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SURVEY OF NEUTRON RADIOGRAPHY FACILITIES

by

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1 Introduction

A directory of neutron radiography facilities around the world was informally compiled about ten years ago under the auspices of the American Society for Testing and Materials (ASTM), Subcommitte E7.05 (Radiology, Neutron). The work lay dormant for a number of years, but was revived in earnest in the fall of 1995. At that time, letters were mailed to all the facilities with available addresses in the original directory, requesting updated information. Additionally, information was gathered at the Second Topical Meeting on Neutron Radiography Facility System Design and Beam Characterization (November, 1995, Shonan Village, Japan). A second mailing was sent for final confirmation and updates in January, 1996. About 75% of the information in the directory has now been confirmed by the facility management.

This paper presents a summary of the information contained in the facility directory. An electronic version of the directory in Wordperfect 6.1, uuencode, or rtf format is available by sending e-mail to the authors at imel@anl.gov or imel@baobab.cad.cea.fr. A WWW site for the directory is presently under construction.

2 Facility Data

There are presently 104 facilities listed in the directory, in 34 countries. Of those total number of facilities, the data contained in 72 of them have been confirmed in the last six months by the authors.

The directory contains an entry for the neutron source type (e.g., reactor, linac, Cf-252 source, etc.). The data were compiled according to three general categories: reactor, acccelerator, and istotopic source. Table 1 gives the distribution by type for all of the countries in the directory. Table 1 is a compilation of all the facilities in the directory, including facilities that are not currently operating, and is presented for historical information. A similiar compilation is made of only those verified operating facilities, and is presented in a following table.

The information in the table is somewhat as expected. About 75% of the facilities use a reactor as the neutron source and Japan and the USA together comprise about 40% of all of the facilities in the directory.

The directory does contain information when known concerning the status of the

Country	acc[a]	rx[b]	src[c]	Total	Country	acc	rx	src	Total
Australia	0	1	0	1	Malaysia	0	1	0	1
Austria	0	1	0	1	Mexico	0	1	0	1
Bangladesh	0	1	0	1	Netherlands	0	2	0	2
Belgium	0	2	0	2	Pakistan	0	1	0	1
Brazil	0	2	1	3	Philippines	0	1	0	1
Canada	0	4	0	4	ROC	0	1	0	1
China	1	2	0	3	Russia	0	4	1	5
Czech	0	1	0	1	Slovenia	0	1	0	1
Denmark	0	1	0	1	Sweden	0	2	0	2
France	1	8	0	9	Switzerland	1	0	0	1
Germany	2	3	1	6	Thailand	1	1	0	2
Hungary	0	1	0	1	Turkey	0	1	0	1
India	0	1	0	1	UK	0	1	0	1
Indonesia	0	1	0	1	USA	4	16	5	25
Iran	0	1	0	1	Vietnam	0	1	0	1
Israel	0	1	0	1					
Italy	0	1	0	1					
Japan	7	9	2	18					
Korea	1	1	0	2	Total	18	76	10	104

[a] Accelerator
[b] Reactor
[c] Isotopic Source

Table 1: Facility Sources for All Facilities in the Directory

facility (e.g., shutdown, operating, undergoing modifications). Table 2 gives the distribution according to source type of only those facilities that have been recently verified to be operating.

As seen by examining Table 2, the reactor percentage is still about 75%, and the combined sum of the facilities in Japan and the USA is now about 50%.

It is interesting to note the countries from which no or little verification has been received. This information is contained in Table 3. Not surprisingly, the highest percentage of verification has come from the USA (80%), Japan (94%), Canada (100%), and many of the Asian countries represented at Shonan Village. It is hoped that the missing European countries can be verified and updated through information obtained at this conference.

A number of facilities in the original directory have since been shutdown. Table 4 contains the distribution by country of facilities that are shutdown, definitely operating, or of unknown status.

The USA has shut down 20% of the facilities that appeared in the original directory, and Japan has shut down 22%. In total, only 16 out of an original 104 facilities have been verified to have been shut down. Because those numbers are based on verified data, it is not possible to speculate how the percentages would change with verification of all of the facilities.

Country	acc[a]	rx[b]	src[c]	Total	Country	acc	rx	src	Total
Bangladesh	0	1	0	1	Netherlands	0	2	0	2
Canada	0	2	0	2	Pakistan	0	1	0	1
China	1	2	0	3	Philippines	0	1	0	1
Denmark	0	1	0	1	ROC	0	1	0	1
France	1	4	0	5	Sweden	0	1	0	1
Hungary	0	1	0	1	Switzerland	1	0	0	1
Iran	0	1	0	1	Thailand	1	1	0	2
Italy	0	1	0	1	Turkey	0	1	0	1
Japan	6	5	2	13	USA	1	12	2	15
Korea	0	1	0	1	Vietnam	0	1	0	1
Malaysia	0	1	0	1					
					Total	11	41	4	56

[a] Accelerator
[b] Reactor
[c] Isotopic Source

Table 2: Sources for Verified, Operating Facilities in the Directory

	Facilities Verified?						
Country	no	yes	Total	Country	no	yes	Total
Australia	0	1	1	Malaysia	0	1	1
Austria	1	0	1	Mexico	1	0	1
Bangladesh	0	1	1	Netherlands	0	2	2
Belgium	1	1	2	Pakistan	0	1	1
Brazil	3	0	3	Philippines	0	1	1
Canada	0	4	4	ROC	0	1	1
China	0	3	3	Russia	5	0	5
Czech	1	0	1	Slovenia	1	0	1
Denmark	0	1	1	Sweden	0	2	2
France	3	6	9	Switzerland	0	1	1
Germany	5	1	6	Thailand	0	2	2
Hungary	0	1	1	Turkey	0	1	1
India	1	0	1	UK	1	0	1
Indonesia	1	0	1	USA	5	20	25
Iran	0	1	1	Vietnam	0	1	1
Israel	1	0	1				
Italy	0	1	1				
Japan	1	17	18				
Korea	1	1	2	Total	32	72	104

Table 3: Facilities that Have Verified the Data in the Directory

	Facilities Operating?								
Country	no	unk[a]	yes	Total	Country	no	unk	yes	Total
Australia	1	0	0	1	Malaysia	0	0	1	1
Austria	0	1	0	1	Mexico	0	1	0	1
Bangladesh	0	0	1	1	Netherlands	0	0	2	2
Belgium	1	1	0	2	Pakistan	0	0	1	1
Brazil	0	3	0	3	Philippines	0	0	1	1
Canada	2	0	2	4	ROC	0	0	1	1
China	0	0	3	3	Russia	0	5	0	5
Czech	0	1	0	1	Slovenia	0	1	0	1
Denmark	0	0	1	1	Sweden	1	0	1	2
France	1	3	5	9	Switzerland	0	0	1	1
Germany	1	5	0	6	Thailand	0	0	2	2
Hungary	0	0	1	1	Turkey	0	0	1	1
India	0	1	0	1	UK	0	1	0	1
Indonesia	0	1	0	1	USA	5	5	15	25
Iran	0	0	1	1	Vietnam	0	0	1	1
Israel	0	1	0	1					
Italy	0	0	1	1					
Japan	4	1	13	18					
Korea	0	1	1	2	Total	16	32	56	104

[a] Unknown

Table 4: Operational Status of Facilities in the Directory

3 Types of radiography

Table 5 shows the types of radiography performed at each operating facility in the directory. The data in Table 5 are compiled according to direct radiography, indirect (or transfer), and real time (radioscopy)[1] . Also shown in the last row of Table 5 are the percentages of the total that each column represents.

In Table 5, the facilities are listed according to the combinations of the types of radiography performed there. If a facility performs both direct and real time radiography, it is listed in that column. A facility is only be listed once in this table, which ensures that the total equals the total number of facilities. It is not surprising that a large fraction of the facilities perform direct radiography. It is interesting to note that the largest fraction of the facilities perform all three types of radiography, and also interesting to note that a non-trivial number of facilities perform only indirect radiography (most useful for reactor fuel inspections).

In Table 6, the total number of facilities performing each of the three types of radiography is simply summed. Also shown in Table 6 is the percentage of 56 total confirmed operating facilities. Thus for example, 68% of the 56 facilities perform direct radiography.

[1] Track etch was not included because of the low number of facilities using this method.

Country	Direct	Direct/ Indirect	Direct/ Indirect/RT	Direct/RT	Indirect	RT	unk[a]	Total
Bangladesh	0	0	1	0	0	0	0	1
Canada	1	1	0	0	0	0	0	2
China	1	0	2	0	0	0	0	3
Denmark	0	1	0	0	0	0	0	1
France	0	0	0	2	2	0	1	5
Hungary	0	0	1	0	0	0	0	1
Iran	1	0	0	0	0	0	0	1
Italy	0	0	0	0	1	0	0	1
Japan	2	0	4	4	0	3	0	13
Korea	0	0	1	0	0	0	0	1
Malaysia	0	0	0	0	0	0	1	1
Netherlands	1	0	0	1	0	0	0	2
Pakistan	0	1	0	0	0	0	0	1
Philippines	0	0	0	0	0	0	1	1
ROC	0	1	0	0	0	0	0	1
Sweden	0	0	0	0	1	0	0	1
Switzerland	0	0	1	0	0	0	0	1
Thailand	0	1	1	0	0	0	0	2
Turkey	0	0	0	0	0	0	1	1
USA	3	1	2	3	1	3	2	15
Vietnam	1	0	0	0	0	0	0	1
Total	10	6	13	10	5	6	6	56
Percentage[b]	18	11	23	18	9	11	11	

[a] Unknown
[b] Out of 56 operating facilities

Table 5: Type of Radiography Performed in the Facilities in the Directory

	Direct	Indirect	RT	Unknown
Number	39	24	29	6
Percentage[a]	70	43	52	11

[a] Out of 56 total facilities

Table 6: Type of Radiography Performed in the Facilities in the Directory

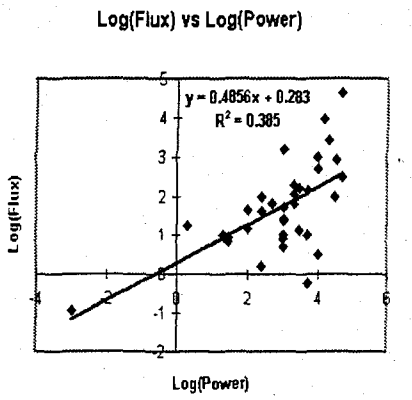

Figure 1: Log(Power in kilowatts) versus Log(Flux times 10^5)

4 Flux, Power, and L/D Data

In this section, some of the data concerning flux, power, and L/D ratios contained in the directory are presented. Figure 1 shows a scatter plot of the $\log_{10}$ of the power (in kilowatts, and for reactors only) versus the $\log_{10}$ of the flux (displaced by 5, as all fluxes were normalized to a base of 10^5 n/cm^2/second). Also shown on Figure 1 is a least squares fit of the data, performed to determine the correlation between reactor power and flux of the facility. The equation of the least squares fit is

$$log(flux) = 0.4856\, log(power) + 0.283$$

for a slope of the log (flux) vs log(power) of about 1/2. Thus the flux increases roughly as the square root of the power, or for a doubling of reactor power, only a 40% increase is realized. The correlation is only $R^2 = 0.385$, which obviously reflects the large scatter in the data. The outliers in the scatter plot are perhaps more interesting than the majority. For instance, one facility with a power of only one watt (!) is able to recover a flux of about 10^4 n/cm^2/second, and conversely there are a couple of facilities with powers over 1 MW that obtain fluxes of only the order of 10^5 n/cm^2/second. These data do demonstrate the wide variety of facilities performing neutron radiography, and perhaps the importance of collimator design.

In a similiar manner, the $\log_{10}$ of the power versus the reported L/D (using nominal values when possible) is shown in Figure 2.

It is seen from examining Figure 2 that the vast majority of facilities operate in the L/D ratio range of 50 to 125 or so, somewhat regardless of the power. This is not surprising because this range of L/D yields adequate resolution; utilizing extreme L/D ratios produces a large penalty in exposure time. It is interesting to note the sharp break in the curve at those reactors above 10 MW. When one has power to spare, one can use larger L/D ratios.

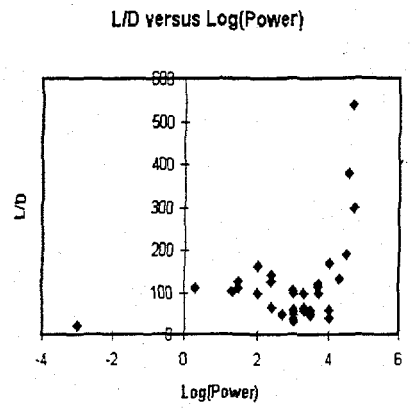

Figure 2: L/D Ratio versus Log(Power in kilowatts)

Mean	Log(Power)[a]	Log(Flux)[b]	Cd Ratio	L/D
Mean	2.63	1.23	55	116
SE Mean	0.24	0.21	17.2	17.6
Median	3.15	1.33	5	100
SD	1.44	1.47	121	104
Kurtosis	7.56	0.14	9.1	8.4
Asymmetry	-2.2	-0.3	3.1	2.7
Minimum	-3	-2.1	1	22
Maximum	4.7	4.6	547	540
Samples	36	50	50	35

[a] Reactors only, power in kilowatts
[b] Flux times 10^5

Table 7: Statistics of Some Parameters of the Facilities

5 Other Statistics

Statistics on the power (for reactors), the flux, the cadmium ratio, and the L/D ratio were compiled, and are presented in Table 7.

Of the parameters shown in Table 7, only the log(flux) exhibits a reasonably normal distribution, as shown by its low kurtosis and coefficient of asymmetry. Regardless of the non-normality of the distributions, it is interesting to note that the mean and median of the log(power) are 2.63 and 3.15 respectively. Thus, the average reactor in the directory has a power of 463 kilowatts, but there are as many reactors over 1.4 MW as there are below that power. Likewise, the mean and median of the log(Flux) are 1.23 and 1.33 respectively; thus the mean flux of the facilities in the directory is $1.7 £ 10^6 n/cm^2/sec$, and the median value is $2.1 £ 10^6 n/cm^2/sec$. The statistics on the cadmium ratio show a fairly high mean (55), but the median (5) is more representative for this very non-normal distribution. The mean and median values for the L/D ratios are 116 and 100 respectively, demonstrating that a value of around 100 provides a good balance between resolution and exposure times.

6 Organization of the Directory

The directory is a collection of pages, with one page per facility. A representative example of the information in the directory is given below.

Country Japan
Location Nagoya
Facility Nagoya University
Neutron Source *Sealed tube neutron generator* (Kaman)
Collimator Horizontal, divergent
Thermal neutron flux 1.0E04
L/D 20 and 25
Source/Object Distance *1 and 1.25 m*
Cd Ratio 5
R/hr in beam 4.0
Image Size 200 x 200 mm
Standards ASTM-81, BPI, SI
Application Basic research experiments to develop neutron radiography techniques using underwater apparatus
Comments Neutrons produced by D-T reaction experiments conducted using various converters, including track-etch, emulsion films, and a TV system.
Contact Dr. Masayoshi Tamaki, Department of Nuclear Engineering, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-01, Japan
Tel./Fax. +81 52 789 4692

7 Summary

This paper has presented a summary of some of the data that exists in the *Directory of Neutron Radiography Facilities*. It is hoped that the data for more of them can be updated in the next six months, and that a WWW page will be created enabling access electronically throughout the world. To reiterate, corrections or additions to the directory should be addressed to the authors, and electronic versions of the directory are available through e-mail.

8 Acknowledgements

The aide of the many facility directors in providing updated information for this survey is greatly appreciated. This work was partially supported by the U. S. Department of Energy under Contract W-31-108-ENG-38.