RESEARCH REACTORS — AN OVERVIEW

Colin D. West
Oak Ridge National Laboratory
P.O. Box 2009
Oak Ridge, TN 37831-8218
(423) 574-0370

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There are (or were in September of 1996) 181 research reactors in operation in 57 countries. In addition, there were 44 training reactors, 27 critical facilities, 17 test reactors and 5 others included in the International Atomic Energy Agency’s (IAEA’s) "Nuclear Research Reactors in the World." (See ref. 1.)

Research reactors have a very wide variety of uses, including neutron scattering (in which beams of thermal neutrons are scattered by the atoms in a sample, revealing its structure, magnetic state, and atomic binding energies); neutron activation analysis; radiography; irradiation testing of materials; and production of radioisotopes for medical, research, and industrial use. These capabilities are applied by researchers in many fields, ranging from archeology to materials science and from fusion research to environmental science. There are few generalizations to be made about the applications for research reactors or about their users.

So-called test reactors, on the other hand, usually have been designed and built with more specialized purposes in mind, such as materials irradiation testing or particular experiments relating to power reactor safety issues: the BORAX and SPERT experiments in the United States, the CABRI facility in France, and the Nuclear Safety Research Reactor in Japan are famous examples of these experimental facilities. Many important fission product release and transport experiments have been carried out with these test reactors, as have measurements and filming of fuel and clad melting following large, rapid increases in fission rate.

The research reactor types listed by the IAEA (which includes the test, training, etc., facilities in this category) are of many different designs:

<table>
<thead>
<tr>
<th>Type</th>
<th>Pool</th>
<th>TRIGA</th>
<th>Tank</th>
<th>Homogeneous</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>78</td>
<td>45</td>
<td>36</td>
<td>21</td>
<td>94</td>
</tr>
</tbody>
</table>

More than half the total are covered by the first three categories, and I will briefly describe examples of them with particular emphasis on their safety-related features.

They present a completely different picture from typical power reactors: the research reactors range from zero to 100 MWa power, although a few test reactors are higher, compared with a typical 3000+ MWa nuclear power plant. The fission product inventory is correspondingly less, as is the stored energy. Cooling water usually has a bulk temperature of less than 100°C.

On the other hand, some of the more powerful research and test reactors have power densities in the core of more than 5,000 kWa/kg of fuel, compared with less than 50 kWa/kg in a power reactor. The adiabatic heat up rate is, therefore, at least potentially, much higher in the research reactors, many of which also use low melting point aluminum cladding and filler in the fuel elements. Table 1, taken from material in ref. 2, illustrates some of these differences: the examples given are all larger U.S. research reactors: most of the operating facilities in the United States and elsewhere have much lower power levels, with even greater differences from the power reactor.

The swimming pool reactor is very simple (see Fig. 1), and more than 40 such reactors have been built in the United States alone, although only 12 of those were still operating last year. The core is often made up of what are called Materials Testing Reactor- (MTR) type type fuel elements, aluminum clad, curved plates of fuel arranged in long rectangular boxes (Fig. 2), which are arranged between grid plates to form the core. Several positions in the grid are not occupied by fuel elements, but by control rods, beryllium reflectors, or experimental capsules. Cooling may be by...
Table 1. Examples of research, test, and power reactors

<table>
<thead>
<tr>
<th>Reactor</th>
<th>Type/location</th>
<th>Operating power (MW&lt;sub&gt;n&lt;/sub&gt;)</th>
<th>Fuel mass (kg)</th>
<th>Radionuclide inventory&lt;sup&gt;a&lt;/sup&gt; (Mci)</th>
<th>Decay heating power at various times after shutdown, (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>50s</td>
</tr>
<tr>
<td>HFBR</td>
<td>Research/ Brookhaven</td>
<td>60</td>
<td>12 (U&lt;sub&gt;3&lt;/sub&gt;O&lt;sub&gt;4&lt;/sub&gt;)</td>
<td>21</td>
<td>2.7</td>
</tr>
<tr>
<td>HFIR</td>
<td>Research/ Oak Ridge</td>
<td>85</td>
<td>12 (U&lt;sub&gt;3&lt;/sub&gt;O&lt;sub&gt;4&lt;/sub&gt;)</td>
<td>43</td>
<td>2.8</td>
</tr>
<tr>
<td>ATR</td>
<td>Test/ Idaho Falls</td>
<td>250</td>
<td>39—46 (U)</td>
<td>240</td>
<td>12.6</td>
</tr>
<tr>
<td>Commercial power</td>
<td>Typical PWR</td>
<td>3,414</td>
<td>101,100 (UO&lt;sub&gt;2&lt;/sub&gt;)</td>
<td>1,600</td>
<td>100</td>
</tr>
</tbody>
</table>

<sup>a</sup>Radiologically important isotopes of Kr, Xe, I, and Cs calculated at shutdown for refueling.

natural convection of the pool water, although this is augmented, for operation at higher power, by pumping pool water through the core. This design led to the tank-in-pool reactor, (Figs. 3 and 4) similar to the open-pool type but with the core contained in an aluminum tank: the cooling (light) water is pumped through the core, but the pressure within the tank is only moderately elevated above that in the open pool, the pressurization being mostly due to the pressure drop across the core of the pumped coolant water flow. Again, in the United States, aluminum clad fuel plates are usual.

Most swimming pool reactors are, at most, of a few megawatts thermal power, although the one at the Hahn-Meitner Institute in Berlin was recently given a major refurbishment and upgrade, with the power raised to 10 MW<sub>n</sub> (ref. 3 ). Successful tank-in-pool reactors have included the 20-MW<sub>n</sub> Oak Ridge Research Reactor, now shut down, and its sisters like the European Community's HFR at Petten, which now operates at 45 MW<sub>n</sub>.

More powerful research reactors, of which the international Institut Laue-Langevin (ILL) facility at Grenoble, France, and the High Flux Isotope Reactor (HFIR) at Oak Ridge, Tennessee, are well known examples, have tanks that are full pressure vessels — for example, the coolant inlet pressure at HFIR is nominally 470 psi, and at ILL it is 200 psi. Again, aluminum clad fuel plates are used, the fuel meat being a layer, ~50 mils thick, of U<sub>3</sub>O<sub>4</sub> particles mixed with powdered aluminum for enhanced thermal conductivity, the layer being clad with aluminum plates ~10 mils thick. In these two reactors, the fuel elements are annular, with curved (involute) plates fitting into axial grooves down two concentric cylinders. (See Figs. 5 and 6.)

The power density in the 85-MW HFIR core is almost 2 MW/L, or 9 MW/kg of uranium in the fuel, and such machines need, and have, sophisticated safety design features, most of which would be familiar to power reactor safety analysts: Emergency core cooling systems; multiple, independent redundant shutdown mechanisms; battery and diesel engine electrical emergency systems; and containment or confinement buildings. Safety analyses of these machines rely on the same tools that are used by power reactor designers, e.g., probabilistic risk assessment and sophisticated thermal-hydraulic codes like RELAP.

Perhaps the most interesting reactor design of the common types, from a technical and safety perspective, is the TRIGA, developed in the 1950s by General Atomic. Its unique fuel and core design concept has a very large (~10<sup>4</sup> Δk/k per °C) and very prompt negative temperature coefficient, the meat being a homogenized mixture of fuel and hydrogenous moderator, in the form of uranium-zirconium hydride. This provides prompt negative feedback, because there is no delay between fuel and moderator temperature variations. This is in addition to the usual prompt Doppler effect in <sup>238</sup>U in reduced enrichment fuels. Beyond these effects, erbium can be added as a burnable poison and adds even more prompt negative temperature coefficient because it has a strong resonance absorption at about 0.5 eV. The fuel/moderator/poison has a design operating temperature of up to 750°C, and a safety limit of 1150°C, obviously much higher than aluminum/fuel mixtures. It is formed into rods clad with stainless steel (Incoloy 800). With this combination of design features, very large reactivity insertions can be tolerated, and many TRIGAs are routinely and safely operated as pulsed reactors with peak power levels, during a few millisecond pulse, of up to 10 GW.

Cooling is by natural convection of light water for power levels up to 2 MW<sub>n</sub>. At higher power levels, forced flow is
used, but the high fuel temperature tolerance and negative reactivity coefficients mean that pony motors are not needed for shutdown cooling following a loss of the primary coolant pumps.

The most powerful TRIGA built is the 14-MW (continuous operation) reactor now in operation for 17 years at the Pitești Institute for Nuclear Research in Romania. A second TRIGA at the same facility can pulse up to 22 GW, with a peak thermal neutron flux during the pulse of $10^{19}$ cm$^{-2}$ s$^{-1}$ — an order of magnitude higher than any spallation neutron source in existence, but with a much longer pulse of course (ref. 4).

Figure 7 is a cutaway drawing of a typical, but early, TRIGA system in its light water pool.

The Advanced Neutron Source (ANS) with a 300-MW$_{ne}$ reactor was, unfortunately, terminated before construction began, but its design illustrates some implications of the differing missions of research and power reactors.

The ANS reactor was designed as a multipurpose scientific facility (ref. 5), but with a major emphasis on neutron beams and, especially, beams of cold neutrons. This led to a design with a very high thermal flux peak ($\sim 7.5 \times 10^{15}$ cm$^{-2}$ s$^{-1}$) in a heavy water reflector outside the three-element, 82.6L, 300-MW$_{ne}$ core design that was the baseline at the time the project ended. It was desirable to have the coolant heavy water and the reflector heavy water at the lowest practical temperature, so that the thermalized neutrons should have a low Maxwellian temperature.

The average heat flux from the fuel plates into the coolant was about 4.5 MW/m$^2$, and aluminum cladding was desirable for its high thermal conductivity compared with zirconium and its low neutron absorption compared with steel, although the lower softening and melting temperature might have been a drawback. For this reason, and to prevent excessive oxide buildup, it is necessary to keep the aluminum surface at a low temperature, which brings other safety benefits, too.

To provide space for the many big neutron scattering instruments, a very large floor area (60-m diam) is needed in the containment, which means that the containment volume would be very large, in relation to the power and stored energy in the reactor. It also means that there would be in-containment space, on other floor levels than the experimental hall, to enclose the entire primary cooling system within containment. Also, the primary piping was mainly under water, in pools, while the valves, instrumentation, and other primary coolant loop equipment needing maintenance, etc., were enclosed in dry cells that, in the event of a break or major leak, would be filled from the leak by heavy water from a large pressurized accumulator that was a permanent part of the primary loops; thus, even a complete pipe break in the primary circuit would not lead to a loss of coolant or to air entering the system, although of course it would cause loss of pressure that the fast, $\sim 30$ ms scram systems could accommodate.

These characteristics of a research reactor were leading, at the time of cancellation, to a very desirable set of safety features (ref. 6) that designers of other reactor types might well envy — see Table 2.

I. SUMMARY

Research and test reactors have made major contributions to our knowledge of normal and accident events in power reactor systems and have supported research in many different fields of scholarship.

Research reactors themselves tend to have a very different set of safety-related parameters from power reactors. Some are helpful differences — like simplicity, relatively low power, and low temperature coolant. Other differences, especially the need for a high power density core, pose challenges not faced in a power reactor: These challenges can be met through thoughtful design solutions.

II. HISTORICAL NOTE

While searching out references for this paper, I was shown a fascinating 1959 article (ref. 7) in the Journal Nucleonics. It described twelve small research reactors offered for sale by seven different companies. Most of the quoted prices were in the range $100,000—$200,000, with one system offered by a British company for only $50,000!

III. ACKNOWLEDGMENTS

I should like to thank many of my colleagues for help and advice in preparing this paper, especially Gabrielle Boudreau, Mike Harrington, Kathy Rosenbalm, Ken Thoms, and William Whittemore.

IV. REFERENCES


Table 2. Some major safety features of the ANS research reactor design concept

<table>
<thead>
<tr>
<th>Feature</th>
<th>Notes</th>
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</thead>
<tbody>
<tr>
<td>• Bulk water temperature below 100°C in all anticipated events</td>
<td>No bulk flashing upon depressurization</td>
</tr>
<tr>
<td>• Maximum fuel clad temperature below saturation in all anticipated events</td>
<td>No coolant boiling or dryout</td>
</tr>
<tr>
<td>• Negative void and temperature coefficients</td>
<td>Stable dynamic behavior</td>
</tr>
<tr>
<td>• Two independent, physically different and physically separated shutdown systems, each one able to shut down indefinitely, even with one of its rods stuck “out”</td>
<td>Negligible ATWS probability</td>
</tr>
<tr>
<td>• Primary piping submerged or in limited volume dry cells within containment</td>
<td>No real loss-of-coolant accident; no steam flashing or blowdown for any size pipe break</td>
</tr>
<tr>
<td>• Long-term heat sinks inside containment and natural circulation adequate for long-term decay heat removal</td>
<td>Passive decay heat removal</td>
</tr>
<tr>
<td>• Containment designed on basis of deterministic calculations to withstand severe accident pressure loads without causing high containment leakage</td>
<td>Protective action guidelines (PAGs) not exceeded off-site for severe accidents</td>
</tr>
</tbody>
</table>


Fig. 1. Basic H2O-cooled swimming-pool reactor
(18) Fuel Plates, 23.75 Long, .050" Thick

Outer Aluminum Plates .100" Thick

Section A - A

Fig. 2. MTR-type fuel element.
Fig. 3. ORR Reactor Assembly.
Fig. 4. View of the ORR Reactor Assembly and the Tank.
The High Flux Isotope Reactor

Fig. 5.
Top Side of Reactor

Fig. 6.
Fig. 7. Cutaway view of basic Mark I TRIGA reactor (Adapted from Reed College 1967).