UNIVERSITY OF CAMBRIDGE
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# Technology and Policy Issues Relating to Future Developments in Research and Radioisotope Production Reactors

**EPRG Working Paper 1129**

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**Abstract** The paper describes the historical roles and the scale of research reactor technology. The various types and uses of a research reactor are described. The paper compares the policy issues of research reactors with those associated with civil nuclear power stations and posits that some issues of concern, such as nuclear security and non-proliferation are greater for research reactors. The benefits of research reactors are described especially the medical benefits arising from radiopharmaceutocal production. The need for a new generation of research reactors is described and recent and current developments are summarised. The paper closes with a description of the role the UK might play in research reactor development for local national needs and to serve wider global demand.

**Keywords** Research Reactor, Nuclear Energy, Medical Isotopes, Non-Proliferation

**JEL Classification** Y80

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# Technology and Policy Issues Relating to Future Developments in Research and Radioisotope Production Reactors

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## 1. Introduction

According to the World Nuclear Association approximately 250 research reactors are operating in 56 countries[1]. This compares with 440 nuclear power stations in 29 countries. As shown in figure 1, the geographical distribution of research reactors extends very widely. The spread is wider than for nuclear power generation. Arguably the historical role of research reactors in nuclear weapons proliferation has been more troubling than that of reactors for civil power generation. Lesser security concerns, such as radiological terrorism, are also a concern. Despite such issues research reactors remain vital for science and engineering and for medical isotope production.

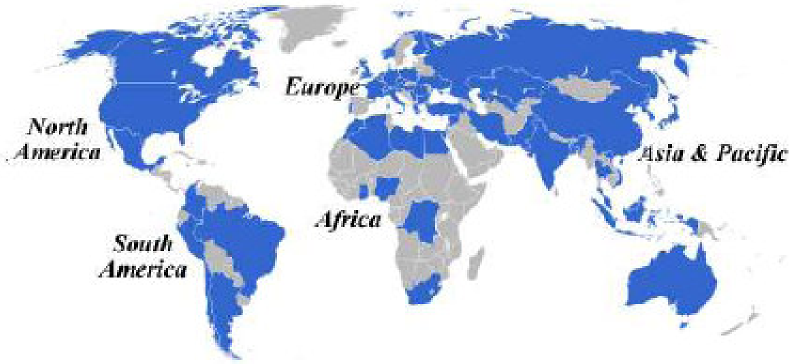

**Figure 1. Global distribution of research reactors. Note presence in Central Africa, South East Asia and Australasia – i.e. regions where no nuclear power plants currently operate[2] (Image: IAEA)**

| CONTINENT | COUNTRIES | NUMBER OF RESEARCH REACTORS WITH HEU |
|---|---|---|
| North America | USA, Canada, Jamaica | 16 |
| South America | Argentina, Chile, Mexico | 3 |
| Europe | Austria, Belgium, Czech Rep., France, Germany, Greece, Italy, Netherlands, Poland, Portugal, Rumania, Russia, Sweden, Switzerland, Serbia, UK | 66 |
| Africa | Ghana | 1 |
| Asia and Australasia | China, Israel, India, Iran, | 20 |

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| | | |
|---|---|---|
| | Japan, North Korea, Kazakhstan, Pakistan, Syria, Taiwan | |

**Table 1. Global distribution of research reactors fuelled with High Enriched Uranium (HEU)**

Figure 2 illustrates the balance between historical research reactors, current capacity and future plans. This figure can give the impression that research reactors represent an endeavour in decline. While it is true that during the period 1985 to 2005 numerous research reactors were closed, the recent trend indicates a resurgence of interest with a growing number of new projects under construction.

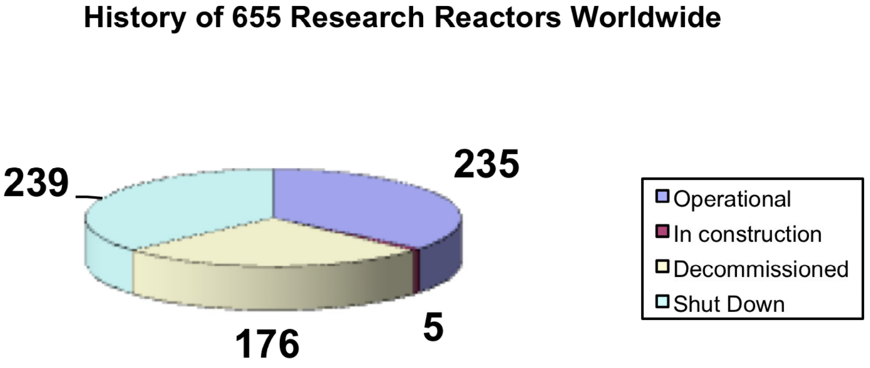

**Figure 2. Research Reactors Past and Present**[3]

Figure 3 shows that from among the totality of research reactors, and with the exception of those rated below 90kW, the balance of enthusiasm for large versus small facilities remains largely unchanged. It would be expected that closures would have been more prevalent among the smaller facilities, but this appears not to be the case.

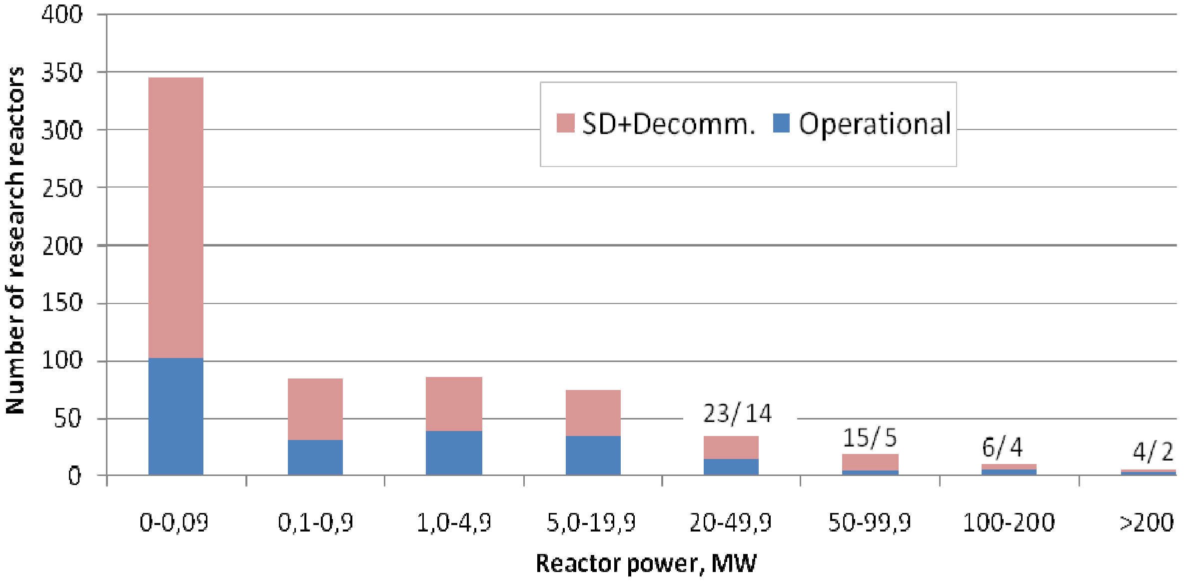

**Figure 3. Breakdown of Research Reactor Status by Reactor Size (Source: as figure 2).**

The shift in the UK from a Government funded nuclear power programme to a privately funded new build programme and the general liberalization of energy markets means that the requirements for a new research reactor is driven predominantly from commercial considerations, although there may be drivers coming from the defence sector as well. Currently, it is difficult to conceive the situation where the Government would put any funding into civil nuclear reactor technology. However, longer term strategies on material management but especially around spent fuel and plutonium stocks may change the policy drivers as the Government realizes that its policy aspirations may not be realized through commercial drivers alone. In the past the justification to Government for funding research reactors had been developed and largely driven by government funded organizations such as the CEGB and UKAEA in pursuance of a power reactor programme. This was especially true in the experimental designs that were built as the UK developed its nuclear power programme through the Magnox and AGR designs. However the present privately funded nuclear industry that will build and operate the new fleet of reactors is unlikely to recognize the strategic relevance for a new UK research reactor that would support national needs to support the power, health and defence programmes. Therefore there is a policy vacuum around any long term investment where the Government has declared that it will not fund "nuclear" and where the industry will only fund what is necessary for commercial success and to safely and securely operate their nuclear plants. Steps are currently underway through the Energy Research Partnership (ERP) Nuclear Roadmap Study to provide advice to Government on future nuclear energy options and necessary investment in nuclear facilities, research and development and skills development. At the time of writing the ERP Roadmap is not yet published[4].

At this point it is appropriate to declare that this paper seeks to frame a set of policy issues relating to present and future research reactors. Future developments can, and should, only progress if they pass market tests grounded in project finance and broader economic considerations. It is not the intention of the authors to apply such tests in this paper, but it is important to note that they will lie ahead.

## 2. What do we mean by the term 'research reactor'?

The analytical and research capabilities of a research reactor are determined primarily by the available thermal neutron flux. Research reactors are categorized as low flux, medium flux and high flux according to the following levels of thermal neutron flux:

- Low flux reactor < 1 x 10 (power 12) neutrons/cm$^2$/s
- Medium flux > 1 x 10 (power 12) and < 1 x 10 (power 14) neutrons/cm$^2$/s
- High flux > 1 x 10 (power 14) neutrons/cm$^2$/s

In this paper we use the term 'research reactor' to include:

- Small low flux and low power facilities (e.g. CONSORT, UK)
- High Flux Reactor (pool) for in-core irradiation (e.g. HFR Petten, NL)
- High Flux Reactor with neutron beam capacity (e.g. ILL, FR)
- Materials Test Reactors, perhaps with large component test capability (e.g. Jules Horowitz Reactor, FR now under development)
- Fast spectrum research reactor (No current EU capability)

Our use of the term 'research reactor' may include ultra-low-power fission assemblies/piles but does not include:

- Accelerator-driven subcritical systems (e.g. former UK boosted target station at

AERE Harwell, known as 'Helios')
- or Fusion facilities (e.g. JET, Culham Centre for Fusion Energy, UK)

There is a far wider variety of designs for research reactor than there is of designs deployed for nuclear power generation. The leading (i.e. most numerous) types of research reactor were developed by individual countries and then deployed internationally whereas power reactors were developed by a limited number of countries and so the variation in designs was less. Some series of research reactors have been operated in a number of countries. The TRIGA type Pool Reactors which were designed in the USA continue to be operated in many countries around the world In Canada the SLOWPOKE heavy water reactors was to be followed by the MAPLE series of reactors but this design had serious technical deficiencies, in particular an unexpectedly positive power coefficient of reactivity[5]. In the UK the development of heavy water and graphite reactor technology led to the DIDO Class of reactors. All such reactors built worldwide are now closed-down.

Many research reactors such as ILL in Grenoble, France are completely unique designs. Each type of reactor will have been designed with a particular purpose or purposes in mind but often has the capability to undertake a wider range of tasks. A research reactor will be utilized predominantly in one or more of the following ways:

- Isotope production – as used in medicine, industry and research
- Neutron scattering – examining the deep structure of materials
- Neutron radiography – archaeology, biology, aeronautics, car industry and materials studies
- Materials and fuel irradiation for nuclear energy – issues of fuel ageing, optimization and testing and material needs for future reactors (fission and fusion)
- Transmutation – materials for the electronics industry (e.g. semiconductor doping)
- Teaching and training – biology, physics and nuclear engineering (including training nuclear operators)
- Neutron Activation Analysis – qualitative and quantitative techniques for trace elements
- Geochronology – dating small quantities of minerals
- Boron Capture Therapy – cancer treatment by loading tumour with Boron and irradiating

The most common type of research reactor is the 'Pool' reactor including the more actively cooled 'tank reactor' concept. One prominent example of a pool reactor design is the 'TRIGA' reactor, with its pulsed capability, designed by General Atomics from 1956. Roughly 70 TRIGA reactors are in operation around the world and much impetus was given to the programme by US President Eisenhower and his 1953 'Atoms for Peace' initiative. The TRIGA design was developed with safety and ease of use in mind. It was recognized that the reactor would be used by early-career individuals, including university students. While the TRIGA design continues to be extremely safe when assessed in conventional (i.e. accident-based) terms, there is a certain irony that the wave of TRIGA reactor exports prompted by the Atoms for Peace programme positively encouraged the global civil use of Highly Enriched Uranium (HEU) which has caused so much policy concern in recent decades[6]. These issues will be considered further later in this paper.

## 3. Risks Associated With Research Reactors

The security of activities associated with nuclear energy is a complex matter involving several concerns and expert competencies. There are narrowly technical concerns for instance relating to special nuclear materials (as termed by the US Nuclear Regulatory Commission). Of greatest concern are the fissile isotopes Pu-239, U-235 and U-233. There are also concerns beyond the nuclear materials themselves. The US-initiated International Framework for Nuclear Energy Cooperation (formerly 'GNEP') has strengthened thinking concerning 'safeguards by design'. In this framework security concerns are included from the outset in the design and operational plans for nuclear facilities. Finally there is the domain of international law and treaty-based international organizations. Globally the International Atomic Energy Agency, a UN body, plays a leading role in establishing norms and rules for nuclear development. Smaller groupings of leading countries, such as the G-8, or regionally, such as Euratom, also play a constructive role. Together best practice in materials handling, facility design and operation, and legal constraints and inspection can provide an enhanced nuclear security framework for the operation of civil research reactors. Noting the breadth of the issues this paper will give emphasis to those issues most directly related to materials of concern. Less attention will be given to important issues in, for instance, facility design or international law.

### 3.1 Nuclear Weapons Proliferation Prevention

All signatories arguably have the right to develop and operate facilities akin to the civil facilities previously developed and operated by the 'P5' nuclear weapon states occupying permanent seats and with veto power on the United Nations Security Council.

Article 4 of the Nuclear Non-Proliferation Treaty (1970) states:

*"Nothing in this Treaty shall be interpreted as affecting the inalienable right of all the Parties to the Treaty to develop research, production and use of nuclear energy for peaceful purposes without discrimination and in conformity with Articles I and II of this Treaty."* [7]

The US has long sought to eliminate Highly Enriched Uranium (HEU) (i.e. uranium enriched to more than 20% U-235) and separated plutonium from all civil nuclear operations. Furthermore George Bunn and colleagues from Stanford University have suggested that research reactors could present a more serious security risk than power reactors. We shall consider these themes further but reasons given by Bunn et al. include:

- Many of the fuel elements could have only modest burn-up and weak radiation fields
- Physically smaller and more easily handled fuel assemblies than power reactors
- Research reactors often located close to population centres
- In some cases research reactor site security weaker than at nuclear power plants
- Intermittent operations with only 'skeleton' staffing during shutdowns
- Some research reactors have been subject to many years of resource constraints

Recent upgrades to security in the UK reflect the significant improvements to research reactor site security in OECD countries.

In recent years there has been much international debate concerning the limits to the phrase in the Non-Proliferation Treaty '*nuclear energy for peaceful purposes*'. Much of this discussion has focused on whether non-weapon states party to the treaty should be permitted to develop unrestrained civil fuel cycle capacity (e.g. fuel enrichment or reprocessing). In a paper for the 2005 NPT Review Conference the Islamic Republic of Iran argued: '*Neither the NPT negotiations nor the text of the Treaty even slightly imply any limit on any specific field of nuclear technology, including the enrichment and fuel cycle fields.*'[8]

Given the long-standing use of highly enriched uranium in civilian research reactors, and given the Non Proliferation Treaty's protection of all treaty states' rights to develop research, production and use of nuclear energy for peaceful purposes without discrimination, there is a risk of looming disputes concerning research reactors. Just as there has been much good effort to strengthen the international non-proliferation regime to eliminate the need for emergent nuclear nations to engage in sensitive fuel cycle activities, there should also be a new international consensus as to what activities are permitted, and encouraged, concerning research reactor capability. One approach would be for all states to agree that the development of peaceful nuclear energy has no need for highly enriched uranium fuelled research reactors and all countries should move to a position where HEU is eliminated from research reactor development and operation. Such thinking lies behind the US led Reduced Enrichment for Research and Test Reactors (RERTR) programme[9].

## 3.2 Risks to, and Arising from, Commercial Use

### 3.2.1 Isotope Production

The Halden Reactor Programme in Norway and other similar centres have provided a focus for nuclear science within Europe and although many of the research reactors are ageing, there are new reactors either being built (e.g. JHR) or being planned (e.g. PALLAS) to replace those planned for closure. However there is a need for alternative routes for isotope production especially for medical purposes. The production of Mo-99 to produce Tc-99m for medical diagnosis requires a high flux reactor with innovative targets such as the Maple reactors in Canada.

The demand for medical isotopes across the world has for some time been under great pressure as the demand continues to increase, but supply is dogged by a general shortage of suitable research reactors. The use of Mo-99 to produce Tc-99m which is the workhorse of nuclear medicine illustrates this. There are more than 30 million patients worldwide that are diagnosed using Tc-99 and this isotope is produced predominantly from 5 research reactors, NRU (Canada), HFR (Netherlands), BR2 (Belgium), OSIRIS (France) and SAFARI (South Africa). In 2010 NRU and HFR were off line under repair for some time and since these two reactors alone are responsible for 70% of Mo-99 production the consequence was that the production of this isotope fell well below the demand with negative consequences for cancer treatments. These two reactors are close to 50 years of age and the clinical demand for the production of this isotope is predicted to remain strong for decades to come so there is a need for new research reactors that can replace and enhance capacity worldwide as old reactors close.

The use of HEU with its higher neutron flux in the production of this isotope speeds up rate at which isotopes can be produced and this is important in the consequential creation of Tc-99m that has a half-life of six hours. Given the very short half-life of the diagnostic isotope Tc-99m the commercial supply of this radio-isotope is via the use of Tc-99m generators based on molybdenum-99. Molybdenum-99 has a half-life of 2.75 days which is sufficiently short to ensure effective Tc-99m generation, but also places severe time pressure on the supply chain from reactor to clinical use.

HEU is a strategically sensitive material and a policy to replace it with LEU would mean that the number of Mo-99 atoms produced is reduced by a factor of five and although there are technical solutions to mitigate this drop, the yield of Mo-99 is still reduced by a factor of two or three. Alternative options are being researched that would replace the use of HEU, but the general conclusion is that production quantities of isotopes that can be produced will be low so many more facilities would be required worldwide to meet demand. So with the current shortage in isotope production, the political push to remove HEU and the risk faced to this production by key research reactors that are getting older, there is an urgent need for the construction of new research reactors. As a rough estimate, the use of LEU would at best decrease production by a factor of two so twice as many research reactors of the same output would be required to produce the same quantity of medical isotopes. The construction of PALLAS and JHR will enhance this capacity for as long as the older reactors continue to operate, but if more reactors are not built (or alternative means of production provided) there is a very high risk that the supply of isotopes used in medicine will fall significantly below demand.

### 3.2.2 Material and Fuel Irradiation

A Materials Test Reactor (MTR) is a high flux research reactor that is used to irradiate materials, components and fuel that are used inside a power reactor and that are exposed to neutron flux during normal operation. The purpose of such tests or research is to assess the physical behaviour of nuclear power plant materials when exposed to neutron fluxes, in order to either predict their behaviour with age or to interpret what has happened when something has gone wrong. Ultimately such interpretation can be used to predict the lifetime of plant and its components and can assess the suitability of specific materials in such hostile environments. As a result nuclear electricity generating companies make a considerable investment in these type of irradiation studies over the full life-time of a plant and use the information to both satisfy to the regulator the continue safety of the plant and commercially to identify plant or component replacement in order to maintain the viability of the plant. A nuclear operating company would also use the neutron flux in a research reactor to calibrate detectors before they are installed into a plant. Therefore access to MTRs for the nuclear utilities for long periods of time over the full life-time operation of plants is an important and essential consideration. The absence of an MTR in the UK means that the utilities have to undertake irradiation studies overseas and the shortage of suitable MTRs means that their forward plan for essential irradiation studies are put at risk by the unavailability of suitable facilities when they are required.

### 3.2.3 Teaching and Training

In many countries research reactors can be used as an important practical way of training people who will work on a nuclear power plant. They learn about nuclear physics, criticality and shielding and access to an operating research reactor provides the means to undertake supervised experiments in a safe and controlled environment. Similarly, postgraduate students visit research reactors as part of academic programmes in order to experience in practical terms how a nuclear reactor works and to pass on know-how on operational safety and safety culture.

## 3.3 Risks from Misuse

### 3.3.1 Illicit Production of Isotopes

The facility for producing medical isotopes can of course be a route for producing Pu and other radioactive elements. A high-flux research reactor, such as the 45MWth HFR at Petten NL, can also produce Pu through the use of a specific target or through the irradiation of fuel. Obviously the higher the flux of a reactor the greater potential for it to produce fissile material, but of course there are many other factors to be taken into account including the time of irradiation, the design of the target and the accessibility of the target area. Therefore it could be argued that there is a key balance between proliferation resistance and commercial viability and these factors could help set one of the criteria for a proliferation resistant research reactor.

In general controls over fuel irradiated in a research reactor are bound up in the difficulty of reprocessing, but this is not the case if an isotope is produced using a target. As already stated the neutron flux is crucial in order to create fissile material and would define the timescale for producing the required levels of fissile material which would be in kilogramme quantities if the intention were to produce a nuclear fission weapon. The production of medical isotopes which would have very short half-lives (days) would require high fluxes, but by definition the irradiation time would have to be short. The same method of production employing a target can also be used to create other radioactive isotopes that may not be fissile but would be poisonous and hence used to produce a radiological dispersion device or “dirty bomb”.

Difficulty in accessing a research reactor with the right targets for sufficient time would be the primary control in producing radioactive material of interest to terrorists. Contrary to this, the nature of the production of isotopes for medical purposes would require a reactor to operate for extended periods with regular sample movements in and out of the target zone.

It was noted earlier by implication that a research reactor is not the easiest source of harmful radiological materials. Such an assessment, however, is predicated on the idea of a robust and professionally competent laboratory management seeking to minimize risks. Clearly the situation is completely different if the laboratory management themselves are intent on providing harmful materials for terrorists.

Also of particular concern must be the actions of a renegade employee. This risk, in terms of likelihood and possible impact, falls between the risk of attempted outside access and willful management involvement in terrorism.

In conclusion it could be argued that a research reactor designed for medical isotope production is inconsistent with being proliferation resistant because it has been designed specifically with the production of isotopes in mind and its only controlling factors are the level of flux, accessibility to its neutrons and the level of surveillance in its use. One final point must be that if proliferation resistance is defined largely by accessibility and surveillance then these will be challenged should the research reactor fall into the hands of those who are set to use the facility for non-peaceful purposes.

It is essential to stress that the ability to produce isotopes is of great public benefit. Measures to improve security should not detract from the ability to provide medical and other benefits from man-made radioisotopes. Any trade-off in this regard must be managed carefully. It is noteworthy that in the UK measures have been adopted to mitigate risks relating to radioactive materials diversion, which are arguably greater than those arising from the operation of reactor facilities. One UK policy concerned an amnesty for the return of unused radioisotopes in hospitals and universities. The policy was operated by the Environment Agency. Clive Williams and co-authors have recently studied that most successful programme[10].

### 3.3.2 Physical Hazards and Wider Impacts

The physical hazards posed by dirty bombs, while very serious, are not likely to be catastrophic in terms of physical harm. The Federation of American Scientists has studied various dirty bomb scenarios. It is interesting that none of the scenarios considered involve radioactive source term in any way linked to civil nuclear energy or research reactors. They report:

> ‘*Consider a typical americium source used in oil well surveying. If this were blown up with one pound of TNT, people in a region roughly ten times the area of the initial bomb blast would require medical supervision and monitoring. An area 30 times the size of the first area (a swath one kilometer long and covering twenty city blocks) would have to be evacuated within half an hour. After the initial passage of the cloud, most of the radioactive materials would settle to the ground. Of these materials, some would be forced back up into the air and inhaled, thus posing a long-term health hazard. A ten-block area contaminated in this way would have a cancer death probability of one-in-a-thousand. A region two kilometers long and covering sixty city blocks would be contaminated in excess of EPA [Environmental Protection Agency] safety guidelines. If the buildings in this area had to be demolished and rebuilt, the cost would exceed fifty billion dollars.*’[11]

Clearly the core issue is whether under such circumstances a part of the centre of a major city would be sealed-off and abandoned, or whether societal tolerance of risk would adjust under the circumstances permitting a return to use following whatever clean-up might be possible. As the scenario above makes clear, many of the issues relate more to fear psychological crisis response than to issues of physical harm.

It is widely reported that the most harmful consequences of an explosive dirty bomb or high profile radiological dispersion event could occur in the areas of public anxiety and social disruption[12]. In the case of an explosive detonation, news management could be especially difficult. In such cases there are the risks of panic effects, mental illness impacts (depression and anxiety) and economic impacts (such as in real estate values). The levels of such harm could far outweigh any physical damage caused by explosion or radiological effects.

### 3.3.3 Terrorist Attack on a Research Reactor

An external terrorist attack on a research reactor facility might include an attack by a road vehicle (such as a ‘truck bomb’) an attack by an aircraft, or an attack by ship. The latter, while possibly a serious threat to coastal civil nuclear power plants, is unlikely to be a threat to research reactors which are not typically located on coasts given their minimal cooling water needs. However the threat will always exist in an uncertain world and where there is planned increase of the use nuclear power and especially by new countries. It is not the purpose of this paper to predict areas of future world instability or regions where there will be conflict, but in general terms the increasing number of countries with nuclear programmes, including use of research reactors, will increase the risk that such reactors will be the target for terrorist attack or conflict between countries.

In the years since the terrorist attacks of September 2001 much progress has been made by intelligence and security organizations to disrupt and prevent conspiracies to attack major targets, such as elements of critical modern infrastructure. Residual threats from Islamist terrorism appear to be dominated by so called ‘lone-wolf’ attacks. Sometimes planned and initiated by people who have been radicalised by terrorist propaganda, but who have never communicated their intentions to anyone including even family and friends[13]. These changing patterns in terrorism and counter terrorism have consequences for the threats posed to nuclear facilities.

## 3.4 Security Barriers and Controls

Security barriers around reactor sites, controls over access to research reactors and material accountancy provide the means to reduce the risk of mis-use of radioactive material. Such risks cannot be eliminated completely but the removal of HEU from research reactors would remove the risk of radioactive material being used for the manufacture of a nuclear weapon. A rigorous programme of safeguards and security regulation for all research reactors where the requirement for barriers and controls are well defined and compliance is regularly checked either at a national, regional or international level is a pre-requisite for the operation of any nuclear facility or plant.

## 3.5 Risks to Safety

In simple terms research reactors can be grouped into three types;

- Those low energy types used for training and teaching
- Those used for isotope production
- Those with high irradiation fluxes used for research and operational purposes.

One issue of potential safety concern would be if a country decided to alter the performance or function of a research reactor. It is possible that a country may not have the competence or experience to attempt such adjustments. In particular, for a zero energy or low energy reactor it should be designed from the outset so that it would be difficult to increase the neutron flux. One way to make such improvised power-upratings impossible (or at last very difficult) would be by making it difficult to obtain different fuel. In addition, changing a research reactor so that it operates differently from its initial design would require special attention be given to avoiding transient conditions.

If risks associated with an illicit alteration of reactor design are to be minimized, the reactor would need to have been constructed using an inherently safe design. For instance, for such a reactor any abnormal behaviour of the core would shut the reactor down and the decay heat would be dissipated by some form of natural circulation. This would be helped if the reactor is of low energy because the decay heat will be low. Using special types of coated particle fuel as used in High Temperature Reactors or hydride fuel as used in a TRIGA reactor would further avoid criticality and these types of ceramic fuel would also be melt-proof and protect against loss of coolant accidents. Finally such particle fuels are difficult to reprocess and therefore this would provide additional resistance against the separation of fissile and radioactive material for deliberately harmful purposes.

A key consideration in regard to safety must include the issue of aging facilities. The IAEA reports more than 50% of today's research reactors are more than 40 years old. Major technical issues facing aging research reactor facilities include[14]:

- Obsolescence of equipment, technology change and original suppliers no longer being in business
- Corrosion
- Radiation induced change of properties
- Mechanical displacement, fatigue and wear
- Regulatory standards change

### **3.6** US Reduced Enrichment for Research and Test Reactors (RERTR) Program

The US Department of Energy (DOE) reports:
*"Reduced Enrichment for Research and Test Reactors (RERTR) Program develops technology necessary to enable the conversion of civilian facilities using high enriched uranium (HEU) to low enriched uranium (LEU) fuels and targets. The RERTR Program was initiated by the U.S. Department of Energy in 1978. During the Program's existence, over 40 research reactors have been converted from HEU (= or >20% U-235) to LEU (< 20% U-235) fuels, and processes have been developed for producing radioisotopes with LEU targets."* [15]

Bunn et al. have argued that the spreading of fissile material around the world initiated by President Eisenhower's *Atoms for Peace* initiative and its encouragement for the spread of HEU fuelled research reactors has left the world with a legacy of threats and problems[16]. Of the self-declared nuclear weapons states (India, Pakistan and North Korea) and the undeclared, but probable, nuclear weapon state (Israel[17]) only Pakistan had any clear linkage between its programme of weapon development and global civil nuclear energy development. In the case of Pakistan the weapon scientist A Q Khan gained insight into uranium enrichment via early career employment with URENCO in the Netherlands[18]. Other countries leveraged international links in their pursuit of nuclear weapons. Proliferation links to civil power production and the civil nuclear fuel cycle are few. Historical links to research reactors are more numerous. For example, it is claimed that India surreptitiously produced plutonium for its 1974 nuclear explosion from its Canadian-designed CIRUS heavy water research reactor[19].

## 4. The Global Medical Isotope Crisis

The medical isotope Mo-99 is produced from the fission of U-235. It is the precursor of Tc-99m as used in 70% of all nuclear medicine procedures[20]. Research reactors refuelled to use LEU fuel still use HEU targets for their Mo-99 production. The US RERTR programme supports the use of LEU targets and has sponsored research and development in that direction.

Moving to LEU raises issues of target design and chemical processing (including waste burdens and Pu-239 production, albeit in small quantities). For a scientific overview of nuclear medicine options see the paper by van der Marck et al[21].

There have been regulatory problems associated with Mo-99 production in Canada including difficult policy trade-offs between nuclear safety regulation and the provision of life-saving medical isotopes for diagnosis and therapy. In Europe the medical isotope supply problem was exacerbated by the 2008 shut-down of the High Flux Reactor at NRG Petten, NL. Future isotope production is a major motivation for the PALLAS reactor proposal at NRG Petten, NL (45MW, 2016).

The vast majority of Mo-99 production is now sourced from between three and five facilities worldwide. The desperate need for Mo-99 production is causing pressure on research reactor maintenance schedules. The risk to medical isotope production is high from both a shortage of suitable research reactors around the world or technical alternatives to produce the isotopes and the policy push to reduce or stop the use of HEU. It is not clear what body or organisation is able to take a lead to address the issues and consequently, if nothing is done then these medical diagnosis and treatments in the medical sector are very much at risk.

## 5. Operating Research Reactors in Europe

The following Tables 2 and 3 provide a listing of the high flux and medium flux reactors that are currently operating in Europe according to the IAEA.

| | |
|---|---|
| Belgium | BR-2 |
| Czech Republic | LVR-15 REZ |
| France | OSIRIS |
| | HFR |
| | CABRI |
| | PHEBUS |
| | ORPHEE |
| Germany | FRG-1 |
| | BER II |
| | FRM II |
| Hungary | Budapest RR |
| Netherlands | HFR |
| Norway | HBWR |
| Poland | MARIA |
| Rumania | TRIGA II PITESTI (SS Core) |
| Ukraine | WWR-M Kiev |

**Table 2. Operating European High Flux Thermal Research Reactors**

| | |
|---|---|
| Austria | TRIGA II Vienna |
| Belgium | BR-1 |
| Finland | FIR 1 |
| France | ISIS |
| Germany | FRMZ |
| Greece | DEMOCRITOS (suspended) |
| Hungary | Nuclear Training Reactor |
| Italy | LENA TRIGA II Pavia |
| | TRIGA RC1 |
| | RSV TAPIRO (Fast only) |
| Netherlands | HOR |
| Norway | JEEP II |
| Portugal | RP1 |
| Rumania | TRIGA II PITESTI (Pulsed) |
| Slovenia | TRIGA II Ljubljana |
| UK | CONSORT |

**Table 3. Operating European Medium Flux Thermal Research Reactors**

## 6. Recent and Future Developments

In Europe the first generation research reactors are approaching necessary operational retirement. Maintenance costs increase and continuity of operations is being compromised by the ageing of materials and components and in some cases by the availability of the specialist fuels and having a route for spent fuel reprocessing. The main European Material Test Reactors (MTRs) operating at this moment are OSIRIS (France), LVR-15 (REZ Czech Republic), HFR (Petten The Netherlands), Halden (Norway) and BR-2 (Mol Belgium). There are plans to build a new reactor in France at Cadarache, the Jules Horowitz Reactor (JHR) and to replace the High Flux Reactor at Petten with PALLAS.

### 6.1 Jules Horowitz Reactor (JHR)

The JHR is being built and will be operated in the framework of an international cooperation between several organizations bound by a consortium agreement. The current partners are CIEMAT, SCK, NRI, VTT, CEA, DAE, JAEA, EdF, AREVA, VATTENFALL and the EC. The research reactor is under construction with expected start of operation in 2014. The reactor is a pool type with a maximum thermal power of 100MW. The core, the primary circuit and experimental rigs are completely enclosed in the reactor building and the reactor pool is connected to several storage pools and hot cells. The reactor core will be operated with a high density low enriched fuel (U enrichment of less than 20%, density 8 $g.cm^{-3}$), requiring the development of U/Mo fuel. The fuel element is of circular shape with set curved plates assembled with stiffeners and comprises a central hole. The JHR will able to accommodate 20 simultaneous experiments for Generation II, III and IV nuclear energy needs. In core it will produce high flux fast neutrons and via a reflector high flux thermal neutrons. In summary[22]the reactor specification is:

JHR: 100MW, 1 to $5.10^{14}$ $n.cm^{-2}.s^{-1}$ including fast spectrum capability
Fuel: Eventually U/Mo LEU Enrichment <20%, but initially $U_3Si_2$ at 27% U-235

### 6.2 Pallas

The High Flux Reactor (HFR) at Petten is approaching the end of its operating life and as a result maintenance costs are increasing and continuity of operation is compromised by the ageing of materials and components; closure is expected in 2015. The current licence holder of the HFR is the Dutch Nuclear Research and Consultancy Group (NRG). NRG plans to build a new research reactor called PALLAS. It is planned to be a state-of-the-art reactor that will be equipped to meet the world growing demand for nuclear knowledge and services and the production of essential medical isotopes. A tender process was started in 2007, but was later suspended. NRG are still actively pursuing funding for the project. The original plan was to construct the reactor between 2012 and 2014 with operation starting in 2015, but this currently looks optimistic. To date NRG has only defined how the research reactor will be operated and it has given no public indication of the type of design, its neutron flux or fuel enrichment.

### 6.3 MTR+I3 Project

The MTR+I3 project was funded under the EC's FP6 Fission Safety Programme. Its main objectives are:

- To build a European materials test reactor (MTR) community with a range of high power but also flexible small power MTRs
- To establish the JHR and to cross fertilise knowledge and expertise between existing and new MTRs
- To support the design, fabrication and test of state-of-the-art devices, components and instrumentation.

The key goal of the European FP6 project MTR+I3 was to build durable cooperation between Material Testing Reactor (MTR) operators and relevant laboratories that can maintain European leadership with up-dated capabilities and competences regarding reactor performances and irradiation technology. Major results were on-line fuel power determination, neutron screen optimisation, simulation of transmutation process, power transient systems, water chemistry and stress corrosion cracking, fission gas measurement, irradiation behaviour of electronic modules, mechanical loading under irradiation, high temperature gas loop technology, heavy liquid metal loop development and safety test instrumentation.

In Table 4 we present summary information for some recent illustrative developments worldwide:

| Reactor | Commissioned | Thermal Power | Flux | Fuel |
|---|---|---|---|---|
| TRIGA II Morocco[23] | 2007 | 2 MW | $4.\ 10^{13}$ n $s^{-1}cm^{-2}$ | UZrH LEU enriched 19% |
| OPAL, Lucas Heights, Australia[24] | 2007 | 20 MW | $4.\ 10^{14}$ n $s^{-1}cm^{-2}$ | LEU Enrichment <20% |
| CARR, China[21] | 2010 | 60 MW ($H_2O$ moderator, $D_2O$ reflector) | $1.\ 10^{15}$ n $s^{-1}cm^{-2}$ | LEU enrichment 19% |

**Table 4. Recently Commissioned Research Reactors Outside Europe (May, 2010)[25]**

## 7. Benefits of a New Proliferation Resistant Research Reactor

Looking to future more proliferation-resistant research reactors a set of considerations can be highlighted. First it is important that an easy opportunity is provided for independent scrutiny of any country's civil nuclear research reactor facilities. Any new facility should be designed with such concerns in mind. Any country developing such a capability should have a robust, and ideally independent, safety and security regulatory agencies.

The provision of a robustly proliferation-resistant research reactor could provide a safe option for those countries unwilling to accept arrangements based on international facilities. Much effort has been devoted to considering possible internationalisation of sensitive parts of the nuclear fuel cycle. Similar approaches could be adopted with regard to research reactors, but it seems unlikely that all countries will accept such restrictions. Such a country might insist on a right to a domestic capability. In that case, and if their intentions are benign, then a highly proliferation resistant design should meet their needs well. If they were to repudiate this second option then their aggressive intentions would be clear for the world to see. A country aiming surreptitiously to develop weapons capability would probably reject international support in constructing a highly proliferation research reactor. To be seen in the global court of public opinion to have rejected such an opportunity could only help international efforts to preserve global nuclear security. At present countries with ambiguous intentions are able to secure support for, or acquiescence with, their nuclear policies from those countries that are distrustful, for whatever reason, of the P5 weapons states. The development of a new highly proliferation-resistant research reactor would be consistent with existing text of Nuclear Non Proliferation Treaty and would require no modification to it.

### 7.1 Desirable attributes of a new enhanced proliferation resistance research reactor

Designing proliferation resistance into new research reactors and the way they are operated and made secure is crucial and the following list provides a general framework for doing so:

- LEU fuel
- Full IAEA Oversight (e.g. to avoid surreptitious irradiations)
- No open pool access (e.g. closed and pressurized tank concept) – this further removes the opportunity for illicit irradiations
- All core access fully interlocked and monitored
- Laboratories to be equipped with airport style security for entry and exit. Such measures reduce the risk of 'inside-job' threats
- Design the reactor from scratch so as to make power up-rates and up-grades sufficiently difficult that they would immediately be apparent to international oversight bodies (e.g. IAEA).
- Fuel-for-life cores (especially for low-flux facilities)

## 8 Possible Models for Future UK Research Reactor Development

### 8.1 Design a New Research Reactor in the UK to meet British and global needs

The UK considered developing a mobile neutron source back in the 1990s. It was proposed to construct a demonstrator for inspection radiography. Further assessments revealed, however, that demand was likely to be somewhat limited. Existing excess radiographic capacity was identified and hence predicted revenue streams for the new project were not strong. The project was terminated on the basis of a weak economic case.

The creation of a civil industry-driven programme to purchase and build a new research reactor would require a strong commercial driver. This would probably serve a portfolio of customers including those connected with medicine and civil nuclear energy. Any such project-financing consortium could be cumbersome and unwieldy. It may prove essential for such an investor-consortium to be facilitated or brokered by direct Government action. Separately various parts of Government responsible for health, defence and homeland security might wish to invest in the project for their own policy reasons.

We note that such a project could support the UK civil nuclear energy business directly. For this a key issue must be the goal of producing a facility that will genuinely be needed. Ancillary benefits would be likely to emerge via spin-out opportunities in technology, international collaboration or nuclear skills, but these are unlikely to be sufficient reasons in their own right. We suggest that unless the UK were actually intending to build a research reactor, then the idea of design project would lose merit. To take a project of this nature forward, a staged process with decision points would be needed. It is important to stress that a project seeking to develop a new design while requiring a broad base of investors, would necessarily be led at a technical level by companies with strong nuclear engineering credentials. It is speculated that if a number of such nuclear companies were to cooperate by committing a level of approximately 3 man-years between them then this would be adequate resource to take a research reactor project through to a conceptual design stage.

### 8.2 Collaboratively Design a New Research Reactor?

For this possible strategy it is perhaps most helpful to illustrate the argument with reference to a specific potential collaborating nation, which we shall term the ‘second-party state’.

Good candidate nations as a second-party state partner would be well integrated into the global economy, be known for the rule of law and political stability and have high levels of technical competence, although probably not yet in the nuclear sector. A good candidate second party state would have excellent trade and communication infrastructures in aviation, shipping and data communication. Ideally it would be home to a prosperous import export/trans-shipment economy, a financial services hub and have a strong regional presence in higher education and research. An added strength would be strong counter-terrorist capacity.

At least one good candidate second-party state for partnership with the UK exists. A key motivation for the second-party state would be the prospect of entry into the already lucrative, and likely to grow substantially, market for medical isotopes in rapidly developing markets, such as in South-East Asia, South Asia and China. Importantly the key driver for the effort described above would be neither markets in the UK nor in the partner second-party state, but rather third-party developing countries.

The suggestion of a new research reactor design suitable for any, and all, states could have some geopolitical advantages. For certain countries, described in this paper as the second-party state, a research reactor project might allow for a local locus of nuclear knowledge independent of the teams forming to build possible commercial nuclear power plants. Those associated with the research reactor could form a good technical cadre in a nascent nuclear safety body ready to assess and approve later new nuclear power plants. A collaborative research reactor design might be an area where the UK might be able to offer assistance in the global advancement of benign civil nuclear technology in accordance with its Non-Proliferation Treaty obligations.

### 8.3 Purchase a New Research Reactor for the UK?

In the UK the defence sector is served by the NEPTUNE reactor at Derby and a TRIGA reactor at Dounreay both of which act in support of the submarine propulsion programme. The only other UK reactor is the low power civil research reactor CONSORT operated by Imperial College. This is considered to be quite limited in what it can do, because of its low power. The long-term future for this facility is that it will be closed and decommissioned. At present, and for the short term at least the facility will remain operational.whilst a shut-down and decommissioning programme is agreed.

Noting current and ongoing national needs it appears that the dominant interest in any new research reactor for the UK is likely to come first and foremost from the UK Ministry of Defence. The probability that the defence sector might seek to purchase a new research reactor to serve its own needs seems to be greater than the chance of some of the other strategic choices mentioned here, although mutually compatible solutions might be possible. We note the precedent set by the Orion laser facility at AWE Aldermaston, which while primarily developed for military research purposes is to be made available to civilian researchers.

It is worth mentioning, however, that an investor consortium presumably led by the radio-pharmaceutical industry might push independently for a new reactor for commercial isotope production. Although a possibility in principle, we see no actual evidence of such a scenario developing at present, but the risks highlighted earlier may change this.

Importantly, if the UK were simply to purchase a research reactor to serve national needs in, for instance defence or healthcare, then it would not benefit from the nuclear knowledge and skills preservation inherent in the options discussed earlier.

## 9 Conclusions

The current ageing of existing research reactors, the world-wide new build programme for nuclear energy and a predicted desire for more regionally-based medical isotope reactor facilities lies behind the global expansion of interest in new civil research reactors. Many such reactors will be required in countries already with fairly sophisticated nuclear technology to replace existing research reactors or to meet increased demands arising from the ageing of existing nuclear power plants or proposals to build new plant. In addition we predict future research reactor requirements from countries with little, or no, previous nuclear heritage.

There is a major political issue as to whether such technology should be operated by countries without the advantage of having a background of nuclear know-how. This is especially true if there is potentially political instability within that country or region.

Given the probable growing demand for research reactors in the future, steps should be taken to further reduce the risk that such technologies might be used for in relation to the production of nuclear weapons or the manufacture of terrorist weapons (e.g. dirty bombs). This paper has explored some of the issues that could represent inputs when deciding criteria that could be used to define a research reactor design as ‘proliferation resistant’, recognizing that ‘proliferation proof’ is probably unrealistic.

In considering the UK’s role in assisting the world community to develop the peaceful uses of nuclear energy and associated technology the UK should consider the possibility that either alone, or in international collaboration, it might seek to develop a new more proliferation resistant design of research reactor for global markets. Such a project would need careful definition and it is suggested that this would be around a set of target criteria that would on the one hand aim to minimize the risk from nuclear weapons proliferation and loss of security and on the other produce a concept design that would be attractive from a commercial perspective. It is suggested that the project should be self-funded from companies and organizations that would have commercial, academic or strategic interest in the development of a proliferation resistant research reactor. Some level of UK Government involvement would appear to be essential, but this could be consistent with existing budgets and mandates. If some project partners were drawn from UK academia, then there would be an enhanced possibility of beneficial spin-out motivating Research Council or Technology Strategy Board funding.

We suggest there is a case for designing a new research reactor in the UK and a different separate case for buying a new research reactor for the UK. We suggest that any decision between two such strategies should be made in a coordinated way as moves to purchase a foreign-designed facility could greatly undermine the case for a new domestic design. In both cases there would need to be strong economic case for the chosen project and this is more likely if a stakeholder group were to be convened in advance of any project decision. There is a case for Government convening such a meeting of minds. There may be a role for public funding in support of the growth of an export-focussed industry, but we do not suggest that such a role is the most important role for Government in this space at this stage.

Finally two other scenarios are worth mentioning. First, there is also a potential scenario where the UK may decide to design a reactor with or without a UK build being considered. Possible delays to or deferment of the defence programme may make it difficult to maintain or grow nuclear expertise for when it is required later on in the programme. The design of a research reactor would be one way of keeping currency of expertise. It could be that this initiative was done in cooperation with the commercial sector especially those companies that saw the potential for selling such a design to countries entering the nuclear sector for the first time. In this case consideration would have to be given to making the design proliferation resistant. A second scenario is that UK users of research reactors might support the development of existing projects underway elsewhere in Europe. Some of these projects have been described elsewhere in this paper.

Looking to the future, it is unclear if the need for access to a research reactor for a range of commercial purposes justifies one being built in the UK. At present, and given the fragmented and uncoordinated stakeholders for such a project, one thing is fairly certain – no British entity (public or private) is in a position alone easily to initiate a new civil research reactor project. Furthermore it is not clear whether there is likely to be a shortage of access to research reactors for UK nuclear companies presently and for new nuclear companies coming into the UK market such as EDF, EON and RWE. We note that these European energy companies will have relatively easy access to research reactors in other European countries. They will not see these issues in ‘British’ terms. Noting the construction of the Jules Horowitz materials test reactor, it is difficult to see the justification for the UK designing, or purchasing, anything similar. As discussed above other research reactor ambitions may be more appropriate and deliverable for the UK perhaps as a partial contribution to building a world less prone to the risks of nuclear weapons proliferation and nuclear terrorism.

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All opinions expressed are those of the authors alone and do not reflect the opinions of those that have provided assistance of any type. All errors and omissions are the responsibility of the authors alone.

# Appendix Research Reactors Operating With HEU in 2000

Data source WNA (footnote 1)

| | Type | Power - kW | Enrichment % | Source of fuel |
|---|---|---|---|---|
| **Argentina** | pool | 500 | 90, now LEU | USA |
| **Austria** | Triga | 250 | 20-70 | USA |
| | Argonaut | 10 | 20-90 | USA |
| **Belgium** | tank | 100,000 | 74-93 | USA |
| **Canada** | pool | 5,000 | 93 | USA |
| | Slowpoke | 20 (x 3) | 93 | USA |
| **Chile** | pool | 2,000 | 90 | France |
| | pool | 5,000 | 20-45 | USA |
| **China** | Crit fast | 0.05 | 90 | China |
| | tank | 125,000 | 90 | China |
| | MNSR | 27 | 90 | China |
| | pool | 5000 | 90 | China |
| | MNSR | 30-33 (x 3) | 90 | China |
| **Czech Rep** | tank | 10,000 | 36, now LEU | Russia |
| | pool | 5 | 36 | Russia |
| **France** | pool | 0.1 | 90-93 | USA |
| | Tank in pool | 0.1 | 3-93 | USA, France |
| | Crit fast | 3 | 12-25 | USA |
| | heavy water | 58,300 | 93 | USA |
| | pool | 14,000 | 93 | USA |
| | FBR - Phenix | 563,000 | 22-28, now closed | France |
| | Argonaut | 100 | 93 | USA |
| | homogeneous | 1 | 93 | USA |
| **Germany** | pool | 4,000 | 45-93 | USA |
| | heavy water | 23,000 | 80-93 | USA |
| | pool | 10,000 | 20-93 | USA |
| | tank | 0.01 | 36 | Russia |
| **Ghana** | MNSR | 30 | 90 | China |
| **Greece** | pool | 5 | 20-93 | USA |
| **Hungary** | tank | 10,000 | 36, now LEU | Russia |
| **Israel** | pool | 5,000 | 93 | USA |
| **India** | pool | 1000 | 93 | UK & France |
| | FBR | 40,000 | 55-70 | India |

| | | | | |
|---|---|---|---|---|
| **Iran** | MNSR | 30 | 90 | China |
| **Italy** | Fast source | 5 | 93 | USA |
| **Jamaica** | Slowpoke | 20 | 93 | USA |
| **Japan** | Argonaut | 0.01 | 90 | USA |
| | tank | 5000 | 93 | USA |
| | Crit fast | 2 | 20-93 | USA, UK |
| | Tank | 50,000 | 20-46 | USA |
| | Crit assembly | 0.1 | 45-93 | USA |
| **Korea (DPRK)** | pool | 8,000 | 36 | Russia |
| **Kazakhstan** | pool | 6,000 | 36 | Russia |
| | tank | 10,000 | 36 | Russia |
| | tank | 60,000 | 90 | Russia |
| **Libya** | pool | 10,000 | 80, now LEU | Russia |
| **Mexico** | Triga | 1000 | 20-70 | USA |
| **Netherlands** | Argonaut | 30 | 90 | USA |
| | pool | 2000 | 20-93 | USA |
| **Pakistan** | MNSR | 30 | 90 | China |
| **Poland** | pool | 30,000 | 36-80 | Russia |
| **Portugal** | pool | 1000 | 93 | USA |
| **Romania** | Triga | 14,000 | 20-93 | USA |
| **Russia** | various | (39 units, 12 being over 1 MW) | Various | Russia |
| **South Africa** | Tank in pool | 20,000 | 87-93, now LEU | S.Africa |
| **Sweden** | pool | 1000 | 93 | USA |
| **Switzerland** | homogenous | 2 | 90 | USA |
| **Syria** | MNSR | 30 | 90 | China |
| **UK** | Fast burst | 0.5 | 37.5 | UK |
| | Pool | 100 | 80 | UK |
| **Ukraine** | tank | 10,000 | 36, now LEU | Russia |
| **USA** | various | (22 units, 13 being 1 MW or more) | Various | USA |
| **Uzbekistan** | tank | 10,000 | 36, now LEU | Russia |
| **Vietnam** | pool | 500 | 36, now LEU | Russia |
| **Yugoslavia (Serbia)** | heavy water | 0.001 | Up to 80 | Russia |
| **Total 38 countries** | | c 130 units | | |
| | | | | |
| **Taiwan** | pool | 30 | 93 | USA |

**Table 1. Research Reactors originally with High-enriched Uranium (HEU) Fuel**

**(source: WNA)**

Note many of the reactors listed in Table 1 have since been decommissioned or converted to use LEU fuels.

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