Analysys of Heavy Water lattice Experiments on Research Reactors for Testing Nuclear Data

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There is a need for updated multigroup libraries for lattices codes of WIMS type for PHWR reactors calculations. Different multigroup libraries are used with WIMS and other codes, but these libraries are not normally updated to the level of last revision of ENDF/B-VI and other evaluated nuclear data files. Then, a special attention to the application of new WIMS libraries on PHWR calculations is justified.

Some research and development activities associated to PHWR type of reactors, that need updated nuclear libraries of WIMS type, are: use of slightly enriched uranium (SEU cycle), use of UO2-ThO2 fuels, use of burnable poisons mixed in fuel pellets (UO2-Gd2O3) and absorber rods, new types of fuel elements (in Argentina: CARA Project-Advanced Fuel for Argentine Reactors)

Taking into account the need of new WIMS libraries associated to these activities, a set of benchmarks have been identified and coded for PHWR lattice calculations.. The experimental benchmarks are identified with the name of the facility or reseach reactor where the measurements were carried out. The main references for this type of benchmarks is the ZED-2 Canadian reactor and DCA Japanese reactor.

This work cover benchmark results of the following cases: ZED-2 analysis: experiments with 37 and 28 CANDU-type rod Fuel Clusters and lattice experiments with 19-rod Clusters with ThO2-UO2 Fuel; DCA analysis: Evaluation of Neutronic Parameters in Heavy Water and Slightly Enriched Uranium UO2 Fuel (28-rod Cluster) and critical experiments on Gadolinium poisoned cluster-type fuel assemblies of 54 rods in heavy water lattices of DCA facility. For several cases, results are included for different pitches and coolants.

The parameters analysed are: k-effective with experimental bucklings, fast fission ratio [U-238 fissions/U-235 fissions], relative conversion ratio [U-238 captures/U-235 fissions], U-235 fission rate distribution, Cu-63 absorption rate distribution, Lutetium-Manganese activity ratio, ratio of Th232 fissions to U235 fissions, ratio of Th232 captures to U235 fissions and thermal neutron flux distributions for a cluster with and without Gd absorber rods.

The calculation were made with WIMS-D code with main transport options DSN (Sn method) and PIJ (two-dimension collision probability method). Then, for each case, a comparison of the results obtained with both methods is made. All calculations were made using three different multigroup libraries: WIMS-1986 British library, and the two preliminary libraries released on the Wims Library Update Project in this year, based on ENDF/B-VI, Revision 3, and JEFF-2 nuclear data files, respectively. Then, for each case, a comparison of the results obtained with the two last mentioned libraries is made. The inclusion of the old WIMS-86 library is for having an additional element of comparison only, for showing the improvements introduced with the new nuclear data and methods adopted for the WIMS library generation with NJOY system.

The main conclusions of the analysis are: JEFF-2 library gives the best results, followed by END/F-VI library; the agreement experiment/calculation is good except for: k-eff of lattices with slightly Enriched Uranium UO2 Fuel with H2O coolant and D2O moderator, fast fission ratio in general and the initial conversion ratio for some lattices.

This work is part of IAEA Research Contract on Definition and Analysis of Heavy Water Reactor Benchmarks for Testing New WIMS-D Libraries, part of Co-ordinated Project: Final Stage of WIMS-D Library Update.

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Introduction

There are six countries with PHWR reactors in the world: Argentina, Canada, India, Korea RP, Pakistan and Romania. A total of thirty PHWR power reactors are in operation (less than 10 % of the total number of power reactors in operation in the world), and height PHWR power reactors are under construction (more than 20 % of the total number of reactors under construction).

The main lattice codes used by the countries with PHWR reactors for different type of calculations are: POWDERPUFS (Canada, Argentina and Romania), WIMS (Argentina, Canada, Korea RP, Pakistan and Romania) and CLUB and CLIMAX, with WIMS Libraries (India).

The Canadian program POWDERPUFS is the most important code for the CANDU lattice calculations. It is available only for the CANDU reactor owners. WIMS is the most frequently utilised lattice cell code for thermal reactors of many types, including PHWRs.

The WIMS Multigroup Libraries used for PHWR calculations are: the standard WIMS81, WIMS86, WIMS-K (Korea RP library) and WIMS-CRNL (restricted Canadian libraries constructed from old Winfrith WIMS Libraries and other sources).

The different multigroup libraries used with WIMS and Indian CLUB and CLIMAX codes should be updated to the level of last revision of ENDF/B and other evaluated nuclear data files. Then, a special attention to the application of new WIMS libraries on PHWR calculations is justified.

The main current uses of cell codes of WIMS type, with multigroup associated libraries of nuclear data, are: calculation of parameters useful in physical start-up tests, accident analyses, and fuel management loading schemes.

Some research and development activities associated to PHWR type of reactors, that need updated nuclear libraries of WIMS type, are: use of slightly enriched uranium (SEU cycle), UO2-ThO2 fuels, burnable poisons mixed in fuel pellets (UO2-Gd2O3) and absorber rods, and new types of fuel elements (in Argentina: CARA Project-Advanced Fuel for Argentine Reactors)

Taking into account the need of new WIMS libraries associated with these activities, a set of benchmarks have been identified and coded for PHWR lattice calculations.

The experimental benchmarks are identified with the name of the facility or reactor where the measurements were carried out. The main reference for this type of benchmarks is the ZED-2 Canadian reactor. Four tasks were selected from experiments on this reactor.

In this report, the results of all the benchmarks calculated and analysed up to the end of August 1999 are presented.

Table 1
Benchmark Index

Identif.	Title
EX.1)ZED-2	
TASK 1	Analysis of Experiments with 37-rod Fuel Clusters
TASK 2	Analysis of Experiments with 28-rod Fuel Clusters (hexagonal pitches)
TASK 3	Analysis of Experiments with 28-rod Fuel Clusters (square pitch)
TASK 4	Analysis of Lattice Experiments with 19-rod Clusters with ThO2-UO2 Fuel
EX.2)DCA	
TASK 1	Evaluation of Neutronic Parameters in Heavy Water and Slightly Enriched Uranium UO2 Fuel (28-rod Cluster)
TASK 2	Analysis of critical experiments on Gadolinium poisoned Cluster-Type Fuel Assemblies of 54 Rods in Heavy Water Lattices of DCA Facility

For choosing the best WIMS input options, a previous work has been made, where the different available alternatives for cluster of rods and heavy water lattices were carefully analysed. The main result of this analysis was the following decision regarding the main transport options adopted: DSN (Sn method) and PIJ/PERSEUS (partial PIJ two-dimension collision probability method up to calandria tube, and one-dimension PERSEUS collision probability method) for all cluster calculations. Then, for each case, a comparison of the results obtained with both methods is made.

Besides, all calculations were made using three different multigroup libraries: WIMS-1986 British library (W86), and the two preliminary libraries released on the Wims Library Update Project in this year, based on ENDF/B-VI, Revision 3 (E6), and JEFF-2 (JEFF) nuclear data files, respectively. Then, for each case, a comparison of the results obtained with the two last mentioned libraries is made. The inclusion of the old WIMS-86 library is for having an additional element of comparison only, for showing the improvements introduced with the new nuclear data and methods adopted for the WIMS library generation with NJOY system.

EX.1)ZED-2

Numerous experiments with different fuel elements of CANDU type have been performed in the Canadian heavy water reactor ZED-2. They were made using UO2 (natural) fuel on 37, 28 and 19 fuel clusters, and ThO2-UO2(enriched) 19 fuel elements, including buckling measurements and several parameters of the cells. Four of these experiments were selected for the present work, and are identified here as TASK 1,2, 3 and 4.

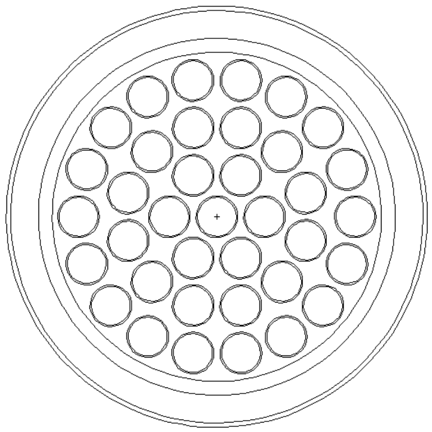
TASK 1. **Analysis of Experiments with 37-rod Fuel clusters [1,2]**

Measurements have been made at a single pitch 28.58 cm square, UO2 (natural) fuel, using heavy water and air as coolants.

Experimental results:

a. Fast fission ratio =[U-238 fis./U-235 fis.]
b. Relative conversion ratio
=[U-238 cap./U-235 fis.]fuel/ [U-238 cap./U235fis.]Maxw.fl.
c. U-235 fission rate distribution
d. Cu-63 absorption rate distribution
e. Lutetium-Manganese ratio
=[ALu/AMn]fuel/[AMn/Alu]Maxw.fl. (A:activation rates)

(a-e,for the four rings and average)



Calculated Parameters:

1)Effective Multiplication Factor **Keff** --- Table 3
2)Fast Fission Ratio **(U238fiss/U235fiss)x** ----------------------------------- Tables 4, 5
3)Initial Conversion Ratio **C=Cx/Cth**;
Cx=[U238capt/U235fiss]x; Cth=Thermal Ref.value ---------------------- Tables 6, 7
4)U-235 Fission Rate **U5FR=(U235fiss)x/(U235fiss)FA** ------------------ Tables 8, 9
5)Relative Copper Activity
RCA=(Cu63abss)x/(Cu63abss)FA -- Tables 10,11
6)Lutetium-Manganese Activity Ratio **LMAR=LMARx/LMARth**
LMARx=(Lu176abss)x/(Mnabss)x; LMARth=Thermal Ref.value -------Tables 12,13
x : position of fuel rods A,B,C,D (from innner to outer annulus);FA: fuel average

Table 2
General Data

Pitch (cm)	28.58 (square)
Coolants	1)D2O; 2)Air
Moderator	D2O
Number of rods	37 (1/6/12/18)
Radius of rod centers (cm)	0.0/1.4885/2.8755/4.3305
Fuel material	UO2-nat
Density of fuel material (g/cm**2)	10.50
Radius of fuel rods (cm)	Central: 0.5965; Others: 0.6050
Sheath material	Zry-4
Density of sheath material (g/cm**2)	6.55
Internal radius of sheath (cm)	0.61
Thickness of sheath (cm)	0.045
Material of pressure and calandria tubes	1050 Al alloy
Density of press.and calandria Tubes (g/cm**2)	2.7
Internal radius of pressure tube (cm)	5.195
Thickness of pressure tube (cm)	0.315
Internal radius of calandria tube (cm)	6.35
Thickness of calandria tube (cm)	0.32
Temperature (all components) (K)	296.0
Experimental buckling (cm**(-2)	1)D2O coolant:2.7E-04; 2)Air coolant:2.0E-04

Table 3
Effective Multiplication Factor: (Keff-1.00000)*100000 (pcm)

COOLANT	METHOD	W86	**E6**	JEFF
D2O	**DSN**	+218	**-164**	+299
	PIJ	+123*	-254	+211
AIR	**DSN**	+235	**+ 16**	+452
	PIJ	+ 89	-125	+317

Table 4
Fast Fission Ratio: Reference Experimental Values

Coolant	A	B	C	D	FA
D2O	0.0768	0.0719	0.0592	0.0411	0.0511
AIR	0.0810	0.0770	0.0664	0.0481	0.0583

Table 5
Fast Fission Ratio: D=(calc/exp-1)*100;(exp.error=1.5 %)

Coolant	Method	Library	D(%)				
			A	B	C	D	FA
D2O	DSN	W86	+ 7.2	+4.2	+2.8	+0.42	+6.1
		E6	+ 8.2	+4.9	+2.6	-1.1	+5.6
		JEFF	+ 6.6	+3.4	+1.3	-2.1	+4.3
	PIJ	W86	- 3.8	+0.58	+2.1	+2.2	+5.2
		E6	**- 3.0**	+1.1	+1.8	+0.75	+4.7
		JEFF	- 4.4	**-0.36**	**-0.52**	**-0.35**	**+3.4**
AIR	DSN	W86	+ 9.6	+6.7	+3.9	+1.0	+5.9
		E6	+10	+6.9	+3.5	-0.38	+5.2
		JEFF	+ 8.2	+5.2	+1.9	-1.6	+3.7
	PIJ	W86	- 1.2	+2.9	+2.4	+1.7	+4.4
		E6	**- 0.97**	+2.9	+2.0	-0.36	+3.7
		JEFF	- 2.6	**+1.2**	**+0.41**	**-0.93**	**+2.2**

Table 6
Initial Conversion Ratio (C): Reference Experimental Values

Coolant	C				
	A	B	C	D	FA
D2O	1.4936	1.4681	1.4254	1.3925	1.4138
AIR	1.3909	1.3590	1.3627	1.3880	1.3765

Table 7
Initial Conversion Ratio (C): D=(Ccalc/Cexp-1)*100;(exp.error=0.35 %)

Coolant	Method	Library	D(%)				
			A	B	C	D	FA
D2O	**DSN**	W86	+0.90	+0.81	-0.67	-0.30	+0.11*
		E6	+2.0	+1.9	+0.23	**+0.23**	+0.86
		JEFF	+1.7	**+1.6**	**-0.03**	-0.35	**+0.60**
	PIJ	W86	+0.32*	+0.80*	-0.42	+0.02*	+0.35
		E6	+1.4	+1.8	+0.50	+0.65	+1.1
		JEFF	**+1.2**	**+1.6**	+0.24	+0.39	+0.87
AIR	**DSN**	W86	+0.89	+1.9*	-1.2	-0.06*	-0.20
		E6	+1.8	**+2.8**	-0.37	**+0.36**	**+0.46**
		JEFF	+1.9	+2.9	-0.25	+0.48	+0.57
	PIJ	W86	-0.14*	+1.9*	-0.98	0.24	0.0*
		E6	**+0.78**	**+2.8**	-0.08	+0.70	+0.69
		JEFF	+0.87	+2.9	**+0.03**	+0.81	+0.79

Table 8
U-235 Fission Rate (U5FR): Reference Experimental Values

Coolant	U5FR			
	A	B	C	D
D2O	0.746	0.787	0.907	1.147
AIR	0.814	0.842	0.927	1.112

Table 9
U-235 Fission Rate (U5FR); D=(U5FRcalc/U5FRexp-1)*100;(exp.error=0.2 %)

Coolant	Method	Library	D(%)			
			A	B	C	D
D2O	DSN	W86	-2.0	-1.1	-0.26	+0.48
		E6	-3.4	-2.3	-0.72	+1.03
		JEFF	-3.4	-2.3	-0.71	+1.0
	PIJ	W86	+2.4	+0.43*	-0.04*	-0.16*
		E6	**+1.1**	+0.55	-0.43	+0.32
		JEFF	+1.2	**-0.53**	**-0.41**	**+0.31**
AIR	DSN	W86	-4.6	-2.3	-0.32	+0.89
		E6	-4.9	-2.9	-0.58	+1.2
		JEFF	-4.8	-2.9	-0.55	+1.2
	PIJ	W86	+1.1	-0.96*	-0.28*	+0.33*
		E6	**+0.47**	-1.5	-0.49	+0.60
		JEFF	+0.53	**-1.4**	**-0.46**	**+0.57**

Table 10
Relative Copper Activity (RCA): Reference Experimental Values

Coolant	RCA				
	A	B	C	D	MA
D2O	0.757	0.794	0.913	1.140	2.096
AIR	0.824	0.844	0.928	1.110	2.024

MA: Moderator Average

Table 11
Relative Copper Activity (RCA); D=(RCAcalc/RCAexp-1)*100; (exp.error=1.0 %)

Coolant	Method	Library	D(%)				
			A	B	C	D	MA
D2O	DSN	W86	+1.1	-0.11*	-0.17	+0.12	+0.63
		E6	-2.1	-0.98	-0.52	+0.60	+2.7
		JEFF	**-0.87**	**-0.48**	+0.54	-6.9	+2.3
	PIJ	W86	+3.1	+1.4	+0.05*	-0.44	+0.16*
		E6	+2.1	+0.65	-0.24	**-0.08**	+2.0
		JEFF	+2.3	+0.77	**-0.19**	-0.15	**+1.6**
AIR	DSN	W86	-3.5	-1.1	+0.16	+0.30	+0.31
		E6	-4.2	-1.6	+0.04	+0.59	+2.1
		JEFF	-4.0	-1.5	**0.0**	+0.53	+1.8
	PIJ	W86	+1.3	+0.15*	+0.21	-0.23	+0.02*
		E6	**+0.83**	+0.27	+0.05	**-0.01**	+1.6
		JEFF	+0.94	**-0.16**	+0.09	-0.07	**+1.3**

MA: Moderator Average

Table 12
Lutetium-Manganese Activity Ratio (LMAR): Reference Experimental Values

Coolant	LMAR				
	A	B	C	D	FA
D2O	1.290	1.273	1.235	1.171	1.206
AIR	1.289	1.272	1.242	1.197	1.223

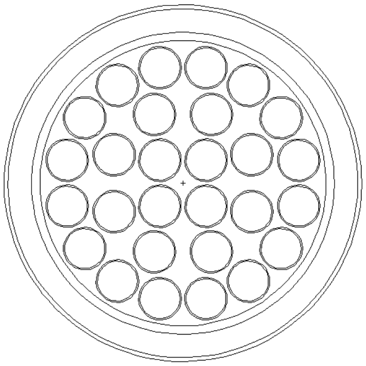
Table 13
Lutetium-Manganese Activity Ratio (LMAR): D=(LUARcalc/LUARexp-1)*100; (exp.error=0.4 %)

Coolant	Method	Library	D(%)				
			A	B	C	D	FA
D2O	DSN	W86	-0.14	-0.30	-0.40	-0.07*	+0.24
		E6	+2.4	+2.2	+2.0	+2.1	+2.5
		JEFF	**-0.08**	**-0.13**	**-0.10**	+0.42	+0.60
	PIJ	W86	-1.8	-1.0	-0.73	-0.20	-0.10*
		E6	+0.79	+1.5	+1.6	+1.9	+2.2
		JEFF	-1.6	-0.88	-0.49	**+0.27**	**+0.22**
AIR	DSN	W86	+1.2	+1.2	+0.80	-0.40*	+0.58
		E6	+3.3	+3.3	+2.8	+1.6	+2.6
		JEFF	+1.9	+2.0	+1.7	+0.85	+1.6
	PIJ	W86	-0.40	+0.62*	+0.48*	+0.52	+0.27*
		E6	+1.6	+2.7	+2.5	+1.5	+2.3
		JEFF	**+0.31**	**+1.4**	**+1.4**	**+0.69**	**+1.3**

TASK 2. Analysis of Experiments with 28-rod Fuel Clusters (hexagonal pitches) [3,4]

Measurements were made using UO2 (natural) fuel, heavy water and air as coolants. Buckling measurements were performed at 8 triangular lattice pitches of 24, 26, 28, 30, 32, 34, 36 and 40 cm for both the coolants, and detailed reaction rate measurements were carried out at 4 lattice pitches of 24, 28, 32 and 40 cm only.

Experimental results:
a. Material bucklings
b. Fast fission ratio
c. Initial conversion ratio
   = [U-238 cap./U-235 abs.]
d. Neutron density distribs.
   (Npt/Nf, Nct/Nf, Nm/Nf)
   (pt:pres.tube; ct:calandria tube;
   m:moderator; f:fuel)



Calculated Parameters:
1)Effective Multiplication Factor **Keff** --------------------------- Table 15
2)Fast Fission Ratio **(U238fiss/U235fiss)fa** ----------------- Tables 16,17
3)Initial Conversion Ratio **C=Cfa/Cth**;
  Cfa=[U238capt/U235abss]fa; Cth=Thermal Ref.value --- Tables 18,19
fa: fuel average; capt: absorption - fission; abss: capture + fission

Table 14. General Data

Pitches (cm)	1)24.0; 2)40.0 (hexag.)
Coolant	D2O
Moderator	D2O
Number of rods	28 (4/8/16)
Radius of rod centers (cm)	1.163/2.652/4.206
Fuel material	UO2-nat
Density of fuel material (g/cm**2)	10.45
Radius of fuel rods (cm)	0.71
Sheath material	Zry-2
Density of sheath material (g/cm**2)	6.55
Internal radius of sheath (cm)	0.715
Thickness of sheath (cm)	0.045
Material of pressure tube	65s Al alloy
Material of calandria tube	50s Al alloy
Density of press.and caland.Tubes (g/cm**2)	2.7
Internal radius of pressure tube (cm)	5.095
Thickness of pressure tube (cm)	0.295
Internal radius of calandria tube (cm)	6.23
Thickness of calandria tube (cm)	0.14
Temperature (all components) (K)	296.0
Experimental buckling (cm**(-2)	1)24 cm pitch:2.804E-04 2)40 cm pitch:2.772E-04

Table 15
Effective Multiplication Factor:: (Keff-1.00000)*100000 (pcm)

PITCH(cm)	METHOD	W86	E6	**JEFF**
24	**DSN**	-414*	-838	**-473**
	PIJ	-459	-880	-483
40	**DSN**	+190	-145	**+136**
	PIJ	-247	-581	-304

Table 16
Fast Fission Ratio:Reference Experimental Values

Pitch(cm)	Fast Fiss.Ratio
24	0.0580
40	0.0547

Table 17
Fast Fission Ratio: D=(calc/exp-1)*100; (exp.error=1.5 %)

PITCH(cm)	Method	Library	D(%)
24	DSN	W86	- 9.2
		E6	-10
		JEFF	-11
	PIJ	W86	- 8.1*
		E6	**- 8.8**
		JEFF	- 9.9
40	DSN	W86	-12
		E6	-13
		JEFF	-14
	PIJ	W86	- 9.6*
		E6	**-10**
		JEFF	-11

Table 18
Initial Conversion Ratio (C): Reference Experimental Values

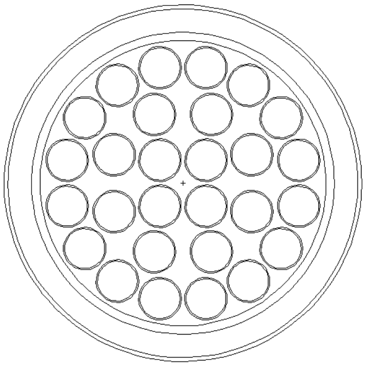
Pitch(cm)	C
24	0.9258
40	0.7663

Table 19
Initial Conversion Ratio (C): D=(Ccalc/Cexp-1)*100;(exp.error=0.6 %)

PITCH(cm)	Method	Library	D(%)
24	DSN	W86	-5.2
		E6	-4.5
		JEFF	-4.3
	PIJ	W86	-4.9
		E6	**-4.1**
		JEFF	-4.3
40	DSN	W86	-6.7
		E6	-6.2
		JEFF	-5.9
	PIJ	W86	-5.9
		E6	-5.3
		JEFF	**-5.0**

TASK 3. Analysis of Experiments with 28-rod Fuel Clusters (square pitch) [5]

Measurement of material buckling has been made at a single pitch 28.575 cm square, using UO2 (natural) fuel and heavy water as coolant.

Experimental result: a. Material bucklings	

Calculated Parameters:
Effective Multiplication Factor **Keff** --------------- Table 21

Table 20
General Data

Pitch (cm)	28.575 (square)
Coolant	D2O
Moderator	D2O
Number of rods	28 (4/8/16)
Radius of rod centers (cm)	1.163/2.652/4.206
Fuel material	UO2-nat
Density of fuel material (g/cm**2)	10.0277
Radius of fuel rods (cm)	0.7105
Sheath material	Zry-2
Density of sheath material (g/cm**2)	6.55
Internal radius of sheath (cm)	0.7155
Thickness of sheath (cm)	0.0454
Material of pressure tube	65s Al alloy
Material of calandria tube	50s Al alloy
Density of press.and caland.Tubes (g/cm**2)	2.7
Internal radius of pressure tube (cm)	5.0965
Thickness of pressure tube (cm)	0.296
Internal radius of calandria tube (cm)	6.23
Thickness of calandria tube (cm)	0.139
Temperature (all components) (K)	296.0
Experimental buckling (cm**(-2)	3.77E-04

Table 21
Effective Multiplication Factor: (Keff-1.00000)*100000 (pcm)

METHOD	W86	E6	**JEFF**
DSN	- 59	-266	**+ 45**
PIJ	-287	-494	-182

TASK 4. Analysis of Lattice Experiments with 19-rod Clusters with ThO2-UO2 Fuel [6-8]

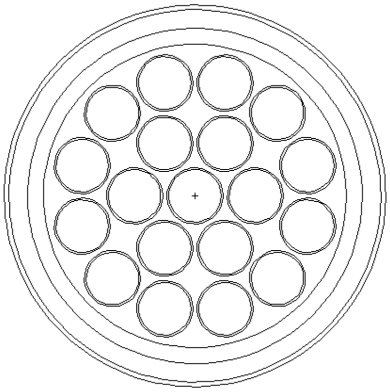
Measurements were made with ThO2 fuel containing 1.5 wt% enriched UO2 (93.02 atm % U235) using heavy water, air and light water as coolants. Buckling measurements were performed at four triangular lattice pitches of 22, 24, 28 and 32 cm and detailed reaction rate measurements were carried out at 24 and 28 cm only.

Experimental results:

a.Material bucklings

b. Th232fis/U235fis

c. Th232cap/U235fis



Calculated Parameters:
1)Effective Multiplication Factor **Keff** ------------------------------ Table 23
2)Th232/U235 Fission Ratio **=Th232fiss/U235fiss)fa** ------ Tables 24,25
3)Conversion Ratio **C=[Th232capt/U235fiss]fa** ---------------- Tables 26,27
fa: fuel average; capt: absorption - fission

Table 22
General Data

Pitches (cm)	1)22.0; 2)28.0 (triangular)
Coolant	a)D2O; b)Air
Moderator	D2O
Number of rods	19 (1/6/12)
Radius of rod centers (cm)	0.0/1.468/2.837
Fuel material	[ThO2(98.5wt%)]- [UO2-93at%(1.5wt%)]
Density of fuel material (g/cm**2)	9.33
Radius of fuel rods (cm)	0.5765
Sheath material	Zry-2
Density of sheath material (g/cm**2)	6.55
Internal radius of sheath (cm)	0.5815
Thickness of sheath (cm)	0.0406
Material of coolant tube	Alcan 6068 Al alloy
Density of coolant tube (g/cm**2)	2.7
Internal radius of coolant tube (cm)	3.683
Thickness of coolant tube (cm)	0.127
Temperature (all components) (K)	298.0
Experimental bucklings (cm**(-2)	1)22 cm pitch a)D2O coolant:2.4E-04 b)Air coolant:2.3E-04 2)28 cm pitch a)D2O coolant:1.5E-04 b)Air coolant:1.6E-04

Table 23
Effective Multiplication Factor: (Keff-1.00000)*100000 (pcm)

PITCH(cm)	COOLANT	METHOD	W86	E6	**JEFF**
22	D2O	DSN	-450	-1101	-399
		PIJ	-446	-1036	**-343**
	AIR	DSN	-129	- 768	- 36
		PIJ	-125	- 709	**+ 26**
28	D2O	DSN	-476	-1067	-576
		PIJ	-445*	- 999	**-513**
	AIR	DSN	-392	- 917	-421
		PIJ	-333	- 810	**-315**

Table 24
Th232/U235 Fission Ratio: Reference Experimental Values

PITCH(cm)	COOLANT	Th232/U235 FR
22	D2O	0.00707
	AIR	0.00691
28	D2O	0.00612
	AIR	0.00688

Table 25
Th232/U235 Fission Ratio: D=(calc/exp-1)*100; (exp.error=10 %)

PITCH(cm)	COOLANT	METHOD	W86	E6	**JEFF**
22	D2O	**DSN**	+14	+16	**+10**
		PIJ	+18	+20	+14
	AIR	**DSN**	+32	+34	**+28**
		PIJ	+32	+35	+29
28	D2O	**DSN**	+27	+30	**+24**
		PIJ	+32	+34	+29
	AIR	**DSN**	+28	+30	**+25**
		PIJ	+28	+31	+25

Table 26
Th-232-CAPT/U235-FISS.Ratio (C): Reference Experimental Values

PITCH(cm)	COOLANT	C
22	D2O	1.089
	AIR	1.077
28	D2O	1.054
	AIR	1.034

Table 27
Th-232-CAPT/U235-FISS.Ratio (C): D=(Ccalc/Cexp-1)*100; (exp.error=1.4 %)

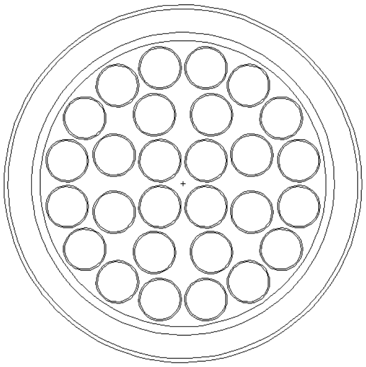
PITCH(cm)	COOLANT	METHOD	W86	**E6**	JEFF
22	D2O	**DSN**	-1.8	**-0.14**	-1.3
		PIJ	-1.7	-0.18	-1.4
	AIR	**DSN**	-1.7	**0.0**	-1.3
		PIJ	-1.5	+0.15	-1.2
28	D2O	**DSN**	-1.9	**-0.42**	-1.2
		PIJ	-1.9	+0.41	-1.2
	AIR	DSN	-1.2	+0.30	-0.53
		PIJ	-1.1	**+0.29**	-0.55

EX.2)DCA (Deuterium Critical Assembly)

DCA is a Japanese critical facility with 28 fuel elements of CANDU type. The fuel is made of UO2 with slightly enriched uranium(1.2 w% U235). Experiments were made including buckling measurements with different coolants, and several cell parameters of 54-rods test cluster placed at the centre of the core with Gd poisons. Two experiments were selected for the present work, and are identified here as TASK 1 and TASK 2.

TASK 1. Evaluation of Neutronic Parameters in Heavy Water and Slightly Enriched Uranium UO2 Fuel (28-rod Cluster) [9-11]

Measurements were made with fuel of enriched UO2 (1.2 w% U235) using heavy water, air and light water as coolants. Buckling measurements were performed at two square lattice pitches of 22.5 and 25.0 cm.

Experimental result: a. Material bucklings	

Calculated Parameters:
1)Effective Multiplication Factor **Keff** -------------------- Table 29

Table 28
General Data

Pitches (cm)	1)22.5; 2)25.0 (square)
Coolants	a)D2O; b)Air; c)H2O
Moderator	D2O
Number of rods	28 (4/8/16)
Radius of rod centres (cm)	1.3125/3.0/4.7575
Fuel material	UO2-1.2w%
Density of fuel material (g/cm**2)	10.36
Radius of fuel rods (cm)	0.74
Sheath material	Al
Density of sheath material (g/cm**2)	2.7
Internal radius of sheath (cm)	0.7515
Thickness of sheath (cm)	0.0850
Material of pressure and calandria tubes	Al
Density of press.and caland.Tubes (g/cm**2)	2.7
Internal radius of pressure tube (cm)	5.84
Thickness of pressure tube (cm)	0.20
Internal radius of calandria tube (cm)	6.625
Thickness of calandria tube (cm)	0.20
Temperature (all components) (K)	295.15
Experimental bucklings (cm**(-2)) (1) Void fraction: 87 % (99.82 atom % of D2O)	1)22.5 cm pitch a)D2O coolant(1): Br**2= 2.47E-04 Bz**2= 7.66E-04 b)Air coolant: Br**2= 2.36E-04

(2) Void fraction: 70 % (88.88 atom % of D2O)	Bz**2= 6.47E-04 c)H2O coolant: Br**2= 2.47E-04 Bz**2= 8.59E-04 2)25.0 cm pitch a)D2O coolant(2): Br**2= 2.47E-04 Bz**2= 7.81E-04 b)Air coolant: Br**2= 2.31E-04 Bz**2= 7.25E-04 c)H2O coolant: Br**2= 2.45E-04 Bz**2= 7.27E-04

Table 29
Effective Multiplication Factor: (Keff-1.00000)*100000 (pcm)

PITCH(cm)	COOLANT	METHOD	W86	**E6**	JEFF
22.5	D2O	**DSN**	+ 317	**+ 153**	+ 634
		PIJ	+ 348	+ 218	+ 703
	AIR	**DSN**	- 606	- 545	**- 33**
		PIJ	- 878	- 827	- 315
	H2O	**DSN**	+ 982	**+ 594**	+1024
		PIJ	+1725	+1478	+1908
25.0	D2O	DSN	- 457	- 269	+ 207
		PIJ	- 713	- 526	**- 49**
	AIR	DSN	+ 217	+ 422	+ 891
		PIJ	- 191	**- 2**	+ 470
	H2O	**DSN**	+1506	**+1118**	+1525
		PIJ	+2404	+2165	+2578

TASK 2. Analysis of critical experiments on Gadolinium poisoned Cluster-Type Fuel Assemblies of 54 Rods in Heavy Water Lattices of DCA Facility [12]

A test fuel cluster of 54 fuel pins composed of UO2 enriched to 1,5 wt% in U235 was placed in the centre of the DCA and was surrounded by 1.2 wt% U-235 enriched UO2 fuel clusters of 28 pins each. To investigate the effect of burnable poison in fuel pellets, a few fuel pins of the test cluster were replaced with 1.5 wt% enriched UO2 pins containing 0.1, 0.5 or 1.0 wt% GdO3.

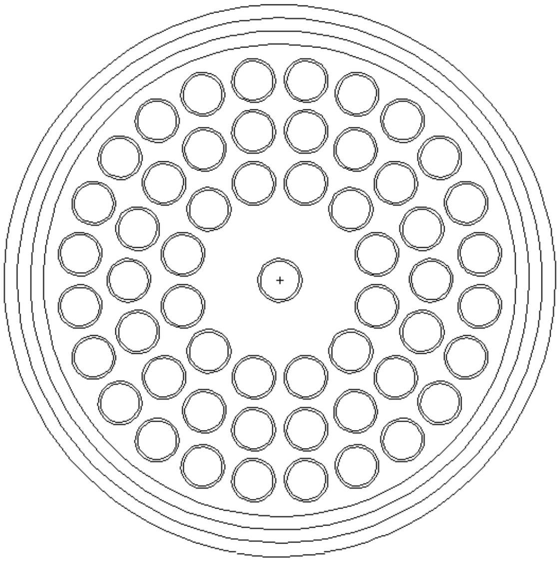
Experimental results:

a. Local power distribution,

b. Thermal neutron flux distribution,

c. Fine structure of the thermal neutron flux distribution on a pin cell within the moderator region,

on test fuel cluster on the center of DCA



Calculated Parameters:

1) Thermal Neutron Flux Distribution in the Cluster ----------------------- Tables 31,32; Figures 1, 2

2) Fine Structure of Thermal Neutron Flux Distribution in the fuel pellets -- Table 33
(this is a pin cell calculation with 32 mesh intervals for detailed radial flux calculation, taking into account the resonance self-shielding)

Table 30
General Data

Pitch (cm)	40.0 (square)
Coolants	a)H2O; b)Air
Moderator	D2O
Number of rods	54 (12/18/24)
Radius of rod centers (cm)	3.825/5.76/7.68
Fuel material	i)Normal: UO2-1.5wt% ii)Poisoned fuel pins: UO2-1.5wt% + Gd2O3-0.1,0.5,or 1.0 wt%
Density of fuel material (g/cm**2)	i) 10.38; ii)10.30
Radius of fuel rods (cm)	i) 0.7385; ii)0.739
Sheath material	Al
Density of sheath material (g/cm**2)	2.7
Internal radius of sheath (cm)	i)0.7515; ii)0.7490
Thickness of sheath (cm)	i)0.0850; ii)0.1355
Material of pressure and calandria tubes	Al
Density of press.and caland.Tubes (g/cm**2)	2.7
Internal radius of pressure tube (cm)	9.0
Thickness of pressure tube (cm)	0.5
Internal radius of calandria tube (cm)	10.0
Thickness of calandria tube (cm)	0.5
Temperature (all components) (K)	293.15

Table 31
Thermal Neutron Flux Distribution (TF): Reference Experimental Values

CASE	COOLANT	A1	A2	A3	M11	M16	M22
without Gd	D2O	0.30	0.32	0.55	1.1	1.4	1.5
	AIR	0.38	0.55	0.75	1.2	2.05	2.30
with Gd	D2O	0.15	0.17	0.06 (1)	1.18	1.68	1.87 (2)

A1,A2,A3: in fuel rods, from inner to outer annulus;
M11,M16,M22: in moderator (r=11,16 and 22 cm from the center)
(1): in the rods with Gd (12 rods with 1% GdO2 on third layer)
(2): M22 is for r= 20 cm for case with Gd

Table 32
Thermal Neutron Flux Distribution (TF); D=TFcalc-TFexp;
(exp.error=±0.10 without Gd;=±0.15 with Gd)

CASE	COOLANT	METHOD	LIBRARY	A1	A2	A3	M11	M16	M22
without Gd	D2O	DSN	W86	-.06	-.07	-.12	-.03	-.01	+.01
			E6	-.07	-.09	-.13	-.03	+.01	**+.03**
			JEFF	-.07	-.09	-.13	-.03	**.0**	**+.03**
		PIJ	W86	+.03	+.02	-.07	-.02	+.09	+.13
			E6	**+.02**	**+.01**	**-.08**	**-.01**	+.12	+.17
			JEFF	**+.02**	**+.01**	**-.08**	**-.01**	+.12	+.17
	AIR	**DSN**	W86	+.02	-.07	-.08	+.01	+.04	+.11
			E6	**+.01**	**-.08**	**-.08**	**+.01**	**+.08**	**+.18**
			JEFF	**+.01**	**-.08**	**-.08**	**+.01**	**+.08**	**+.18**
		PIJ	W86	+.02	-.08	-.09	-.03	+.07	+.16
			WE6	**+.01**	-.09	-.09	-.02	+.12	+.23
			JEFF	**+.01**	-.09	-.09	-.02	+.12	+.23
with Gd	D2O	DSN	W86	+.08	-.05	+.02(1)	-.07	-.05	-.07 (2)
			E6	**+.08**	**-.05**	**+.01** (1)	**-.07**	**-.03**	**-.04** (2)
			JEFF	**+.08**	**-.05**	**+.01** (1)	**-.07**	-.04	-.05 (2)

A1,A2,A3: in fuel rods, from inner to outer annulus;
M11,M16,M22: in moderator (r=11,16 and 22 cm from the center)
(1): in the rods with Gd (12 rods with 1% GdO2 on third layer)
(2): M22 is for r= 20 cm for case with Gd

Figure 1
Thermal Neutron Flux Distribution (TF) on a 54-pin cluster without poisoned fuel pins
(JEFF results vs. experimental values)

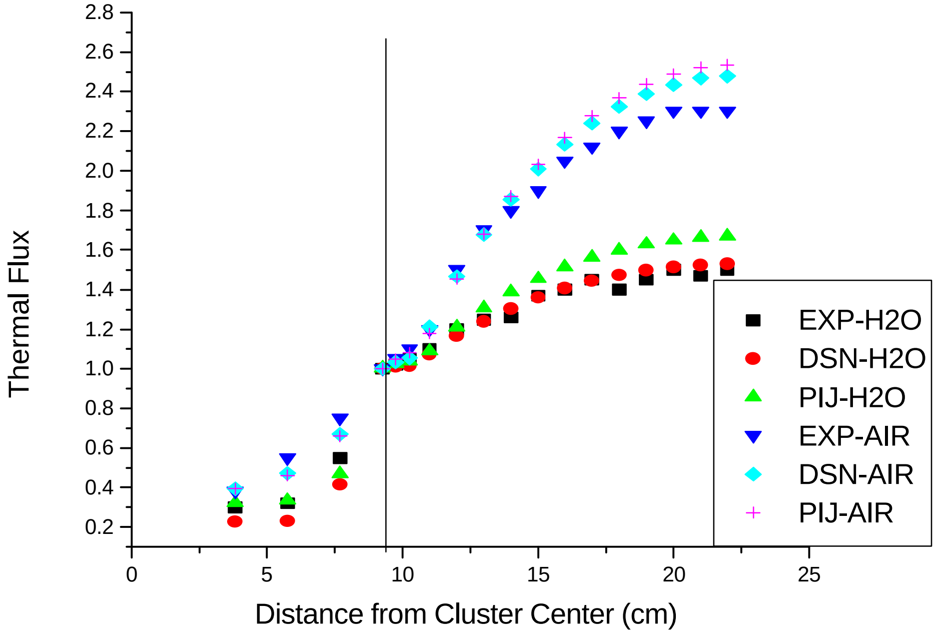


Figure 2
Thermal Neutron Flux Distribution (TF) on a 54-pin cluster with 12 poisoned fuel pins in the third layer (H2O coolant) JEFF and ENDF/B-VI results vs. experimental values

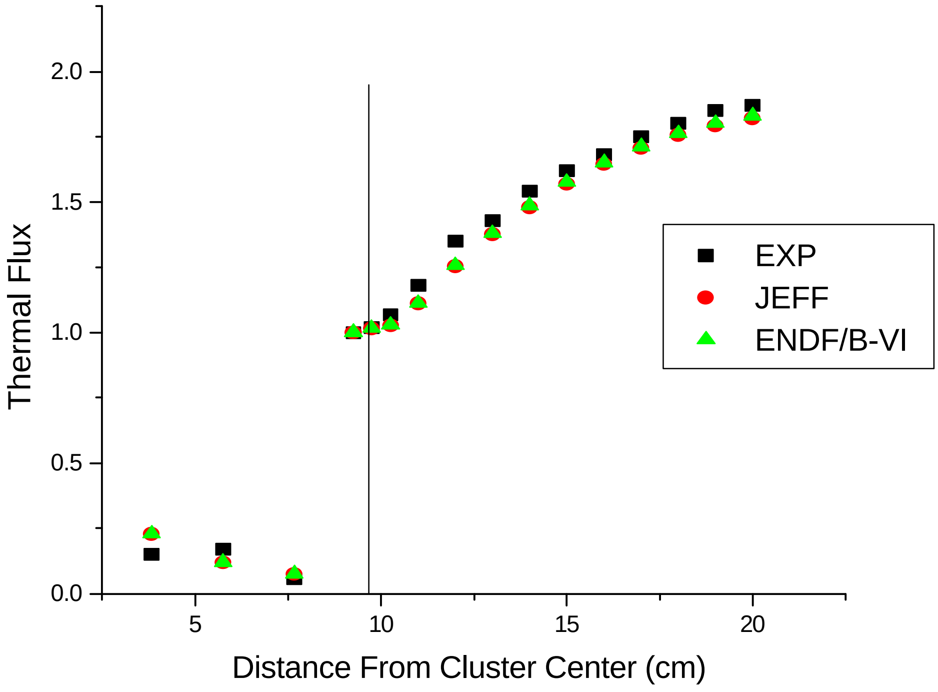


Table 33
Fine Structure of Thermal Neutron Flux Distribution: Average Dysprosium Reaction Rates (ADR): D=ADRcalc-ADRexp

Case	ADR Exp	exp.error	ADR W86	Dw86	ADR E6	De6	ADR **JEFF**	Djeff
without Gd	0.922	.032	0.915	-.007	0.915	-.007	0.915	-.007
0.1 wt% Gd2O3	0.723	.029	0.659	-.064	0.659	-.064	**0.660**	**-.063**
0.5 wt% Gd2O3	0.424	.016	0.387	-.037	0.389	-.035	**0.391**	**-.033**
1.0 wt% Gd2O3	0.317	.011	0.303	-.014	0.305	-.012	**0.307**	**-.010**

General Observations:

Effective Multiplication Factor:

BEST LIBRARY: JEFF in 3 cases; ENDF/B-VI in 2 cases

BEST METHOD: DSN in 5 cases; PIJ in 1 case (EX.1)ZED-2 TASK 4 ThO2-UO2 Fuel)

AGREEMENT EXPERIMENT/CALCULATION: good (less than 1000 pcm),
except EX.2)DCA TASK 1 Slightly Enriched Uranium UO2 Fuel and H2O coolant

Fast Fission Ratio:

BEST LIBRARY: JEFF in 2 cases; ENDF/B-VI in 1 case **(**EX.1)ZED-2 TASK 2**)**

BEST METHOD: PIJ in 2 cases; DSN in 1 case (EX.1)ZED-2 TASK 4 ThO2-UO2 Fuel)

AGREEMENT EXPERIMENT/CALCULATION:
>good for (EX.1)ZED-2 TASK 4 ThO2-UO2 Fuel) pitch of 22 cm and D2O coolant;
>rather good for EX1)ZED-2 TASK 1
>not so good for the other cases

Initial Conversion Ratio (C):

BEST LIBRARY: ENDF/B-VI in 2 cases; JEF in 1 case **(**EX.1)ZED-2 TASK 1**)**

BEST METHOD: >DSN in 1 case (EX.1)ZED-2 TASK 1**)**
>PIJ in 1 case (EX.1)ZED-2 TASK 2)
>slightly better for DSN (EX.1)ZED-2 TASK 4)
except for pitch of 28 cm, AIR coolant, where PIJ is slightly better than DSN

AGREEMENT EXPERIMENT/CALCULATION: good except(EX.1)ZED-2 TASK 2);
better for exterior annulus

U-235 Fission Rate, Relative Copper Activity, and Lutetium-Manganese Activity Ratio:

BEST LIBRARY: JEFF
BEST METHOD: PIJ AGREEMENT EXPERIMENT/CALCULATION: good except Lutecium-Manganese Ratio for AIR

Thermal Neutron Flux Distribution:

Best library: WE6 and JEFF give similar results
Best method (for cases without Gd): PIJ for D2O coolant; DSN for AIR coolant (slightly better)
Agreement exper./calcul.: good

>DSN and PIJ errors are inverted in absolute values from the fuel to the moderator regions; in the fuel, PIJ method gives better results than DSN (for H2O coolant) and in the moderator DSN method gives better results than PIJ (for H2O and AIR).
>The calculations underestimates the thermal flux in the fuel region and overestimates the thermal flux on the moderator region.

Fine Structure of Thermal Neutron Flux Distribution:

Best library: JEFF results are slightly better than ENDF/B-VI results, except for the case without Gd, where both libraries give similar results.

Agreement exper./calcul.: good for the cases without Gd and with 1.0 wt % Gd2O3.

GLOBAL OBSERVATIONS:

BEST LIBRARY: JEFF in 8 cases, ENDF/B-VI in 5 cases

BEST METHOD: DSN in 8 cases (more for Keff); PIJ in 6 cases (more for U-235 Fission Rate, Relative Copper Activity, and Lutetium-Manganese Activity Ratio)

AGREEMENT EXPERIMENT/CALCULATION: not so good for:
>Keff for EX.2)DCA TASK 1 Slightly Enriched Uranium UO2 Fuel and H2O coolant;
>Fast fission ratio in general (except for EX.1)ZED-2 TASK 4 ThO2-UO2 Fuel pitch of 22 cm and D2O coolant);
>Initial Conversion Ratio for EX.1)ZED-2 TASK 2;
>Lutecium-Manganese Ratio for AIR
>Fine Structure of Thermal Neutron Flux Distribution for 0.1 and 0.5 wt % Gd2O3.

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