Report on Generation IV Technical Working Group 3: Liquid Metal Reactors

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This paper reports on the first round of R&D roadmap activities of the Generation IV (Gen IV) Technical Working Group (TWG) 3, on liquid metal-cooled reactors. Liquid metal coolants give rise to fast spectrum systems, and thus the reactor systems considered in this TWG are all fast reactors. Gas-cooled fast reactors are considered in the context of TWG 2.

As is noted in other Gen IV papers, this first round activity is termed "screening for potential", and includes collecting the most complete set of liquid metal reactor/fuel cycle system concepts possible and evaluating the concepts against the Gen IV principles and goals. Those concepts or concept groups that meet the Gen IV principles and which are deemed to have reasonable potential to meet the Gen IV goals will pass to the next round of evaluation.

Although we sometimes use the terms "reactor" or "reactor system" by themselves, the scope of the investigation by TWG 3 includes not only the reactor systems, but very importantly the closed fuel recycle system inevitably required by fast reactors.

The response to the DOE Request for Information (RFI) on liquid metal reactor/fuel cycle systems from principal investigators, laboratories, corporations, and other institutions, was robust and gratifying. Thirty three liquid metal concept descriptions, from eight different countries, were ultimately received. The variation in the scope, depth, and completeness of the responses created a significant challenge for the group, but the TWG made a very significant effort not to screen out concepts early in the process.

With the number and diversity of concepts submitted in response to the RFI, it was incumbent upon the TWG to seek a grouping of concepts within some logical framework. The rationale for placing concepts into groups was simply that thirty three concepts would be impossible to screen individually with the resources available, and further that this was not needed anyway because some concepts shared many attributes. The issue was how to define the grouping so that a maximum number of concepts fit within a given group, without making the group definition so broad that it would lose practical significance. It was accepted from the start that individual concepts would likely be left over after grouping that would be subjected to individual screening.

The principal guiding criterion for grouping was geared to the product of this specific Gen IV activity: an R&D roadmap. Thus it seemed natural to seek groupings on the basis of common R&D requirements, very loosely defined at this stage. The TWG never intended to use the concept grouping approach as a means to dilute or destroy individual concept attributes. While retention of individual concept attributes may be imperfect or vague in preliminary rounds, it is the TWG intent to retain these individual attributes, and to highlight their individual R&D requirements.

Most of the concepts were initially assigned to one of five concept groups, A through E. In the first round of evaluation the job was to understand the technologies employed, noting specific differences or features that were unique to a specific concept. A cursory evaluation was done of the status of the technologies attendant to the concept group, and finally a preliminary evaluation was done of the R&D that would be required to bring the concept group to deployment reality. This latter subject, the R&D requirements, will be much more extensively addressed in later stages of the roadmap activity. Nevertheless, the TWG felt that at least a limited look at R&D requirements in the first phase would materially aid the process of screening for potential, and that this would provide a useful start to the next phase.

A sixth evaluation, in three parts, was also done. These were termed "base technology evaluations" for fuels, coolants, and fuel cycles. This was done in order to avoid separate subgroups of the TWG doing redundant evaluations as part of the concept group analyses.

With these considerations in mind, five concept groups encompassed 27 of the 33 three concepts submitted:

- concept group A: medium-to-large sodium-cooled, mixed-oxide fueled reactors with advanced aqueous reprocessing and ceramic pellet or vibratory compaction fabrication (5 concepts).

- group B: medium-to-large sodium-cooled, metal-fueled (U-TRU-Zr metal) reactors with electrochemical fuel cycle technology (pyroprocessing) (6 concepts)

- group C: Medium-sized Pb or Pb-Bi cooled; MOX or Th-U-TRU-Zr metal alloy fueled reactors (one concept had nitride fuel); pyroprocess fuel cycle for the metal-fueled concepts, advanced aqueous or unspecified "dry" process for the ceramic fueled concepts. (9 concepts)

- group D: Small, Pb or Pb-Bi cooled; metal or nitride fueled reactors with long-life "cartridge" or cassette cores. Fuel cycles vary. (4 concepts).

- group E: Sodium-cooled concepts that eliminate the traditional secondary sodium loops by development of novel new steam generators. (3 concepts)

In addition one concept was more a statement of fuel cycle principles. Rather than an evaluation, it was considered in the context of the fuel cycle technology. Five concepts were evaluated by themselves (three direct energy conversion schemes, a concept involving the CANDLE burnup approach, and a concept that would develop Russian Pb-Bi submarine reactor technology for commercialization).

Two things are apparent from the grouped concepts. First, the technology maturity decreases from group A to group E. Put another way, group A is nearer-term than group B, etc. Second, there is more similarity in the technical features and in the R&D requirements within groups A and B than in groups C, D, and E.

"Advanced aqueous" processing or the electrochemical pyroprocess were adopted in the vast majority of concepts. Both aim to avoid separation of pure plutonium. Both technologies will require considerable development. Use of lead or lead-bismuth coolant has been done successfully in Russia, but the technology is little known in the rest of the world. Corrosion control and pumping power are concerns, but depending on the specific concept, seismic and other structural issues require resolution. These coolants permit higher temperatures to be reached (one concept that is aimed at production of hydrogen has core outlet temperature of 1050 K) if fuels, cladding, and structural material challenges can be solved. Of course, of the candidate fuels, mixed oxide is well developed (cited as the reference or backup fuel in 10 concepts), with metal fuels requiring continued development (reference or backup in 16 concepts) and nitride fuel essentially starting from scratch (6 concepts).

Not surprisingly, since all of the concepts are fast reactors, all have the capability to utilize almost 100% of the uranium resource, and so a Gen IV goal of sustainability is met by all TWG 3 concepts with respect to fuel supply. Uranium mining can be avoided for decades for fast reactor fuel supply, reducing environmental impact of mining and enrichment. In all but a very few cases the high level wastes contain very little plutonium and minor actinides, recycling these material to the reactors. This eases the technical requirements on repositories and reduces the volume of high level wastes sent to repositories, compared to LWRs operated once-through. However, since essentially all the fast reactor concepts capture these advantages, there is little discrimination afforded amongst concepts. Some discrimination is possible wherever real variation exists: size, temperature, modular versus monolithic, specific fuels employed (from something as simple as UO2 to a more complex Th-U-TRU-Zr metal alloy), and safety. While in general there is a pervasive theme to base the safety case on intrinsic or inherent safety characteristics, the general design features adopted to accomplish this vary considerably.

A number of Gen IV criteria deal with economic potential, and anyone close to fast reactor development understands the great challenge to make these systems cost-competitive. The general trends are toward simplification of both reactor systems and fuel cycle technologies; involving smaller space, fewer components, less commodities, less nuclear safety-grade design, etc.