FUTURE NEEDS FOR HEU-FUELED CRITICAL ASSEMBLIES

Frank N. von Hippel
Program on Science and Global Security
Princeton University, 221 Nassau St, 2nd floor, Princeton, NJ 08542-4601 – USA

ABSTRACT

This is an unofficial report on the results of an IAEA-commissioned consultation on the "Future use of Critical and Subcritical Assemblies" that was carried out in Vienna in February 2005.

The recommendations were for:

1) Improvements in the IAEA's research-reactor database (RRDB) in terms of content and accuracy;

2) Need-based planning for existing and new critical facilities and decisions for which existing facilities are no longer needed and can be decommissioned and which new or improved facilities are required to facilitate the development of innovative reactor designs;

3) Minimization of use of HEU and plutonium and the enrichment of HEU used in critical facilities; and

4) Data preservation and sharing so that experiments useful for benchmarking computer simulations of reactor neutronics need not be repeated.

The report contains a list of operating and shutdown but not decommissioned fueled critical and subcritical assemblies.

1. Introduction

The IAEA hosted a consultation on "The Future Use of Critical and Subcritical Assemblies" in Vienna, February 7-10 2005. The consultants were:

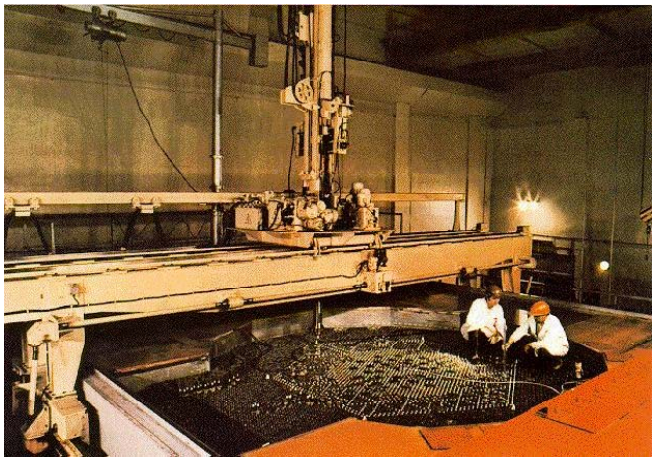
- Nikholai V. Arkhengelskij, RosAtom, Russia
- Sergei Chigrinov, SOSNY Scientific and Technical Center, Belarus
- Robert Jacqmin, Cadarache Centre, CEA, France
- Takamasa Mori, Japan Atomic Energy Research Institute, Japan
- Frank N. von Hippel, Princeton University, USA

The consultation was co-hosted by the Physics Section in the IAEA Department of Nuclear Science and Applications with the collaboration of the research-reactor team in the Department of Nuclear Energy and Applications led by Iain Ritchie and Pablo Adelfang. The IAEA's concerns were the future needs for critical and subcritical assemblies and the need to minimize the danger that HEU or plutonium in critical facilities could be diverted to weapons use.

Critical assemblies have been largely ignored by the RERTR program because these reactors have lifetime cores and therefore cannot be converted using the RERTR strategy of replacing HEU with LEU fuel when regular refueling is carried out. (However, a few critical assemblies

that are core mockups of high-powered research reactors are being converted by the RERTR program as the associated research reactors are converted.)

The amounts of HEU in the cores of critical assemblies are huge, however, when they are mockups of fast or naval-propulsion reactor cores. Naval propulsion reactors typically contain on the order of 100 kg of U-235 in HEU.[1] The operating BFS fast critical facility at the Institute for Physics and Power Engineering in Obninsk, Russia and the shutdown but not decommissioned Zero Power Physics Reactor at the Idaho National Laboratory contain tons of HEU and plutonium in tens of thousands of small fuel elements.[2] The radioactivity of these elements is so low that the cores are loaded by hand (see Figures 1 [3]).



QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

Figure 1 left, **BFS2 critical assembly, Inst. of Physics and Power Engineering, Obninsk, Russia;** right, **Zero Power Physics Reactor, Idaho National Laboratory, U.S.**

In what follows, I will discuss the recommendations from the consultation with regard to:

- Improvements in the IAEA's Research Reactor Database
- Need-based planning for existing and future critical facilities
- Minimization of the use of HEU and plutonium, and
- Preservation and sharing of the results of criticality experiments.

This is an unofficial report and, in places, I add material based on my own subsequent research.

2. Improvements in the IAEA's Research Reactor Database

We began by trying to determine the size of the universe of critical and subcritical facilities, starting with the IAEA's Research Reactor Database, parts of which are on line.[4] This database is based exclusively on submissions by reactor operators. In some cases the reactor operators do not report. This results in some bizarre listings. For example, the database lists Chicago Pile number 1 as shutdown but not decommissioned. This is because neither Enrico Fermi nor the U.S. Government informed the IAEA that the pile had been torn down. The University of Chicago's library now occupies the site.

We suggested that the IAEA devote significant resources to updating the database, including site visits. (Data from the site visits of inspectors from the Safeguards Division cannot be used because there is a wall of confidentiality surrounding the data collected on those visits.)

We also suggested upgrading the database to include: a brief technical description of each facility, summary information on the type of research being pursued, and references to a few published articles or research reports when available.

There is not a clean definition of critical assemblies in the IAEA database. A printout of the October 2004 version of the IAEA's RRDB lists 54 critical assemblies. However, 72 research reactors are shown to have a power of 0-0.5 kWt and an additional 20 to have a power of between 1 and 10 kWt. I think that we adopted a cutoff of 0.5 kWt. Our numbers don't exactly correspond to the RRDB because individual consultants were aware of: two critical facilities and one subcritical facility not in the RRDB, that three critical facilities listed in the RRDB as shutdown have not been shutdown, and that two critical facilities listed as shutdown have actually been decommissioned.

A post-Sept. 11, 2001 development is that fuel-enrichment information is no longer available on the IAEA's website. The concern is that terrorists might use such information to target specific facilities. Of course, making this information difficult to obtain creates difficulties for researchers as well as terrorists. In any case, much of this information is still available on other websites (e.g. that of the Nuclear Threat Initiative) and on the websites of the research-reactor facilities themselves. The IAEA did make available to the consultation the data it has on the fissile material used in critical facilities. Table 1 shows the results of our quick analysis of this data.

Table 1. **Critical and subcritical assemblies and their fuel by country**
(based on RRDB, Oct. 2004 plus information from the consultants)

Countries	**Number**		**HEU and/or Pu Fueled** (range reflects cases in which no information was provided to IAEA)	
	Operational	**Shutdown**	**Operational**	**Shutdown**
France	6	0	5	0
Japan	6	1	2	0
Russia	31	14	20-24	8-13
United States	9	18	6-7	10-16
Rest of World	23	10	5-6	1-10
Total	75	43	38-44	19-39

Obviously, this data needs to be improved. However, a number of observations can be made:

- More than one quarter of the 275 operational research reactors in the IAEA's database are critical or sub-critical assemblies;
- There are many shut-down critical and sub-critical assemblies not known – to the IAEA RRDB at least -- to be decommissioned;
- About half of the critical and sub-critical facilities are fueled with HEU and/or plutonium; and
- Russia accounts for approximately one half of the world's operating HEU-fueled critical assemblies.

3. Need-based planning for critical facilities

Table 2 shows an age profile of the critical and subcritical facilities listed in the consultants' report. The age distribution is similar to that for research reactors in general. Research reactors have many uses, however, while critical assemblies, aside from their teaching and training functions, are single-purpose. Their purpose is to mockup fresh reactor cores or measure integral cross-sections for use in the simulation of such cores. As computer simulations improve, therefore, critical assemblies tend to work themselves out of a job. For example, thirty-eight research reactors have been converted from HEU to LEU fuel by the RERTR program without the use of critical facilities.

Table 2. **Operating HEU/Pu-fueled Critical Facilities by Decade of First Criticality**

Countries	1950s	1960s	1970s	1980s	1990s-
France	1	3	1	0	0
Japan	0	1	1	0	0
Russia	0	6	8	5	1
United States	3	3	0	0	0
Rest of the World	0	1	1	1	2 (Belarus, subcriticals)
Total	4	13	11	6	3

Of course, one never can depend upon an untested computer code. One needs a variety of benchmark experiments. Many such experiments have been done, however. So, if they are properly documented, computer codes for variations in standard reactor design types can be tested against archived experiments.

Since 1995, the mission of the OECD-NEA International Criticality Safety Benchmark Evaluation Project has been to archive such experiments. The September 2004 edition of its *International Handbook of Evaluated Critical Safety Benchmark Experiments* contains "379 evaluations with benchmark specification for 3331 critical, near critical, or sub-critical configurations."[5]

One indication that many critical assemblies are no longer needed is a 2002 joint proposal by the Kurchatov Institute of Atomic Energy and Argonne National Laboratory to assess the potential future use of 6 operating research reactors and 14 critical facilities [11 HEU fueled] at the Kurchatov Institute and decommission "those which have reached the end of useful life.[6]

The report of the IAEA consultation recommended that workshops of reactor designers and critical and sub-critical assembly experts be convened to consider which existing facilities are still needed and which upgraded or new facilities are required to facilitate the development of specific innovative reactor designs.

4. Minimization of weapon-useable materials

When critical facilities are mockups of HEU fueled or plutonium-fueled reactors, they necessarily use HEU or plutonium. U.S. and U.K. naval reactors use weapon-grade uranium. Russian naval reactors currently use medium (circa 40%) -enriched uranium.[1] But how many critical facilities are needed? Perhaps only one flexible facility is really needed by each country – or perhaps none. It is interesting in this connection that the IAEA research-reactor list contains one naval-reactor mockup (LEU fueled) in France, Russia has eight (all HEU-fueled) plus four more shutdown but not yet decommissioned, and the United Kingdom and the United States appear to have none.

Plutonium is usually required for fast-neutron reactors mockups. Some fast reactors, such as Russia's BN600, however, are fueled with enriched uranium. This must be one reason for the

huge quantity of HEU at Russia's BFS critical facility. However, the peak enrichment in the BN600 core is 26 percent.[7]

In fact, even for mockups with average uranium enrichments of 5- 9 percent, the BFS experimentalists use 90-percent as well as 36-percent enriched uranium.[8] One reason could be the flexibility that this allows in fine-tuning the average enrichment of a stack of uranium disks. Table 3a gives the enrichments and masses of uranium in the uranium-containing disks used in the BFS facility. The top half of Table 3b illustrates the small steps in the average enrichments between 20- and 30-percent that are achievable using the HEU (90%) disks to make fine adjustments. However, if we add two light depleted-uranium disks to Table 3a (shown in italics), then, as shown in the bottom half of Table 3b, the same fine-tuning of enrichments is achievable without 90-percent enriched HEU. Thus, if high enrichments are not needed, medium-enriched uranium and depleted uranium will suffice.

The report of the consultation urged that the inventory of direct-use fissile material and the enrichment of HEU in critical facilities be minimized and that experts from the critical-facility and nonproliferation communities should examine these issues together. It also suggested that papers on this subject be invited for presentation at the annual meetings of the RERTR community.

Table 3a. **Uranium disks used in BFS facility** [9]

Type of disk	**U**(gms)
DU_1 (metal, 0.42% ^{235}U)	298.
DU_2 (oxide, 0.42% ^{235}U)	122.
Hypothetical DU_3 (oxide, 0.42% ^{235}U)	35.
Hypothetical DU_4 (metal, 0.42% ^{235}U)	*8.6*
MEU (metal, 36.2% ^{235}U)	150.
HEU_1 (metal, 89.8% ^{235}U)	8.6
HEU_2 (metal, 89.8%)	149.
HEU_3 (oxide, 88.25%)	13.2

Table 3b. **Average enrichments achievable with the BFS disks between 20 and 30 percent**

Disk combination	**Average Uranium enrichment** (%)
MEU + DU_2	20.2
MEU + DU_2 +HEU_1	22.3
MEU + DU_2 + HEU_3	23.3
MEU + DU_2 + HEU_1 + HEU_3	25.2
MEU + DU_2 + 2 HEU_1 + HEU_3	27.1
MEU + DU_2 + HEU_1 + 2HEU_3	28.0
MEU + DU_2 + 2HEU_1 + 2HEU_2	29.6
Hypothetical	
MEU + DU_3 + 8DU_4	21.6
MEU + DU_3 + 7DU_4	22.3
MEU+ DU_3 + 6DU_4	23.1
MEU + DU_3 + 5DU_4	24.0
MEU + DU_3 + 4DU_4	24.9
MEU + DU_3 + 3DU_4	25.9
MEU + DU_3 + 2DU_4	27.0
MEU + DU_3 + DU_4	28.1
MEU + DU_3	29.4

5. Data preservation and sharing

It is wasteful to repeat critical experiments. It also undermines international security if the need to repeat such experiments results in there being more locations at which HEU and plutonium can be found than would otherwise have been the case. The consultants therefore supported existing efforts to archive the results of past critical experiments and urged that these efforts be strengthened and broadened.

The trend toward making unique critical facilities available for experiments by groups in other institutes is to be welcomed. A Japanese group recently did experiments at Cadarache, a series of experiments has been done at the BFS facility for the Idaho National Laboratory, and a far-reaching proposal for data and facility sharing for fast-reactor criticality experiments has recently been put forward.[10, 11]

6. Conclusions

Critical facilities have thus far not been addressed *per se* by the international effort to reduce the number of locations where HEU can be found – but they should be. A significant number of these facilities have inventories of only slightly irradiated HEU that are large enough to make at least one nuclear weapon.

Computer simulation of reactor cores has become good enough that, for standard types of reactors, they only need to be tested against benchmark experiments and enough archived criticality experiments are available to provide benchmark tests in such cases. It should therefore be possible to retire and decommission many critical facilities. At least a few will be required, however, to test refinements in the codes and to check the accuracy of their predictions for new types of reactors.

HEU and plutonium are required in critical experiments relating to reactors whose fresh fuel contains HEU or plutonium. However, the number of such critical facilities should be minimized and their inventories, and the enrichment of their HEU should be minimized as well.

Efforts to archive and share the results of past and future critical experiments should be expanded – especially in the case of criticality experiments using HEU or plutonium – so that there will be no need to repeat these experiments in the future.

7. References

[1] Ma Chunyan and Frank von Hippel, "Ending the Production of Highly Enriched Uranium for Naval Reactors," *Nonproliferation Review*, Spring 2001, p. 86.

[2] I.P. Matveyenko *et al*, "Physical inventory of nuclear materials on BFS facility," paper presented at the MPC&A-2000 conference, Obninsk, Russia, May 22-26, 2000, state that the BFS facility contains 8.7 tons of 36% and 90% enriched HEU and 0.8 tons of plutonium – mostly in the form of more than 90,000 4-5-cm diameter disks. David Albright *et al*, *Plutonium and Highly Enriched Uranium 1996: World Inventories, Capabilities and Policies*, Oxford University Press, 1997, Table 3.5, state that the ZPPR facility contains 3.8 tons of plutonium in the form of small plates.

[3] http://www.rssi.ru/IPPE/MPCA/Images/BFS2.jpg and http://www.ne.anl.gov/ne_web_photos/index.php?cid=15&pid=97, both accessed August 20, 2005

[4] IAEA Research Reactor Database – RRDB, http://www.iaea.org/worldatom/rrdb/

[5] *International Handbook of Evaluated Critical Safety Benchmark Experiments*, OECD Nuclear Energy Agency, NEA/NSC/DOC(95)03, September 2004, edition, Vol. 1, p. ii.

[6] N.N. Ponomarev-Stepnoi and S.K. Bhattacharyya, "Russian Research Center Kurchatov Institute/ Argonne National Laboratory Project on conversion of the RRCKI to a secure, safe and clean nuclear research center within the boundaries of the City of Moscow," April 2002.

[7] See e.g. O.M. Saraev, "Operating experience with the Beloyarsk fast reactor BN600 NPP," *Technical committee meeting on unusual occurrences during LMFR operation*, Vienna, Austria, November 9-13, 1998, p. 103. The BN-600 has three enrichment zones containing 17, 21 and 26 percent enriched uranium.

[8] "K-infinity experiments for ^{238}U in fast neutron spectra: Measurements with enriched uranium or plutonium mixed with depleted uranium (BFS-35, BFS-33, BFS-38, BFS-31, and BFS-42 assemblies)," *International Handbook of Evaluated Critical Safety Benchmark Experiments*, Volume 6, MIX-MISC-FAST-001.

[9] *Ibid*, pp. 13-14.

[10] "Critical experiments with heterogeneous compositions of highly enriched uranium, silicon dioxide, and polyethylene," *International Handbook of Evaluated Critical Safety Benchmark Experiments*, Volume 2, HEU-MET-MIXED-005; "Critical experiments with heterogeneous compositions of plutonium, silicon dioxide, and polyethylene, *ibid*, Vol. 1, PU-MET-MIXED-001. The experiments were done in 1999 and 2000.

[11] "Is it time to consider global sharing of integral physics data?" by Harold F. McFarlane, Idaho National Laboratory, abstract of a paper to be presented at the *Global 2005 International Conference on Nuclear Energy Systems for Future Generations and Global Sustainability*, Tsukuba, Japan, October 9-13, 2005.