ULTRASONIC IN-CORE FUEL IDENTIFICATION FOR SAFEGUARDING LARGER CORE SMRS

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INTRODUCTION: It has been previously proposed that an ultrasonic in-core fuel assembly identification system could be employed for preserving continuity of knowledge of fuel contents in a sealed or long-life core of a liquid-metal-cooled reactor. This proposal consists of a series of notches of various depths read by independent ultrasonic transducers; the depth of a notch is identified by the time of flight of the ultrasonic pulse from the transducer. The transducer signals are collected and translated into fuel assembly identification numbers. The present paper extends this proposal to consider the use of multi-step notches with a single transducer to read the entire fuel assembly identification number. This approach can reduce the number of required transducers, which is potentially beneficial for SMRs with many (~100) fuel assemblies in the core. The paper considers some practical aspects of this implementation, intended as an external measure for enhancing the safeguardability of fast reactors with opaque liquid metal coolant.

OVERVIEW

Many countries are showing interest in small modular reactors (SMRs) to meet their projected energy needs. There is a variety of SMR designs being proposed, a number of them featuring long-life cores that may be factory sealed before being deployed at the site of operation. Non-nuclear weapon states signatory to the non-proliferation treaty are obligated to provide sampling of fuel at regular intervals for physical inventory verification. Typically, physical inventory verification occurs annually; reduced core access and reduced refuelling frequency must be reconciled with this practice [1]. This could be achieved, for example, by providing methods to identify fuel within the reactor core on demand.

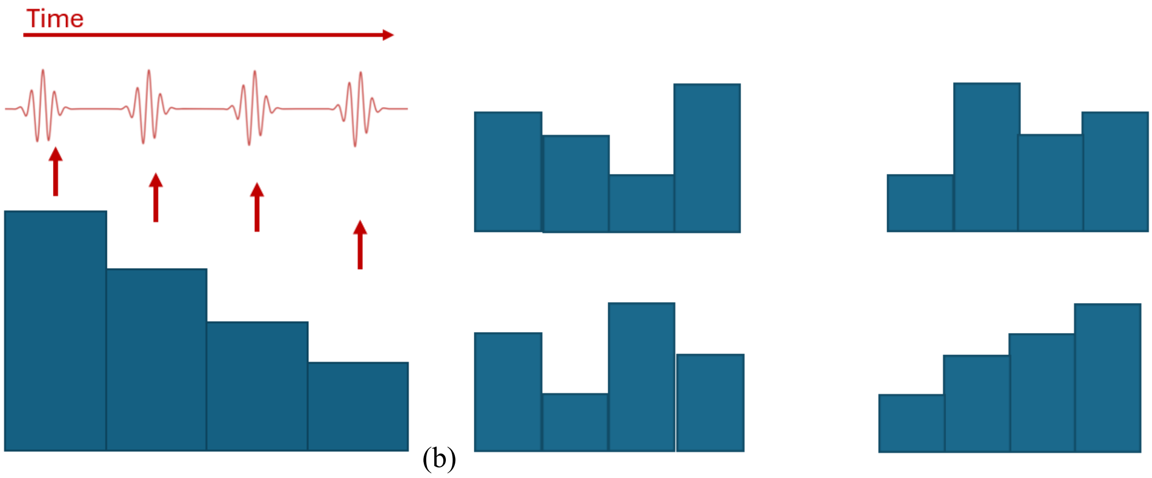
In the case of reactor cores that employ liquid metal coolant, it would not be possible to use optical means for identification of fuel in the coolant. Ultrasonic measurement techniques, however, can provide a practical alternative means of identifying fuel in opaque coolant. Ultrasonic under-sodium viewing was demonstrated in 1967 to identify immersed reactor subassemblies [2]. Subsequently the idea was proposed of using a physical encoding of notches in the top surfaces of fuel subassembly handling sockets [3]. A setup consisting of a circular array of transducers which monitor a circular array of notches on the reactor fuel assembly encoding its identification (ID) is described in [4]. Such an encoding system has been implemented in lead-bismuth coolant in the MYRRHA reactor [5][6]. In more recent work, a wide range of other possible encoding schemes were considered for the identification of fuel through time-of-flight reading of notches etched in the tops of in-core fuel assemblies [7]. These schemes were characterized in the context of a sealed microreactor. Below, in contrast, a modified approach is described for implementation in a liquid metal cooled reactor with a larger core.

IMPLEMENTATION IN A MICROREACTOR VS. A LARGER SMR CORE

Ref. [7] used design information of the SEALER reactor design [8] from LeadCold Reactors (Stockholm, Sweden) as an example to illustrate details of encoding in-core fuel identification using ultrasonic time-of-flight measurement techniques. The SEALER reactor is designed to produce 3 MW of electric power for 27 full-power years, without reshuffling or reloading its fuel [9]. The SEALER design thus classifies as a factory-sealed microreactor, with a relatively small long-life core, consisting of 19 fuel assemblies [8]. For the SEALER example, it was envisioned that each fuel assembly could accommodate up to 12 notches, above each of which an ultrasonic transducer is positioned to measure the time-of-flight signal from the notch. Each transducer thereby provides a separate digit in the identification of the fuel assembly.

Larger liquid metal-cooled SMRs such as the ARC-100 from ARC Clean Technology Canada (St. John, NB, Canada) are envisioned to have significantly more fuel assemblies, 99 in the case of the ARC-100 [10]. As an example for further discussion, the ARC-100 also is envisioned to have a long-life core, 20 years between refuelling events [10]. Hence, the ARC-100 would also benefit from employing ultrasonic means of identifying in-core fuel for safeguards purposes. However, deploying individual transducers to monitor the individual notches on each fuel assembly would result in a number of transducers which is considerably larger than feasible to implement.

In the example of the ARC-100 reactor, an alternative approach might be taken for the implementation of fuel assembly identification that would reduce the number of required ultrasonic transducers. In this approach, the fuel ID encoding would be contained in a single notch consisting of several steps, with each step having varying depths. A single ultrasonic transducer positioned in proximity to the notch would read all the time-of-flight signals from the steps; steps with the same depth would simultaneously relay their signal to the transducer, while steps with differing depth would relay their signals to the transducer at different times (FIG. 1(a)). Further, permutations among the relative positions of the step heights would need to be accounted for in the creation of notch step configurations that produce distinct identification encoding for the fuel assembly (FIG. 1(b)).



(a) (b)

FIG. 1. (a) The collection of time-of-flight signals from a single notch with multiple steps. (b) Example notch step configurations with the same ultrasonic time-of-flight signal, and hence the same encoding.

In the SEALER example, for the deployment of 100 reactor units, a library of 2000 identifiers would suffice to identify fuel for servicing 27 full-power years at each deployed unit [7]. In the example of the ARC-100, where each deployed unit is refuelled once during 40 years of full-power operation, a library of 6000 identifiers would suffice to identify fuel for servicing 30 deployed units during their operational lifetime.

REQUIREMENTS FOR MULTIPLE-STEP NOTCHES

In the example of the ARC-100, analytical calculations were performed to determine how many depths d would be required in order to distinctly label 6000 fuel assemblies for a given number of steps s in a notch. In doing so, the number of combinations was calculated as the binomial coefficient

$$\binom{s+d-1}{s} = \frac{(s+d-1)!}{s!(d-1)!}, \quad (1)$$

which applies as the *s* steps are grouped together from *d* distinct depths: the order does not matter in this case, as all steps with the same depth are measured simultaneously. This binomial coefficient is equal to the number of ways in which *s* items can be selected from *d* types of items (such that there are *d*-1 dividers between the types of items), where repetition is allowed and the number of items chosen from is essentially unlimited. The outcome of the calculation is shown in FIG. 2. In this calculation, anywhere from 2 to 20 steps were considered in a notch, and the corresponding number of depths required for the steps to support a library of 6000 identifications was determined. It is seen from FIG. 2 that as many as 110 depths are required for the 2-step case, to as few as 5 depths for the cases of 18, 19, and 20 steps.

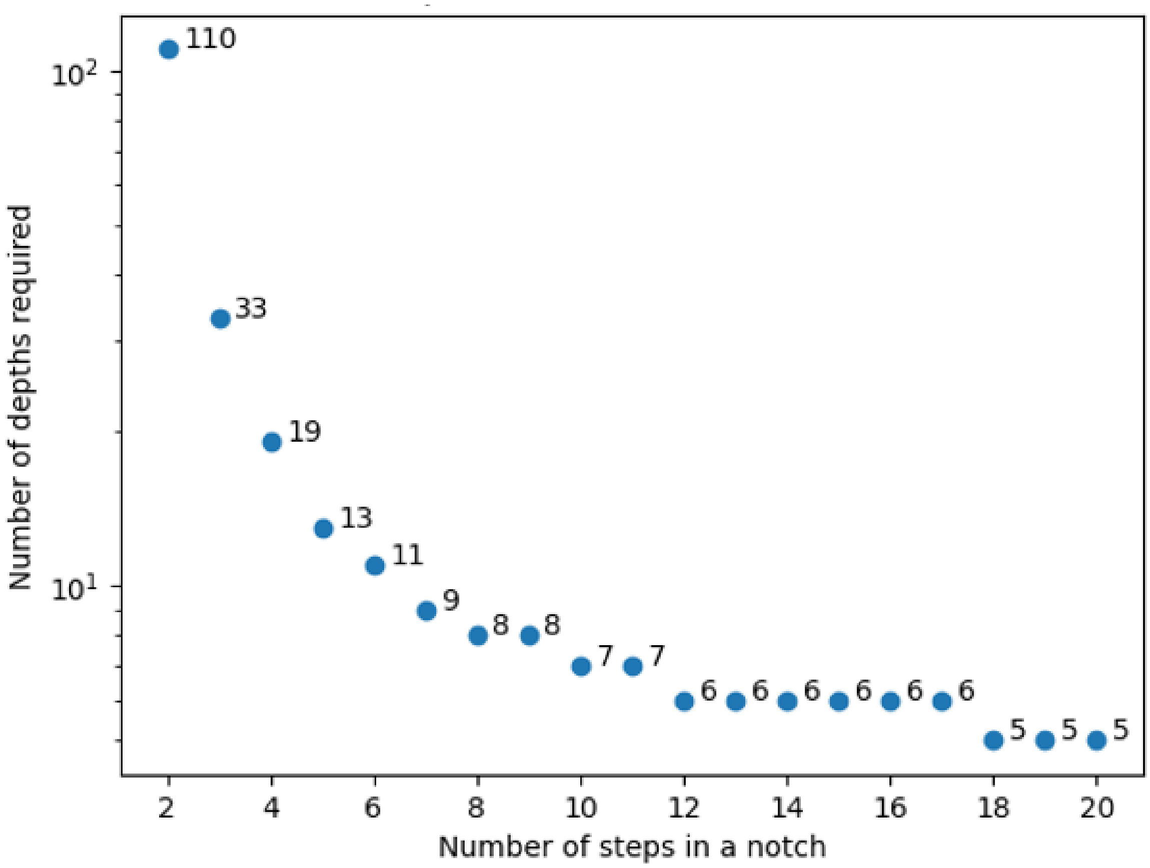


FIG. 2. The computed combination of depths and notches to label 6000 fuel assemblies. The numbers labelling each point is the number of depths required for the given number of steps at that point, provided for clarity.

In Ref. [7], it is discussed how ~1 mm time-of-flight spatial resolution should be achievable for reading different notch depths at 4.75 MHz ultrasonic frequency, such that a 25 mm deep annulus could support 13 distinct notch depths, in steps of more than 1 mm. With such resolution, a 25 mm deep notch in this example could employ as few as 5 steps, and perhaps as many as 20 steps, whatever the geometry of the annulus, the size of transducer, and the required minimum step length would accommodate.

In the scheme considering multiple transducers for a single assembly identification, with each notch holding one step, a number of encoding schemes were considered for their resiliency against loss of function of some of the transducers: for some schemes up to 8 of 12 transducers could fail while still guaranteeing that the fuel assembly ID can be recovered [7]. In the present example, the entire fuel assembly ID is preserved as long as the single transducer that reads it still functions. If the transducer fails, the entire fuel assembly ID cannot be read. To compensate for this possibility, the fuel assembly ID can be duplicated in copy notches with their own transducers in the same fuel assembly. Perhaps as many as four or more copy notches might be implemented in a fuel assembly, depending on practical considerations for the number of transducers and notches that could be implemented.

CONCLUSIONS

To enhance the safeguardability of fast reactors with opaque liquid metal coolant through innovative verification techniques, it has been proposed that ultrasonic measurements of in-core fuel assembly IDs could be implemented [7]. The present work extends this proposal by considering an alternative multi-step notch implementation that reduces the number of required ultrasonic transducers. Such an alternative is beneficial for implementation in SMRs that have a significantly larger number of in-core fuel assemblies.

ACKNOWLEDGEMENTS

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