Existing Experimental Criticality Data Applicable to Nuclear Fuel Transportation Systems

S. R. Bierman

February 1983

**Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830**

**Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
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PACIFIC NORTHWEST LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC06-76RLO 1830

Printed in the United States of America
Available from
National Technical Information Service
United States Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151

NTIS Price Codes
Microfiche A01

Printed Copy	
Pages	Price Codes
001-025	A02
026-050	A03
051-075	A04
076-100	A05
101-125	A06
126-150	A07
151-175	A08
176-200	A09
201-225	A010
226-250	A011
251-275	A012
276-300	A013

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EXISTING EXPERIMENTAL CRITICALITY
DATA APPLICABLE TO NUCLEAR FUEL
TRANSPORTATION SYSTEMS

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SUMMARY

Analytical techniques are generally relied upon in making criticality evaluations involving nuclear material outside reactors. For these evaluations to be accepted the calculations must be validated by comparison with experimental data for a known set of conditions having physical and neutronic characteristics similar to those conditions being evaluated analytically. The purpose of this report is to identify those existing experimental data that are suitable for use in verifying criticality calculations on nuclear fuel transportation systems. In addition, near term needs for additional data in this area are identified.

Of the considerable amount of criticality data currently existing, that are applicable to non-reactor systems, those particularly suitable for use in support of nuclear material transportation systems have been identified and catalogued into the following groups:

- Critical Assemblies of Fuel Rods in Water
- Critical Assemblies of Fuel Rods in Water Containing Soluble Neutron Absorbers
- Critical Assemblies Containing Solid Neutron Absorber
- Critical Assemblies of Fuel Rods in Water with Heavy Metal Reflectors
- Critical Assemblies of Fuel Rods in Water with Irregular Features

A listing of the current near term needs for additional data in each of the groups has been developed for future use in planning criticality research in support of nuclear fuel transportation systems. The criticality experiments needed to provide these data are briefly described and identified according to priority and relative cost of performing the experiments.

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EXISTING EXPERIMENTAL CRITICALITY DATA APPLICABLE TO NUCLEAR FUEL TRANSPORTATION SYSTEMS

INTRODUCTION

Fissionable materials experience many different environments during activities associated with their transportation from one location to another. Conditions must be controlled during all phases of transportation of fissionable material to preclude criticality. Analytical techniques are generally relied upon to establish acceptable conditions with respect to criticality. However, the acceptability of these analytically based techniques for design, operating, or accident conditions is dependent on their validation by comparison with experimental data. Such data need to be obtained for a known set of conditions having physical and neutronic characteristics similar to the conditions being evaluated.

A considerable amount of criticality data currently exists that are applicable to the various non-reactor operations associated with the nuclear fuel cycle. The objective of this report is to identify those specific data that are particularly suitable for use in verifying the calculational techniques used in making criticality assessments of transportation systems, and to identify the near term needs for additional data judged to be of value in criticality analyses of nuclear transportation systems.

Although the compilation may not be complete, it is considered unlikely that any current major data sources are missing that would change the conclusions contained herein. The tables are structured so that missing data can be easily added and any new data included as it becomes available.

EXISTING EXPERIMENTAL DATA

Most of the existing experimental criticality data on systems closely simulating nuclear material transportation systems have been generated at the following experimental critical facilities:

- The Babcock and Wilcox Company CS-1D Critical Facility at Lynchburg, Virginia, U. S. A.
- The French Commissariat Al'énergie Atomique Criticality Station at Valduc, Cote-D'ore, France
- The Japanese Atomic Energy Research Institute Critical Facilities at Tokai-Mura, Naka-Gun, Ibaraki-Ken, Japan
- The United States Department of Energy Critical Mass Laboratory at Richland, Washington, U. S. A.

The data have been catalogued herein into the following classifications to facilitate identification:

- Critical Assemblies of Fuel Rods in Water
- Critical Assemblies of Fuel Rods in Water Containing Soluble Neutron Absorbers
- Critical Assemblies Containing Solid Neutron Absorbers
- Critical Assemblies of Fuel Rods in Water with Heavy Metal Reflectors
- Critical Assemblies of Fuel Rods in Water with Irregular Features

For each of the classifications, the experiments are briefly described as an aid to judging whether or not a set of data would be appropriate for a particular application. The primary parameter measured (i.e., critical height, size, separation, etc.) in each series of experiments is also identified. The primary area of application, or purpose, for each series of experiments is also identified. Utilization of the data is not necessarily limited to the indicated application or purpose. A publically available reference is identified for each series of experiments.

CRITICAL ASSEMBLIES OF FUEL RODS IN WATER

The criticality experiments that have been performed with fuel rods in water under conditions possible in transportation systems are listed in Table I. The conditions covered by the experiments listed in Table I involve water flooded (or partially flooded) assemblies of fuel rods only. Conditions involving structural materials, etc, are covered in the sections of this report that follow.

The experiments provide data on UO_2 fuels enriched with up to about 5 wt% ^{235}U , $\text{PuO}_2\text{-UO}_2$ Light Water Reactor (LWR) recycle type fuels containing up to 4 wt% PuO_2 in natural or depleted UO_2 and $\text{PuO}_2\text{-UO}_2$ fast breeder reactor fuels containing about 20 wt% PuO_2 in depleted UO_2 . The experiments cover single and multi-array assemblies over the full range of neutron moderation from tight packed rods (minimum lattice spacing) to the well overmoderated. However, the full range of neutron moderation is not covered for all fuels. Also data does not exist on multi-arrays of all the fuels. All of the experiments except for one set have been performed with unirradiated fuel.

TABLE I: Critical Assemblies of Fuel Rods in Water

<u>Area of Data Application Or Purpose of Experimental Measurements</u>	<u>Measurement Data</u>	<u>Description of Critical Assembly</u>	<u>Data Source (Author and Publication)</u>
Experiments to provide benchmark data on the effect that water gaps between LWR type fuel elements have on criticality.	Critical separation between fuel clusters submerged in water.	Three rectangular fuel clusters of either 2.35 wt% or 4.31 wt% ^{235}U enriched UO_2 rods aligned in a row in water near optimum neutron moderation.	S. R. Bierman, et. al. <u>Nucl. Tech.</u> , p. 237, 1979.
Experiments to provide benchmark data on the effect that water gaps between LWR type fuel elements have on criticality.	Critical separation between fuel clusters submerged in water.	Three rectangular fuel clusters of either 2.35 wt% or 4.31 wt% ^{235}U enriched UO_2 rods aligned in a row in water at an undermoderated water-to-fuel volume ratio of 1.6.	S. R. Bierman, et. al. NUREG/CR-1784, 1981. <u>Nucl. Tech.</u> , p. 131, 1981.
4 Experiments to provide benchmark data on the effect that water gaps between LWR type fuel elements have on criticality.	Critical water height as a function of distance between fuel clusters.	Four rectangular fuel clusters of 4.75 wt% ^{235}U enriched UO_2 rods arranged in a 2 x 2 rectangular pattern in water at a water-to-fuel volume ratio of 2.3.	J. C. Manaranche, et. al. DSN No. 399/80, 1980.
High density shipping and storage of irregularly spaced LWR type fuel assemblies of different sizes.	Critical separation between fuel clusters submerged in water.	Four rectangular fuel clusters of either 2.35 wt% or 4.31 wt% ^{235}U enriched UO_2 rods arranged in a 2 x 2 rectangular pattern in water at a water-to-fuel volume ratio of 1.6.	S. R. Bierman, et. al. NUREG/CR-1547, 1980.
High density shipping and storage of LWR type fuel assemblies.	Critical water height as a function of distance between fuel clusters.	Nine rectangular fuel clusters of 2.46 wt% ^{235}U enriched UO_2 rods arranged in a 3 x 3 rectangular pattern in water at a water-to-fuel volume ratio of 1.84.	Gary S. Hoovler, et. al. <u>Nucl. Tech.</u> , p. 217, 1980.
High density shipping and storage of LWR type fuel assemblies.	Critical water height as a function of distance between fuel clusters and neutron moderation.	Either single or four rectangular fuel clusters of 2.6 wt% ^{235}U enriched UO_2 rods arranged in 1 x 1 and 2 x 2 rectangular patterns in water at water-to-fuel volume ratios of 1.5, 1.83, 2.48 and 3.00.	Harumichi Tsuruta, et. al. JAERI 1254, 1978.
Shipping and storage of disassembled LWR type fuel assemblies as close packed fuel rods.	Critical water height as a function of distance between tight packed fuel clusters.	Twenty five rectangular fuel clusters of 2.46 wt% ^{235}U enriched UO_2 rods arranged in a 5 x 5 rectangular pattern in water at water-to-fuel volume ratios of 0.37, 0.44 and 0.59.	Gary S. Hoovler, et. al. <u>ANS Trans.</u> , 38: 360, 1981.

TABLE I: Critical Assemblies of Fuel Rods in Water

<u>Area of Data Application Or Purpose of Experimental Measurements</u>	<u>Measurement Data</u>	<u>Description of Critical Assembly</u>	<u>Data Source (Author and Publication)</u>
Experiments to measure the effect of fuel element shape on the critical separation between LWR type fuel elements.	Critical separation between fuel clusters submerged in water.	Three rectangular fuel clusters of 2.35 wt% ^{235}U enriched UO_2 rods aligned in a row at different assembly widths in water at a water-to-fuel volume ratio of 2.92.	S. R. Bierman, et. al. PNL-2438, 1977.
Shipping and storage of LWR type fuel elements in a non-rectangular pattern.	Critical water height at separation distances of 0 and 0.65cm.	Three rectangular fuel clusters of 4.75 wt% enriched UO_2 rods arranged in a triangular pattern at a water-to-fuel volume ratio of 3.81.	J. C. Manaranche, et. al. DSN No. 399/80, 1980.
Experimental data on the neutron isolation distance between LWR type fuel elements.	Relative neutron count rate as a function of separation between fuel clusters submerged in water.	Three rectangular fuel clusters of either 2.35 wt% or 4.31 wt% ^{235}U enriched UO_2 rods aligned in a row in water at water-to-fuel volume ratios of 1.6 and 3.88.	S. R. Bierman, et. al. NUREG/CR-1547, 1980 PNL-2615, 1978.
5 Experimental data on single fuel clusters of LWR type fuel.	Critical size of fuel lattices.	Single rectangular fuel clusters of either 2.35 wt% or 4.31 wt% ^{235}U enriched UO_2 rods in water at water-to-fuel volume ratios of either 2.92, 3.88 or 1.6.	S. R. Bierman, et. al. Nucl. Tech., p. 237, 1979. Nucl. Tech., p. 231, 1981. NUREG/CR-1784, 1981. NUREG/CR-1547, 1980. PNL-2615, 1978. PNL-2438, 1977.
Experimental data on single fuel clusters of LWR type fuel.	Critical water height.	Single rectangular fuel clusters of 4.75 wt% ^{235}U enriched UO_2 rods in water at water-to-fuel volume ratios of 1.82, 3.81, 7.58 and 9.8 with the fuel rods in square pitch and 1.80, 3.81 and 7.60 in triangular pitch.	J. C. Manaranche, et. al. NS&E, 71: 154, 1979. DSN No. 399/80, 1980.
Experimental data on single fuel clusters of LWR type fuel.	Critical water height.	Single rectangular fuel clusters of 2.6 wt% ^{235}U enriched UO_2 rods in water at water-to-fuel volume ratios of 1.5, 1.83, 2.48 and 3.0.	Harumichi Tsuruta, et. al. JAERI 1254, 1978.
Experimental data on single fuel clusters of LWR type fuel.	Critical size of fuel lattices.	Single hexagonal fuel clusters of 2.35 wt% ^{235}U enriched UO_2 rods in water at water-to-fuel volume ratios of 1.2, 2.41 and 3.69 with fuel rods in a square pitch.	R. I. Smith and G. J. Konzek EPRI NP-196, vol. 1, 1976.
Experimental data on single fuel cluster of irradiated low enriched UO_2 fuel.	Effective neutron multiplication constant (k_{eff}) as a function of lattice size.	Single hexagonal fuel clusters of 1.25/0.95 wt% ^{235}U enriched tube-in-tube irradiated uranium metal at near optimum neutron moderation.	H. Toffer UM-238 Add1, 1976.

TABLE I: Critical Assemblies of Fuel Rods in Water

Area of Data Application Or Purpose of Experimental Measurements	Measurement Data	Description of Critical Assembly	Data Source (Author and Publication)
Experimental data on the effect of shape on the critical size of LWR type fuel elements.	Critical size of fuel lattices.	Single rectangular fuel clusters of either 2.35 wt% or 4.31 wt% ^{235}U enriched UO_2 rods at different assembly widths in water at a water-to-fuel volume ratio of 1.6.	S. R. Bierman, et. al. NUREG/CR-1547, 1980.
Experimental data on single fuel clusters of LWR plutonium recycle type fuel.	Critical water height.	Single rectangular fuel clusters of $\text{PuO}_2\text{-UO}_2$ rods (3.0 wt% PuO_2 in natural UO_2) in water at water-to-fuel volume ratios of 2.42, 2.98, 4.24 and 5.55 (402, 494, 703 and 921 H/Pu atom ratios).	Harumichi Tsuruta, et. al. JAERI 1254, 1978.
Experimental data on single fuel clusters of LWR plutonium recycle type fuel.	Critical size of fuel lattices.	Single hexagonal fuel clusters of $\text{PuO}_2\text{-UO}_2$ rods (2 wt% PuO_2 in natural UO_2 in water at water-to-fuel volume ratios of 1.2, 2.53 and 3.64 arranged in square pitch.	R. I. Smith and G. J. Konzek EPRI NP-196, Vol. 1, 1976.
Experimental data on single fuel clusters of LWR plutonium recycle type fuel.	Critical size of fuel lattices.	Single hexagonal fuel clusters of $\text{PuO}_2\text{-UO}_2$ rods (either 1.5 wt%, 2.0 wt% or 4.0 wt% PuO_2 in natural UO_2) in water at water-to-fuel volume ratios of 0.8 to 9.0 (230 to 922 H/Pu atom ratios).	V. O. Uotinen, et. al. <u>Nucl. Tech.</u> , p. 257, 1972.
Experimental data on the effect of shape on the critical size of LWR plutonium recycle type fuel.	Critical water height.	Single rectangular fuel clusters of $\text{PuO}_2\text{-UO}_2$ rods (3.01 wt% PuO_2 in natural UO_2) at different assembly widths in water at water-to-fuel volume ratios of 2.42, 2.98, 4.24 and 5.55 (402, 494, 703 and 921 H/Pu atom ratios).	Iwao Kobayashi, et. al. <u>J. of Nucl. Sci. & Tech.</u> , 15: (3), 1978.
Experimental data on single fuel clusters of fast breeder reactor type fuel.	Critical size of fuel lattices.	Single rectangular fuel clusters of $\text{PuO}_2\text{-UO}_2$ rods (20 wt% PuO_2 in natural UO_2) in water at water-to-fuel volume ratios of 1.67, 3.33, 3.49, 6.87, 10.88 and 17.53.	S. R. Bierman, et. al. <u>Nucl. Tech.</u> , p. 141, 1979.

CRITICAL ASSEMBLIES OF FUEL RODS IN WATER CONTAINING SOLUBLE NEUTRON ABSORBERS

The existing experiments involving soluble compounds of strong neutron absorbers and fissionable material under conditions that might be encountered in transportation systems are presented in Table II. The experiments provide data for the thermal absorbers Cd, B and Gd, in water with 2 to 5 wt% ^{235}U enriched UO_2 rods. Data are available for boron up to 0.6 g B/l over the full range of neutron moderation and from 0.7 g B/l to 1.0 g B/l in the undermoderated range. Data also exist for up to 10 g B/l over the full range of neutron moderation with PuO_2 - UO_2 LWR recycle type fuels.

Data are available for cadmium up to 1.0 g Cd/l and gadolinium up to 0.6 g Gd/l over the full range of neutron moderation with UO_2 rods having ^{235}U enrichments near 4.5 wt%.

TABLE II. Critical Assemblies of Fuel Rods in Water Containing Soluble Neutron Absorbers

Area of Data Application or Purpose of Experimental Measurements	Measurement Data	Description of Critical Assembly	Data Source (Author and Publication)
Shipping and storage of LWR type fuel elements in boron poisoned water.	Critical water height as a function of boron concentration.	Nine rectangular fuel clusters of 2.46 wt% 235-U enriched UO ₂ rods arranged in a 3 x 3 rectangular pattern in water at a water-to-fuel volume ratio of 1.84 with 700 to 1000 mg B/l and 1.64 cm between the fuel clusters.	G. S. Hoovler, et.al., Nucl. Tech. 2. 217, 1980.
Shipping and storage of LWR type fuel elements in gadolinium poisoned water.	Critical absorber concentration with all but about 3 cm of the fuel submerged in the solution.	Single hexagonal fuel cluster of 4.75 wt% 235-U enriched UO ₂ rods in water at water-to-fuel volume ratios of 1.80, 3.81, and 7.60 with 600, 435, and 175 mg Gd/l respectively.	J. C. Manaranche, et.al., DSN No. 399/80, 1980.
Experimental data on single clusters of LWR type fuel in boron poisoned water.	Critical size of fuel lattice as a function of boron concentration.	Single hexagonal fuel clusters of 2.35 wt% 235-U enriched UO ₂ rods in water at water-to-fuel volume ratios of 1.2, 2.45, and 3.69 in square pitches with up to about 600 mg B/l.	R. I. Smith and G. J. Konzek, EPRI NP-196, Vol. 1, 1976.
Experimental data on single fuel clusters of LWR type fuel in boron, gadolinium and cadmium poisoned water.	Critical size of fuel lattice as a function of lattice spacing and absorber concentration.	Single hexagonal fuel clusters of 4.31 wt% 235-U enriched UO ₂ rods in water at water-to-fuel volume ratios of 3.2, 5.4, and 8.0 with boron (60 to 610 mg/l), cadmium (430 to 1060 mg/l) or gadolinium (30 to 210 mg/l).	R. C. Lloyd, et.al., NS&E, 71, p. 164, 1979.
Experimental data on single fuel clusters of LWR type fuel in boron, gadolinium and cadmium poisoned water.	Critical water height as a function of lattice pitch and absorber concentration.	Single rectangular fuel clusters of 2.6 wt% 235-U enriched UO ₂ rods in water at water-to-fuel volume ratios of 1.5, 1.83 and 2.48 with up to 554 mg B/l.	Harumichi, Tsurath, et.al., JAERI 1254, 1978.
Experimental data on single fuel clusters of LWR plutonium recycle fuel in boron poisoned water.	Critical size of fuel lattice as a function of boron concentration.	Single hexagonal fuel clusters of PuO ₂ -UO ₂ rods (2 wt% PuO ₂ in natural UO ₂) in water at water-to-fuel volume ratios of 1.2, 2.54 and 3.64 in square pitched lattices with up to 1020 mg B/l.	R. I. Smith and G. J. Konzek, EPRI NP-196, Vol. 1, 1976.

CRITICAL ASSEMBLIES CONTAINING SOLID NEUTRON ABSORBERS

The experiments simulating transportation systems in which solid neutron absorbers are used for criticality control are listed in Table III. Experimental data are provided for single and multi-arrays of UO_2 rods containing up to about 5 wt% ^{235}U . Data exists for undermoderated and near optimum neutron moderation with these UO_2 fuel rods in water and the following neutron absorbers:

- Boral^{tm} Plates
- Type 304L Steel Plates
- Type 304L Borated Steel Plates
- Copper Plates
- Copper Plates Containing 1 Wt% Cd
- Cadmium Plates
- Aluminum Plates
- Zircaloy-4 Plates
- Boroflex^{tm} Plates
- Hafnium Plates
- B_4C Pins

Limited experimental data exist for PuO_2 - UO_2 LWR recycle type fuel rods in water with cadmium plates, and for PuO_2 - UO_2 fast breeder type fuel rods in water with cadmium plates and Gd_2O_3 pins.

TABLE III: Critical Assemblies Containing Solid Neutron Absorbers

Area of Data Application Or Purpose of Experimental Measurements	Measurement Data	Description of Critical Assembly	Data Source (Author and Publication)
Shipping and storage systems that rely on solid (fixed) neutron absorbers to maintain sub-criticality and achieve high density storage of LWR type fuel elements.	Critical separation between fuel clusters submerged in water with neutron absorber materials between the fuel clusters.	Three rectangular fuel clusters of either 2.35 wt% or 4.31 wt% ^{235}U enriched UO_2 rods aligned in a row, in water at near optimum neutron moderation with the following materials in the form of plates, between the fuel clusters: Boral ^{tm} Type 304L stainless steel Type 304L stainless steel with 1.1 wt% and 1.6 wt% boron Copper Copper with 1 wt% cadmium Aluminum Zircaloy-4 Cadmium	S. R. Bierman, et. al., <u>Nucl. Tech.</u> , p. 237, 1979.
Shipping and storage systems that rely on solid (fixed) neutron absorbers to maintain sub-criticality and achieve high density storage of LWR type fuel elements.	Soluble boron concentration in water to achieve a constant critical height with neutron absorbers between fuel clusters.	Nine rectangular fuel clusters of 2.46 wt% ^{235}U enriched UO_2 rods arranged in a 3 x 3 rectangular pattern in water at a water-to-fuel volume ratio of 1.84 with either boral plates having different boron concentrations, steel plates, or B_4C pins between the fuel clusters.	Gary S. Hoovler, et. al., <u>Nucl. Tech.</u> , p. 217, 1980.
Shipping and storage systems that rely on solid (fixed) neutron absorbers to maintain sub-criticality and achieve high density storage of LWR type fuel elements.	Critical separation between fuel clusters submerged in water with neutron absorber materials between the fuel clusters.	Rectangular fuel clusters of either 2.35 wt% or 4.31 wt% ^{235}U enriched UO_2 rods arranged in a 1 x 3 or a 2 x 2 rectangular pattern in water at a water-to-fuel volume ratio of 1.6 with the following materials, in the form of either plates or cruciforms, between the fuel clusters: Boral ^{tm} of different thicknesses and boron loadings Type 304L stainless steel Type 304L stainless steel with 1.1 wt% and 1.6 wt% boron Copper Copper with 1 wt% cadmium Aluminum Zircaloy-4 Cadmium Boroflex ^{tm} of different thicknesses	S. R. Bierman and E. D. Clayton, NUREG/CR-1784, 1981. <u>Nucl. Tech.</u> , p. 131, 1981.

TABLE III: Critical Assemblies Containing Solid Neutron Absorbers

Area of Data Application Or Purpose of Experimental Measurements	Measurement Data	Description of Critical Assembly	Data Source (Author and Publication)
Shipping and storage systems that rely on solid (fixed) neutron absorbers to maintain sub-criticality and achieve high density storage of LWR type fuel elements.	Critical water height as a function of distance between fuel clusters with absorber plates between the fuel clusters.	Four rectangular fuel clusters of 4.75 wt% ^{235}U enriched UO_2 rods arranged in a 2 x 2 rectangular pattern, in water at a water-to-fuel volume ratio of 2.30 with the following materials in the form of cruciforms between the fuel clusters: Hafnium Boral ^{tm} Cadmium Borated Steel	J. C. Manaranche, et. al., DSN No. 399/80, 1980.
Shipping and storage systems that rely on solid (fixed) neutron absorbers to maintain sub-criticality and achieve high density storage of LWR type fuel elements.	Critical water height as a function of distance between fuel clusters encased in absorber materials.	Four rectangular fuel clusters of 4.75 wt% ^{235}U enriched UO_2 rods arranged in a 2 x 2 rectangular pattern in water at a water-to-fuel volume ratio of 3.81 with each encased in either boral or borated steel.	J. C. Manaranche, et. al., DSN No. 399/80, 1981.
Shipping and storage systems that rely on solid (fixed) neutron absorbers to maintain sub-criticality and achieve high density storage of LWR type fuel elements.	Critical water height as a function of absorber thickness and distance from the fuel cluster.	Single rectangular fuel clusters of 4.75 wt% ^{235}U enriched UO_2 rods in water at a water-to-fuel volume ratio of 3.81 with hafnium plates up to 5mm thick.	J. C. Manaranche, et. al., DSN No. 399/80, 1981.
Experiments to measure the effect of heavy biological shielding materials on the absorption properties of solid (fixed) neutron absorbers used to maintain sub-criticality in shipping systems for LWR type fuel.	Critical separation between fuel clusters submerged in water with neutron absorbers between the fuel clusters and thick steel walls on either side of the fuel clusters.	Three rectangular fuel clusters of either 2.35 wt% or 4.31 wt% ^{235}U enriched UO_2 rods in water aligned in a row at near optimum neutron moderation and at a water-to-fuel volume ratio of 1.6 with steel reflecting walls parallel to and on either side of the fuel clusters. Each of the critical assemblies has one of the following materials between the fuel clusters: 304L steel 304L steel with 1.1 wt% B Boral ^{tm} Boroflex ^{tm} Cadmium Copper Copper with 1 wt% Cd	S. R. Bierman and E. D. Clayton, NUREG/CR-1784, 1981.

TABLE III: Critical Assemblies Containing Solid Neutron Absorbers

Area of Data Application Or Purpose of Experimental Measurements	Measurement Data	Description of Critical Assembly	Data Source (Author and Publication)
Experimental data for use in developing calculational models to properly handle flux traps in shipping and storage systems for LWR type fuel.	Critical size as a function of distance between fuel clusters submerged in water with absorber plates on opposing faces.	Two rectangular fuel clusters of either 2.35 wt% or 4.31 wt% ^{235}U enriched UO_2 rods in water at a water-to-fuel volume ratio of 1.6 with either 0.231cm thick boral or 0.302cm thick stainless steel attached to the two opposing parallel faces.	S. R. Bierman, et. al., <u>Nucl. Tech.</u> , p. 342, 1981.
Experimental data for use in developing calculational models to properly handle flux traps in shipping and storage systems for LWR type fuel.	Critical water height as a function of distance between fuel clusters with two absorber plates between the fuel clusters.	Two rectangular fuel clusters of 4.75 wt% ^{235}U enriched UO_2 rods in water at a water-to-fuel volume ratio of 2.30 with the following plates positioned between and parallel to each of the two opposing faces: Boral ^{tm} with 250mg B/cm ² Boral ^{tm} with 500mg B/cm ² Boral ^{tm} with 250mg B/cm ² with a sheet of Hf Steel with 13mg B/cm ²	J. C. Manaranche, et. al., DSN No. 399/80, 1980.
Shipping and storage of LWR type fuel elements in a non-rectangular pattern.	Critical water height as a function of fuel cluster enclosure with boral.	Three rectangular fuel clusters of 4.75 wt% enriched UO_2 rods arranged in a tri-hedral pattern with Boral either between or enclosing the fuel clusters.	J. C. Manaranche, et.al., DSN No. 399/80, 1980.
Shipping and storage systems for LWR plutonium recycle type fuels that utilize a centered poison region for criticality control.	Critical size as a function of absorber material density.	Single hexagonal fuel clusters of PuO_2 - UO_2 rods (2 wt% PuO_2 in natural uranium oxide) in water with either a hafnium oxide or a boron loaded rod in the center of the fuel clusters, with and without a cadmium sleeve about the absorber rods, and water-to-fuel volume ratios of 2.8 and 5.	V. O. Uotinen, et.al., <u>Nucl. Tech.</u> , p. 257, 1972.

TABLE III: Critical Assemblies Containing Solid Neutron Absorbers

Area of Data Application Or Purpose of Experimental Measurements	Measurement Data	Description of Critical Assembly	Data Source (Author and Publication)
Shipping and storage systems for fast breeder reactor type fuel that utilize gadolinium or cadmium for criticality control.	Critical size as a function of type and location of absorber material.	Either single or two rectangular shaped fuel clusters of $\text{PuO}_2\text{-UO}_2$ rods (20 wt% PuO_2 in natural uranium oxide) in water at water-to-fuel volume ratios of 24.87, 19.35, 15.37, 12.42 and 3.49. For each degree of neutron moderation, the critical assemblies contained the following, one at a time: - Cadmium plate along one edge - Cadmium plate between two fuel clusters - Row of Gd_2O_3 pins along one edge - Row of Gd_2O_3 pins between two fuel clusters Gd_2O_3 pin every fifth fuel position on a 5 x 5 matrix	B. M. Durst, et. al., <u>Nucl. Tech.</u> , p. 128, 1980.
Experimental data for use in developing calculational techniques for assessing criticality of high density systems with low degree of neutron moderation.	Critical size as a function of type and thickness of absorber material.	Parallelipeds of $\text{PuO}_2\text{-UO}_2$ compacts containing either 14.62 wt% or 30.3 wt% PuO_2 in depleted UO_2 (30.6 and 2.8 atomic H/Pu + U) and having either single or double regions of the following absorber materials in plate form: - Type 304L stainless steel - Type 304L stainless steel containing 1.1 wt% boron - Type 304L stainless steel containing 1.6 wt% boron - Uranium depleted to 0.2 wt% ^{235}U - Boral^{tm} - Cadmium - Lead - Copper - Copper containing 1 wt% cadmium	S. R. Bierman, et. al., <u>NS and E</u> , 65, 41-48, 1978. <u>NS and E</u> , 53, 58-66, 1974.

CRITICAL ASSEMBLIES WITH HEAVY METAL REFLECTORS

Criticality experiments simulating transportation systems such as irradiated fuel shipping casks in which heavy metal biological shielding is present are listed in Table IV. Unlike some of the previously referenced experiments, all of the experiments presented in Table IV were specifically designed to simulate a transportation system.

Data exist for the commonly used shielding materials, lead, steel and depleted uranium, and multi-arrays of UO_2 rods containing up to about 5 wt% ^{235}U . The data covers the range of neutron moderation from slightly undermoderated to slightly overmoderated for these rods in water.

TABLE IV. Critical Assemblies of Fuel Rods in Water with Heavy Metal Reflectors

	Area of Data Application or Purpose of Experimental Measurements	Measurement Data	Description of Critical Assembly	Data Source (Author and Publication)
	Systems employing lead or depleted uranium as a biological shield in shipping or storage of LWR type fuel elements.	Critical separation between fuel clusters submerged in water as a function of separation between the metal reflectors and the fuel assembly.	Three rectangular fuel clusters of either 2.33 wt% or 4.31 wt% ²³⁵ -U enriched UO ₂ rods in water aligned in a row at near optimum neutron moderation and at an undermoderated water-to-fuel volume ratio of 1.6 with either lead or depleted uranium walls located equal distance from and parallel to the sides of the assembly.	S. R. Bierman, et. al., Nucl. Tech., p. 51, 1980 NUREG/CR-2829, 1979. NUREG/CR 0796, V. II, 1981.
15	Systems employing reactor grade steel as a biological shield in shipping or storage of LWR type fuel elements.	Critical separation between fuel clusters submerged in water as a function of separation between the metal reflector and the fuel assembly.	Three rectangular fuel clusters of either 2.35 wt% or 4.31 wt% ²³⁵ -U enriched UO ₂ rods in water aligned in a row at near optimum neutron moderation ratio and at an undermoderated water-to-fuel volume ratio of 1.6 with steel walls located equal distances and parallel to the sides of the assembly.	S. R. Bierman, et. al., NUREG/CR-1784, 1981.
	Systems employing lead or steel as a biological shield in shipping and storage of LWR type fuel elements.	Critical water height as a function of separation between the metal reflector and the fuel assembly.	Four rectangular fuel clusters of 4.75 wt% enriched UO ₂ . Rods arranged in a 2 x 2 rectangular pattern in water at a water-to-fuel volume ratio of 3.81, each cluster encased in Boral with 2 cm separation distance between the encased fuel clusters. The four fuel clusters are enclosed equidistance from either 15 cm thick lead or 10 cm thick steel walls.	J. C. Manaranche, et.al, SN No. 399/80, 1980.

CRITICAL ASSEMBLIES WITH IRREGULAR FEATURES

A few criticality experiments have been performed under conditions useful in evaluating transportation systems that are not characterized by any of the four previously discussed classifications. These experiments are identified in Table V and for the most part were done to provide data for checking computer code routines and techniques.

TABLE V: Critical Assemblies of Fuel Rods in Water with Irregular Features

<u>Area of Data Application Or, Purpose of Experimental Measurements</u>	<u>Measurement Data</u>	<u>Description of Critical Assembly</u>	<u>Data Source (Author and Publication)</u>
Experimental data for use in developing calculational models to properly handle voids and water holes in LWR type fuel elements.	Critical size	Single rectangular fuel cluster of either 2.35 wt% or 4.31 wt% ^{235}U enriched UO_2 rods in water at a water-to-fuel volume ratio of 1.6 with either 25 voids or water holes equally spaced in a 5 x 5 arrangement.	S. R. Bierman and E. D. Clayton NUREG/CR-1547, 1980.
Experimental data for use in developing calculational models to properly handle voids and water holes in LWR type fuel elements.	Critical water height	Single rectangular and hexagonal fuel clusters of 4.75 wt% ^{235}U enriched UO_2 rods in water at water-to-fuel volume ratios of 1.82, 1.80, 3.81 and 7.60 with water holes.	J. C. Manaranche, et. al. NS&E, 71: 154, 1979. DSN No. 399/80, 1980.
Experimental data for use in developing calculational models to properly handle voids and water holes in LWR type fuel elements.	Critical water height	Single rectangular fuel cluster of either 2.35 wt% ^{235}U enriched UO_2 rods or $\text{PuO}_2\text{-UO}_2$ rods (2 wt% PuO_2 in natural uranium oxide) in water with either slab or cross voids and water regions.	P. Loizzo, et. al. BNWL-1379, 1970.
Experiments to provide benchmark data on the effect that reduced density moderation between LWR type fuel elements has on criticality.	Critical water height	Four rectangular fuel clusters of 4.75 wt% ^{235}U enriched UO_2 rods arranged in a 2 x 2 rectangular pattern in water at a water-to-fuel volume ratio of 2.3 with either air, expanded polystyrene, polyethylene powder, polyethylene balls or water between the fuel clusters.	J. C. Manaranche, et. al. Nuc. Tech., 50: 148, 1980. DSN No. 399/80, 1980.

SUMMARY LISTING OF EXISTING DATA

The existing data covered in the previous five sections have been arranged into broad summary type groupings to facilitate identifying areas where criticality data do not exist for transportation systems. This summary listing is presented in Table VI.

TABLE VI: Summary Listing of Existing Data

Critical Assemblies of Fuel Rods in Water	Critical Assemblies of Fuel Rods in Water Containing Soluble Neutron Absorbers	Critical Assemblies Containing Solid Neutron Absorbers	Critical Assemblies with Heavy Metal Reflectors	Critical Assemblies with Irregular Features
Near optimum and under-moderated clusters of UO_2 rods, 2 to 5 wt% ^{235}U enriched, in uniform rectangular planar arrays as follows: 1 x 1 1 x 2 1 x 3 2 x 2 3 x 3 Tight packed clusters of UO_2 rods, 2.46 wt% ^{235}U enriched, in a uniform 5 x 5 rectangular planar array. Near optimum moderated clusters of UO_2 rods, 4.75 wt% ^{235}U enriched in a planar trihedral array. Overmoderated to under-moderated single assemblies of $\text{PuO}_2\text{-UO}_2$ rods containing up to 4 wt% PuO_2 in natural UO_2. Overmoderated to under-moderated single assemblies of $\text{PuO}_2\text{-UO}_2$ rods containing 20 wt% PuO_2 in natural UO_2. Near optimum moderated single assembly of 1.25 wt% ^{235}U enriched tube-in-tube irradiated uranium metal fuel elements.	Overmoderated to under-moderated (without soluble absorbers) single assemblies of UO_2 rods, 2 to 5 wt% ^{235}U enriched, in water containing up to 0.6 g B/l. Undermoderated (with soluble absorbers) clusters of UO_2 rods, 2.46 wt% ^{235}U enriched, in a uniform 3 x 3 rectangular planar array in water containing 0.7 to 1.0 g B/l. Near optimum to under-moderated (without soluble absorbers) single assemblies of $\text{PuO}_2\text{-UO}_2$ rods, 2 wt% PuO_2 in natural UO_2, in water containing up to 1 g B/l. Overmoderated to near optimum moderated (without soluble absorbers) single assemblies of UO_2 rods, 4.31 wt% ^{235}U enriched, in water containing 0.4 to 1.0 g Cd/l. Overmoderated to under-moderated (without soluble absorbers) single assemblies of UO_2 rods, around 4.5 wt% ^{235}U enriched UO_2 rods in water containing up to 0.6 g Gd/l.	Near optimum and under-moderated clusters of UO_2 rods, 2 to 5 wt% ^{235}U enriched, in water with the following neutron absorber materials: Boral^{tm} plates Type 304L steel plate Type 304L steel with boron plates Copper plates Copper with cadmium plates Cadmium plates Aluminum plates Zircaloy-4 plates Boroflex^{tm} plates Hafnium plates B_4C pins Near optimum to under-moderated assemblies of $\text{PuO}_2\text{-UO}_2$ rods (2 wt% PuO_2 in natural uranium oxide) with either a boron or hafnium rod, with and without cadmium sleeves. Undermoderated to over-moderated 1 x 1 and 1 x 2 arrays of $\text{PuO}_2\text{-UO}_2$ rods (20 wt% PuO_2 in natural uranium oxide) in water with the following neutron absorber materials: Cadmium plate along one edge Cadmium plate between two fuel clusters Row of Gd_2O_3 pins along one edge Row of Gd_2O_3 pins between two fuel clusters Gd_2O_3 pin every fifth fuel position on a 5 x 5 matrix	Near optimum and under-moderated clusters of UO_2 rods, 2 to 5 wt% ^{235}U enriched, in water with single thicknesses of either lead, steel or depleted uranium reflecting walls with varying thicknesses of water between the walls and the fuel clusters. Undermoderated single assemblies of $\text{PuO}_2\text{-UO}_2$ rods, 2 wt% PuO_2 in natural UO_2, in water with slab shaped voids or water holes. Near optimum moderated clusters of UO_2 rods, 4.75 wt% ^{235}U enriched, in a uniform 2 x 2 rectangular, water flooded, planar array with either air or expanded hydrogenous material between the fuel clusters.	Overmoderated to under-moderated single assemblies of UO_2 rods, 2 to 5 wt% ^{235}U enriched, in water with uniformly spaced voids or water holes. Undermoderated single assemblies of $\text{PuO}_2\text{-UO}_2$ rods, 2 wt% PuO_2 in natural UO_2, in water with slab shaped voids or water holes. Near optimum moderated clusters of UO_2 rods, 4.75 wt% ^{235}U enriched, in a uniform 2 x 2 rectangular, water flooded, planar array with either air or expanded hydrogenous material between the fuel clusters.

TABLE VI: Summary Listing of Existing Data

<u>Critical Assemblies of Fuel Rods in Water</u>	<u>Critical Assemblies of Fuel Rods in Water Containing Soluble Neutron Absorbers</u>	<u>Critical Assemblies Containing Solid Neutron Absorbers</u>	<u>Critical Assemblies with Heavy Metal Reflectors</u>	<u>Critical Assemblies with Irregular Features</u>
		Undermoderated assemblies of solid PuO_2-UO_2 compacts (15 wt% and 30 wt% PuO_2 in depleted uranium oxide) and having either single or double regions of the following absorber materials in plate form: Type 304L stainless steel Type 304L stainless steel containing 1.1 wt% boron Type 304L stainless steel containing 1.6 wt% boron Uranium depleted to 0.2 wt% ^{235}U Boral^{tm} Cadmium Lead Copper Copper containing 1 wt% cadmium		

CONCLUSIONS

The listings of experimental criticality data covered in the preceding sections identify several areas in which data are missing. In some of these areas, however, there is no current recognizable application for the data. Consequently there is no real need for some of these missing data. The criticality experiments to provide those missing data believed needed in support of fuel transportation systems over the near term have been identified in Table VII. The list is based on the opinions of personnel involved in the transportation of nuclear materials and is believed to be reasonably complete for the foreseeable future. However, data requirements will vary with time in accordance with changes in system design and operating practices.

An attempt has been made to rank the experiments listed in Table VII according to need and according to relative cost to perform the experiments. Of most immediate interest are those experiments which would provide data to the various calculational work groups currently attempting to establish comparability between calculational techniques. The calculational model designed to test the calculations should be modeled experimentally also. This has been assigned the highest priority in Table VII.

With the rapidly developing ability to non-destructively measure burnup and time-out-of-core, allowance for fuel irradiation exposure in setting criticality controls is becoming feasible. However, the search for criticality data applicable to fuel transportation systems revealed that only a single criticality experiment with spent reactor fuel existed that was suitable for verifying calculations. A series of critical and sub-critical experiments involving interacting arrays of spent reactor fuel, typical of the LWR fuel cycle are needed. However, such experiments will probably be some of the most expensive to perform, as indicated in Table VII.

TABLE VII. Near Term Needs for Additional Criticality Data

Critical Assemblies of Fuel Rods in Water		Critical Assemblies of Fuel Rods in Water Containing Soluble Neutron Absorbers		Critical Assemblies Containing Solid Neutron Absorbers		Critical Assemblies with Heavy Metal Reflectors		Critical Assemblies with Irregular Features	
Single lattices of near 5 wt% ²³⁵ U enriched UO ₂ rods in water over full range of neutron moderation.	P1 C1	Single lattices of less than 8 wt% ²³⁵ U enriched UO ₂ rods in water contain- ing up to 3 g B/l.	P1 C4	Effect of biological shield- ing materials on the poison- ing worth of solid neutron absorbers located between low enriched (≤8 wt% ²³⁵ U) UO ₂ rods and the shielding material.	P4 C2	Effect of shielding mat- erial thickness on criti- cality of UO ₂ rods enriched to less than 8 wt% ²³⁵ U.	P8 C6	2 x 2 array of low enriched (≤8 wt% ²³⁵ U)UO ₂ rods with flux trap between fuel clusters.	P2 C3
Single lattices of irradi- ated low enriched (≤8 wt% ²³⁵ U)UO ₂ rods.	P7 C1	Arrays of less than 8 wt% ²³⁵ U enriched UO ₂ rods in water with up to 3 g B/l	P9 C5	Arrays of less than 8 wt% ²³⁵ U enriched UO ₂ rods in water with 30-50% hold- down in reactivity.	P6 C9	Effect of nodular steel shielding on criticality of UO ₂ rods enriched to less than 8 wt% ²³⁵ U.	P3 C7	Effect of reduced density moderation on criticality of UO ₂ rods enriched to less than 8 wt% ²³⁵ U (in- cluding assemblies with solid neutron absorbers and heavy metal reflectors).	P11 C8
Arrays of irradiated low enriched (≤8 wt% ²³⁵ U)UO ₂ rods.	P6 C11							Arrays of low enriched (≤8 wt% ²³⁵ U) unmoderated UO ₂ powder (i.e., damp oxide).	P13 C12
								Computational models as defined by Nuclear Energy Agency Work Group of Criti- cality Codes for Spent Fuel Transport Containers.	P1

P1 = Highest Priority

C1 = Lowest Cost

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