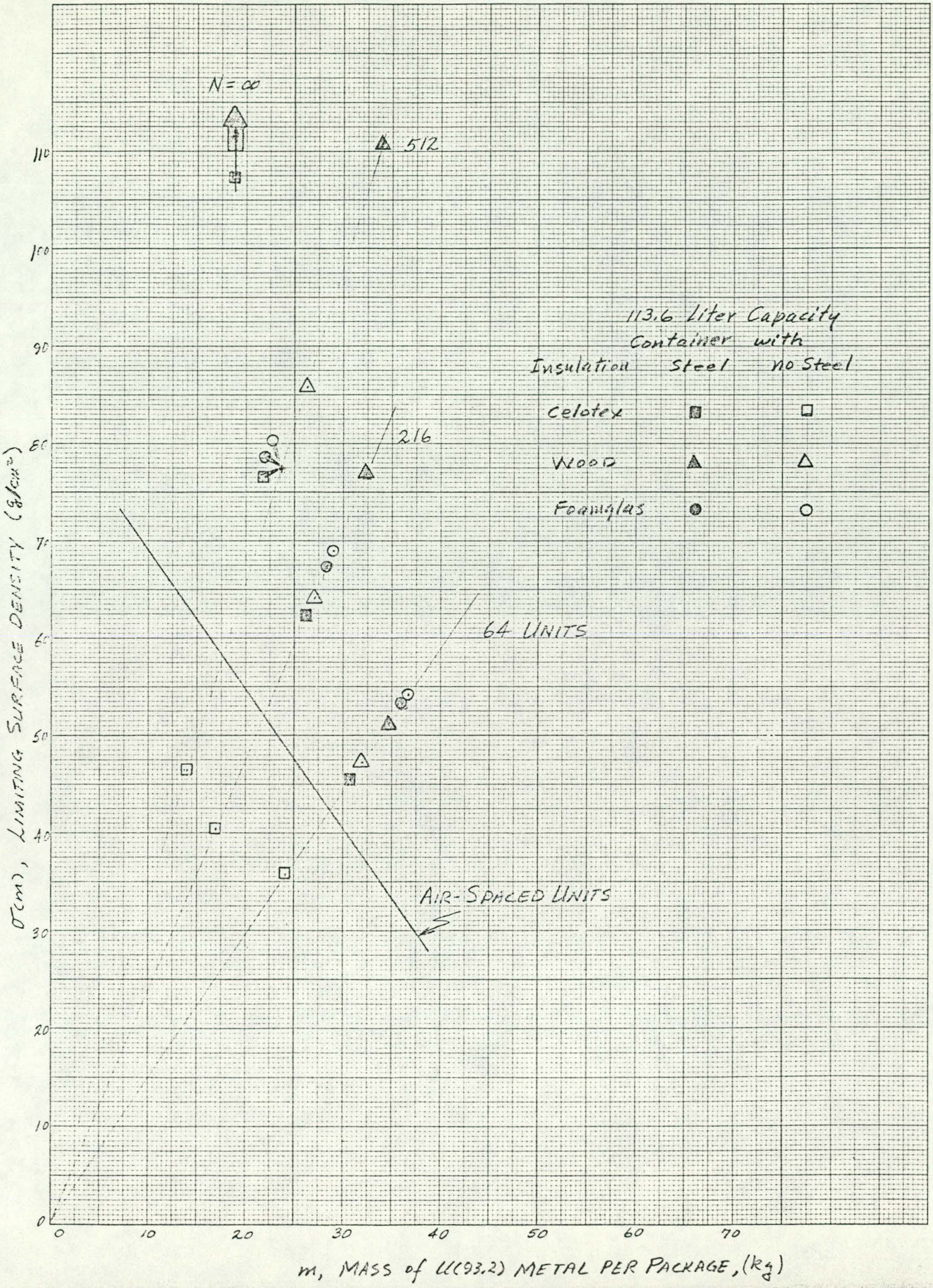


FIG. 3 Critical water-reflected cubic arrays of 208.2 liter containers with different thermal insulating materials.

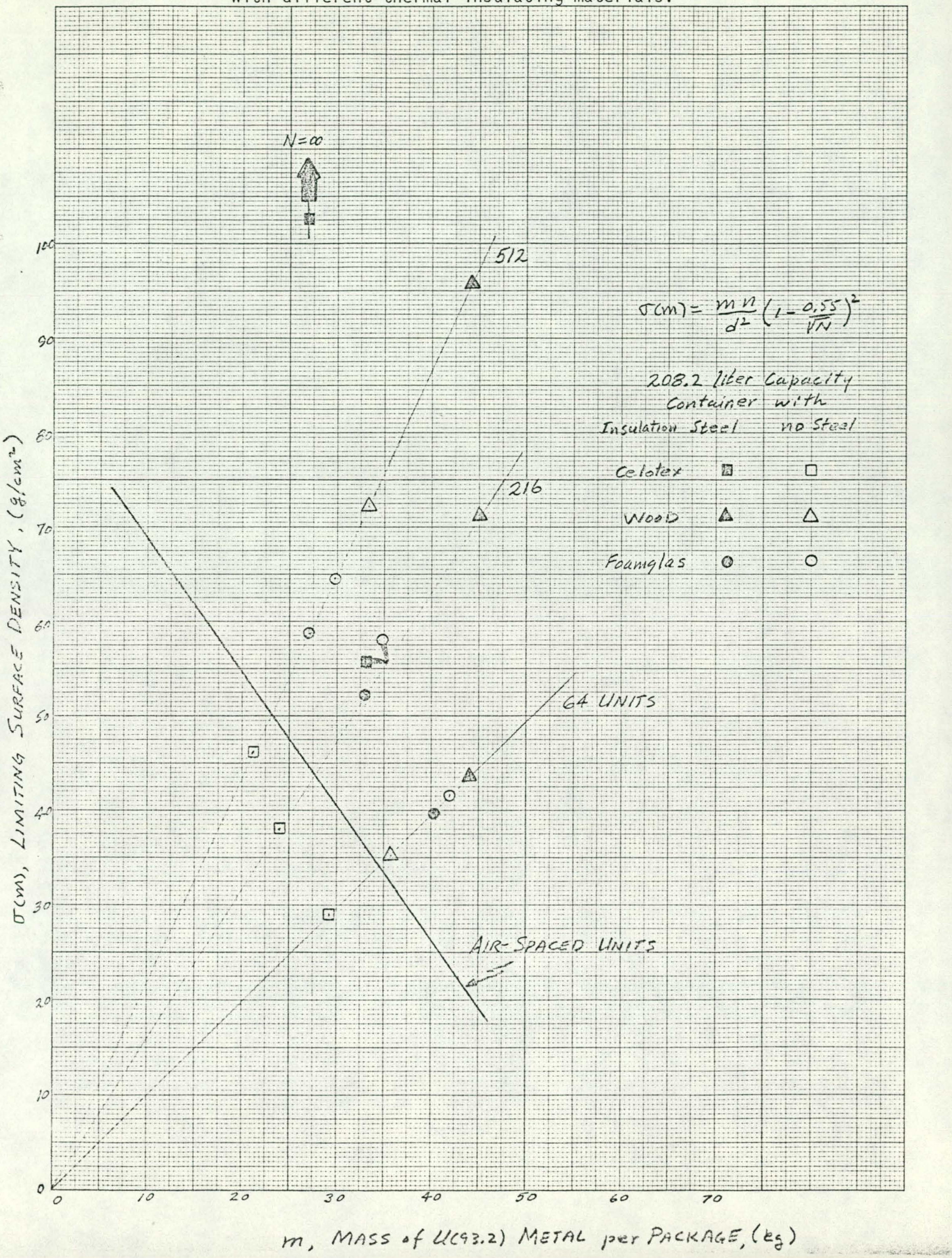
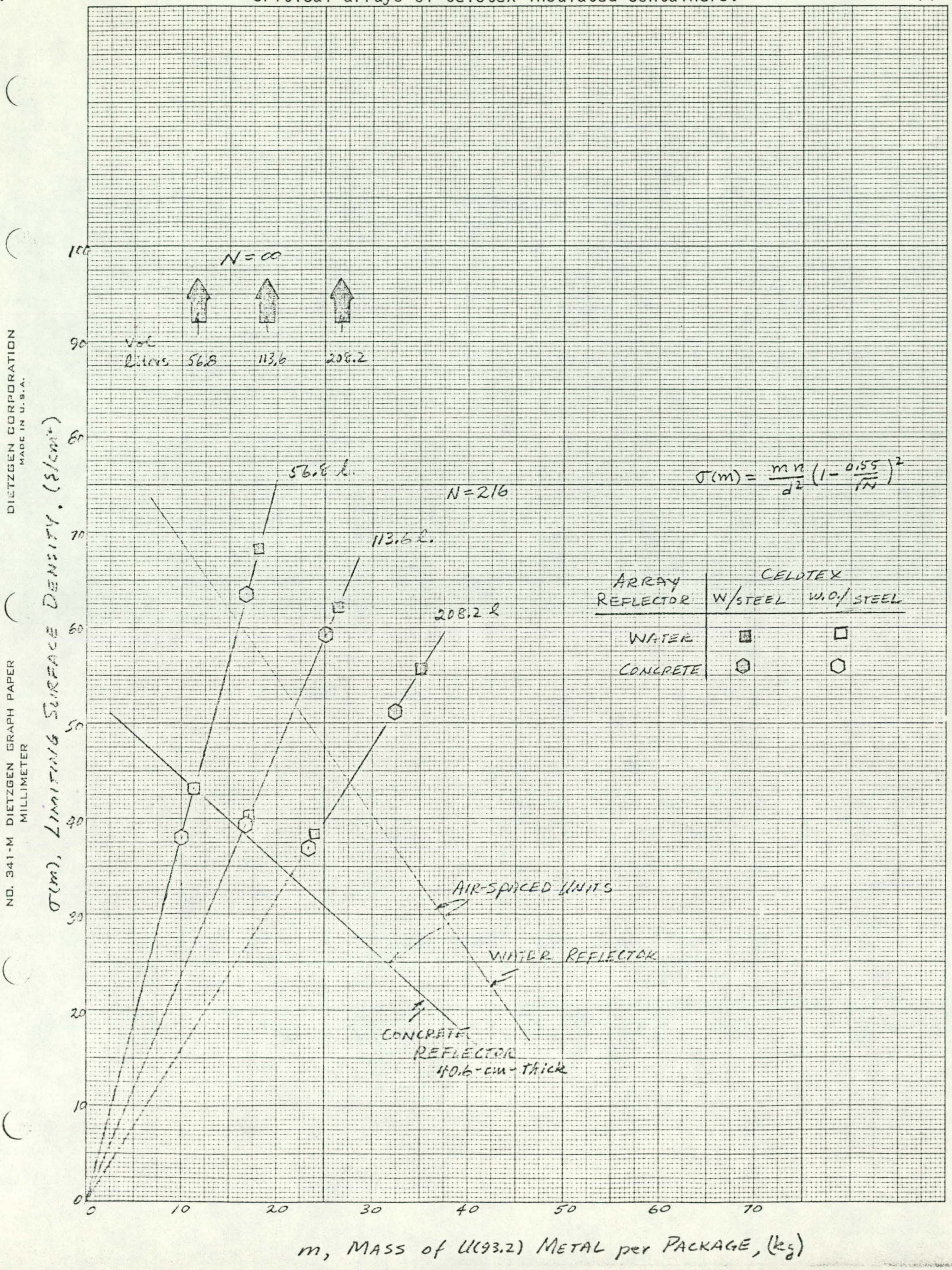


FIG. 4 Comparison of concrete and water as reflectors about critical arrays of Celotex insulated containers.



A change in the number of packages in reflected arrays also results in a diminished effect on the array k_{eff} than is observed for air-spaced units and is strongly influenced by the type of insulation. For example, in the case of wood, it has already been remarked that the mass loading is slowly varying with respect to the number of units. Reducing the number of packages from 512 to 64, i.e., to 1/8 the number will change the reactivity in the 113.2 ℓ container (∿ 34 kg U(93.2) loading) by less than 1%. A similar change for Celotex (∿ 24 kg U(93.2)) would produce ∿ 8% loss in reactivity and the largest effect would be ∿ 12% for the Foamglas (∿ 24 kg U(93.2)). The latter two materials are comparable to the reactivity changes observed for air-spaced units given in Table 3, while the reactivity loss for wood is much smaller; again, indicative of a small neutron coupling among the packages.

The effects so far studied suggest changes in shape of the units, cell and array as well as reduction in cell volume will be less than observed for the air-spaced arrays because of reduced neutron coupling and the proximity of container materials to the fissionable materials.

Array moderation, i.e., introduction of hydrogenous materials between units, has been reported[4] for the Celotex insulation. The 7.6-cm-thickness of Celotex contains an amount of hydrogen near that producing the maximum increase in reactivity due to neutron moderation. There is, however, a potential problem if fissionable materials are at less than theoretical density. For example, a mass loading of $U(93.2)O_2$ at theoretical density resulting in a critical array of packages will become supercritical, especially in small capacity containers, if the density is reduced to typical bulk oxide densities. This effect is being investigated further.

Discussion

The use of uranium metal as fissionable material in packages does provide the largest leakage fraction of neutrons from the units with the fission neutron energy spectrum. This has the advantage of improving the statistical investigation of the array k_{eff} response changes in packages and arrays of packages. Actual package design may call for greater thicknesses of wood and Foamglas than the 8.9 cm used for nuclear criticality investigations. Greater thicknesses than 8.9 cm may be required for thermal protection, but these would result in reducing the neutron coupling among the packages in the array without a significant change in the mass loadings reported here.

The use of water as a reference reflector material in the regulations is acceptable provided the reflector conditions encountered in transport do not return neutrons to arrays of packages more effectively than does water. Unfortunately, concrete can be a more effective neutron reflector than water. Further, partial reflection by concrete is easily envisioned in the commerce environment, and total reflection by concrete has become credible contingency in this era of fissionable material safeguards.

The allowable number of packages in a shipment, i.e., 1/5 the number demonstrated to be subcritical, results in a variable decrease in array reactivity dependent upon mass loading, container materials and reflector conditions. The data presented suggest this factor of safety may not be adequate in the case of containers with 8.9-cm-thick wood as an insulator. The data also indicate that large mass loadings in large packages are more weakly neutron coupled, are less sensitive to reflector conditions and arrays of these packages are subject to smaller reactivity changes than are reduced loadings in small packages.

The regulations are applicable to all containers proposed for use in transportation of fissionable materials. This work suggests the requirement of some minimum margin of subcriticality would be prudent.

REFERENCES

1. L. M. Petrie and N. F. Cross, "KENO-IV - An Improved Monte Carlo Criticality Program, ORNL/4938, Oak Ridge Naitonal Laboratory (1975).

2. G. E. Hansen and W. H. Roach, "Six and Sixteen Group Cross Sections for Fast and Intermediate Critical Assemblies," LAMS-2543, Los Alamos Scientific Laboratory (1961).

3. J. T. Thomas, "Critical Three-Dimensional Arrays of U(93.2) Metal Cylinders," Nucl. Sci. & Eng. 52, 350 (1973).

4. J. T. Thomas, "Evaluation of Criticality Criteria for Fissile Class II Packages in Transportation," Proceedings on Symposium on "Transport Packaging for Radioactive Materials," IAEA-SR-10/10, International Atomic Energy Agency, Vienna (1976).

5. D. W. Magnuson, "Critical Three-Dimensional Arrays of Neutron Interacting Units: Part III Arrays of U(93.2) Metal Separated by Various Materials," Y-DR-83, UCCND Y-12 Plant (1972).

6. R. M. Graziano's Tariff, "Hazardous Materials Regulations of the Department of Transportation," Bureau of Explosives of the Association of American Railroads (1977).