PULSED TRIGA® REACTOR AS SUBSTITUTE FOR LONG PULSE SPALLATION NEUTRON SOURCE

W. L. Whittemore
General Atomics[1]

ABSTRACT

TRIGA® reactor cores have been used to demonstrate various pulsing applications. The TRIGA reactor fuel (U-ZrH_x) is very robust especially in pulsing applications. The features required to produce 50 pulses per second have been successfully demonstrated individually, including pulse tests with small diameter fuel rods. A partially optimized core has been evaluated for pulses at 50 Hz with peak pulsed power up to 100 MW and an average power up to 10 MW. Depending on the design, the full width at half power of the individual pulses can range between 2000 μsec to 3000 μsec.

Until recently, the relatively long pulses (2000 μsec to 3000 μsec) from a pulsed thermal reactor or a long pulse spallation source (LPSS) have been considered unsuitable for time-of-flight measurements of neutron scattering. More recently considerable attention has been devoted to evaluating the performance of long pulse (1000 to 4000 μs) spallation sources for the same type of neutron measurements originally performed only with short pulses from spallation sources (SPSS). Adequate information is available to permit meaningful comparisons between CW, SPSS, and LPSS neutron sources. Except where extremely high resolution is required (fraction of a percent), which does require short pulses, it is demonstrated that the LPSS source with a 1000 μsec or longer pulse length and a repetition rate of 50 to 60 Hz gives results comparable to those from the 60 MW ILL (CW) source. For many of these applications the shorter pulse is not necessarily a disadvantage, but it is not an advantage over the long pulse system. In one study, the conclusion is that a 5 MW 2000 μsec LPSS source improves the capability for structural biology studies of macromolecules by at least a factor of 5 over that achievable with a high flux reactor.

Recent studies have identified the advantages and usefulness of long pulse neutron sources. It is evident that the multiple pulse TRIGA reactor can produce pulses comparable to those from the LPSS but at a considerably lower cost. Using the well proven and developed TRIGA reactor technology for this application would avoid the many complexities associated with either increasing the power of spallation sources or increasing the pulse length for the LPSS. An increasing problem with the spallation target is the thermal fatigue in the LPSS, a problem avoided in the pulsed TRIGA reactor. A properly designed cold source installed in a D_2O reflector of the multiple pulsed TRIGA reactor can provide pulsed cold neutrons for neutron guides used in many neutron scattering applications.

1. INTRODUCTION

Until recently time-of-flight studies of neutron scattering have been performed with short pulses of source neutrons. Short pulses from spallation sources (SPSS) were considered essential and were engineered for pulse widths of about one microsecond. Recently, an awareness has been developing that longer pulses are also suitable for scattering measurements. The 750 μs pulse from the IBR-2 Russian fast reactor is such an example. The Finnish group under Hiismäki[1)] has successfully applied the RTOF method of the Fourier chopper to the IBR-2 fast reactor *without an additional chopper* for the measurement of metal strain. Use of the entire thermal neutron pulse in this application greatly enhances the efficiency of data collection.

A major effort has been devoted to identifying the advantages of long pulse spallation sources (LPSS). Conrad[2)] has evaluated the performance of long duration pulses (1500 μsec to 4000 μsec) at 60 Hz for Small Angle Scattering measurements. Jauch[3)] has demonstrated that the LPSS system

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[1] 10240 Flanders Court, San Diego, CA 92121 USA

cannot be used with epithermal neutrons but works exceedingly well with thermal neutrons. In particular, a 5 MW 2000 μs LPSS system can improve the statistical accuracy of structural biology measurements on macro molecules at least five times compared to that achievable at a 60 MW high flux reactor. Hjelm et., al.[4] have performed a careful analysis of a LPSS system for Small Angle Scattering. The performance of the optimized LPSS instrument was found to be comparable with present world standard instruments. Except where extremely high resolution (fraction of a percent) is required, which requires short pulses, the LPSS sources with long pulses (≥ 1000 μsec) and repetition rates of 50 to 60 Hz give results comparable with those from the 60 MW ILL reactor source. Fitzsimmons[5] has analyzed neutron reflectometry with steady state and pulsed neutron sources. He predicts that future spallation sources will have pulse lengths considerably greater than at present.

The above described developments indicate that a growing need exists for pulsed neutron sources with long pulses (1000 to 4000 μsec) at a repetition rate of 50 to 60 Hz. In 1966 the TRIGA reactor was first shown to be capable of pulsing to high power levels at a repetition rate of 50 Hz with pulse widths of 2000 to 3000 μsec[6]. Development of the robust TRIGA LEU fuel has supported the concept of a multiply pulsed TRIGA reactor and makes the concept practical.

2. TECHNICAL DEVELOPMENTS THAT SUPPORT A MULTIPLE PULSING TRIGA

2.1 Small Diameter TRIGA Fuel for Higher Power Operation

Although the present high power pulsed TRIGA reactors use a large diameter fuel (38 mm), the smaller diameter fuel developed originally for higher power steady state power levels (5-15 MW) has also been successfully tested in a long series of applications. The smaller diameter fuel (12.95 mm) has been used in the high power steady state TRIGA reactor in Romania (14 MW) with great success[7] continuously since 1980 with a fuel burnup of 13000 MWD for the core. The local burnup in certain of these fuel rods reached 83%. The smaller diameter TRIGA fuel using the Low Enriched Uranium (LEU) successfully completed all the RERTR fuel tests for LEU fuel with fuel rod burnup reaching 65% for some rods. To demonstrate the robust nature of the small diameter TRIGA LEU fuel, several of the 12.95 mm diameter TRIGA LEU fuel rods were tested in the large pulsing reactor at General Atomics and underwent a long series (~300) of high power pulses plus a very large number of power cycles (zero power to full steady state power) without any evidence for fuel distress.

The remarkably successful development of the smaller diameter TRIGA fuel rod in the LEU format offers considerable advantages for the proposed rapidly pulsed TRIGA producing 50 pulses per second. Considerably lower peak fuel temperatures will result for the same average power levels compared to use of the standard 38 mm diameter fuel rods assumed in the early calculations[6] for the TRIGA reactor. Since the TRIGA fuel now proposed for the multiple pulsing reactor is the fully qualified LEU fuel, all requirements for non-proliferation will be satisfied. Furthermore, the proposed TRIGA fuel with its erbium burnable poison will provide an exceptionally long core life, a considerable advantage for neutron beam experiments since the normal operating cycle can be extended to several months if desired. In addition, the quantity of erbium can be altered to enhance the prompt negative temperature coefficient of reactivity.

3. THE MULTIPLY PULSED TRIGA REACTOR FOR NEUTRON BEAM EXPERIMENTS

3.1 Principle of Multiply Pulsed TRIGA Reactor.

A modification of the pulsing mechanism traditionally used with pulsed TRIGA reactors is discussed which will permit the reactor to be pulsed repetitively many times per second to a peak power level in the 100-megawatt region with the power between pulses of the order 1.0 megawatt. All of the inherent safety features associated with the large prompt negative coefficient of reactivity are retained for the proposed reactor.

It is not sufficient simply to pulse the reactor to a power level of the order 100 MW by adding a step insertion of positive reactivity and relying on the prompt negative temperature coefficient to limit the peak since the resulting pulse will be quite wide (> 0.010 sec) with a "tail" which contains a significant amount of unwanted energy. Rather, it is proposed to shape the pulse through the successive insertions of positive and negative reactivity. The programmed insertion of negative reactivity will have the beneficial effect of strongly perturbing the reactor flux and will result in a substantial reduction of the trailing edge and tail of each pulse. Taking advantage of this feature, one can add a larger amount of positive reactivity than actually needed to produce the desired peak power, relying on the clipping to limit the peak as well as the tail of the pulse. The advantage of adding as much positive reactivity as possible in this manner is to decrease the reactor period and thus reduce the pulse width. It is essential to reduce as much as possible the tail of the pulse (due fundamentally to delayed neutrons) as well as the width of the pulse in order to reduce the average power. The insertion of negative reactivity, as proposed here, serves both these needs.

For slow neutron beam research, the low power of the reactor between pulses will contribute to improved signal-to-noise ratio compared with the use of a reactor operating at a steady-state power sufficient to produce a source flux of 10^{15}n/cm^2.s. Further improvement of the signal-to-noise ratio is possible without loss of neutron beam intensity through the use of a partial D_2O reflector tank and tangential beam tubes.

The pulse width at half-height will be on the order of 2000 or 3000 μsec. This is considerably wider than desired for some neutron beam research where pulse widths of the order 10 to 20 μsec are desired. However, the broad source pulses can be efficiently used for the RTOF technique based on the Fourier Chopper, as noted in Section 1.0 above. Also, the broad pulses are suitable for the applications noted above for the LPSS sources. The pulsed thermal reactor considered here also provides an excellent opportunity to produce “cold” neutrons in a cryogenic source since the cold source can be of optimum size. The cold source can thus be designed for maximum intensity of “cold” neutrons and not be limited in size or “poisoned” as usual with cryogenic sources used with spallation sources.

3.2 **Description of Pulsed Reactor System**

The proposed reactor system is expected to use the 12.95-mm diameter fuel rods containing TRIGA LEU UZrH-Er fuel. The uranium loading is expected to be 30 wt-% or 45 wt-%, depending on the core lifetime desired. The average power for the core will be on the order of 10 MW. Forced cooling with light water would be used. Similar thermal hydraulic considerations have been successfully applied to the Romanian 14-MW reactor[7)]. The pulsing mechanism would be a sequenced insertion of positive and negative reactivity. A rough conceptual sketch of the core and one possible pulsing mechanism consisting of one or two wheels is shown in Figure 1. The core and pulsing mechanism will be located in a usual TRIGA shield with possibly a partial D_2O reflector surrounding the core. Presumably the wheel(s) will spin in a water-free environment, though this detail has not yet been settled.

Within the general framework discussed above, a number of parameters for the pulsed system can be varied to satisfy various needs. Among these parameters will be notably average power and pulse frequency. Although other selections can be made, this study has been aimed at providing a suitable system with an average power in the range of 4 to 10 megawatts with a pulse rate of 50 per second. Table 1 is a summary of the results of two different sets of calculations for the large diameter fuel made with the General Atomics kinetics code BLOOST[8)]. Also shown in Table 1 are results for the small diameter fuel. For this fuel, the kinetic parameters are changed which necessitates a reduction in positive reactivity insertion.

Reactivity Sequence

The schedule for reactivity (positive and negative) insertions needed to provide the results or Table 1 for the large diameter fuel is shown in Figure 2. The reactor is brought to a steady-state power with the insertion of \$3.00 excess reactivity (above cold critical). For one schedule of pulsing (shown by the solid curve of Figure 2 and corresponding to the uniform rate of insertion of +\$5.50 reactivity followed by the uniform rate of insertion of -\$6.00 reactivity) a peak power of 40 megawatts is produced. If the insertion of negative reactivity is accelerated as shown by the dotted curve in Figure 2, the narrower pulse results in a 43 percent reduction in average power while the peak power is reduced by only 28 percent. Figure 3 shows the actual time dependence of the equilibrium pulses associated with these two sequences of reactivity insertions. The average core fuel temperature is about 200°C for the smaller diameter fuel proposed for this system. Since the smaller diameter fuel rods can accommodate larger peak power levels and somewhat increased average power with still acceptable fuel temperatures, a slight change in phase of the pulsed reactivity insertion prior to the insertion of the -\$6.00 can increase the peak pulsed power levels to 100 MW or more. For larger peak powers (up to ~100 MW), the average power would be increased to about 10 MW and the average core temperature would be increased to about 290°C.

Table 1

Summary of Operational Characteristics
for an Unoptimized System

	Uniform Pulsing and Clipping *		Accelerated Clipping *		Accelerated Clipping**
Fuel Diameter	38	12.95	38	12.95	12.95
Pulses per second	50		50		50
Reactivity Insertion, \$	5.5	4.25	5.5	4.25	4.25
(δk/k)	(0.0385)	(0.030)	(0.395	(0.030)	(0.030)
Shutdown Reactivity, \$	-8.0		-8.0		-8.0
Peak Power (MW)	40		29		72.5
Average Power (MW)	7		4		10
Minimum Power between Pulses (MW)	0.6		0.5		1.25
Pulse Width at half power (sec)	3×10^{-3}		2×10^{-3}		$\sim 2 \times 10^{-3}$
Peak Thermal Leakage Flux in reflector (n/cm^2-sec)	0.5×10^{15}		0.4×10^{15}		1×10^{15}
Prompt Neutron Lifetime, μsec	35	17	35	17	~17
Prompt Negative Temperature Coefficient ((δk/k°C)	12×10^{-5}	6×10^{-5}	12×10^{-5}	6×10^{-5}	6×10^{-5}
Average Fuel Temperature (°C)	365	200	355	190	290
Temperature Variation in Fuel During Pulse (°C)	~1	~1	~1	~1	~1

*Performance for 12.95 mm fuel adjusted to equal that for 38mm diameter fuel
**Performance partially optimized for 12.95 mm diameter fuel

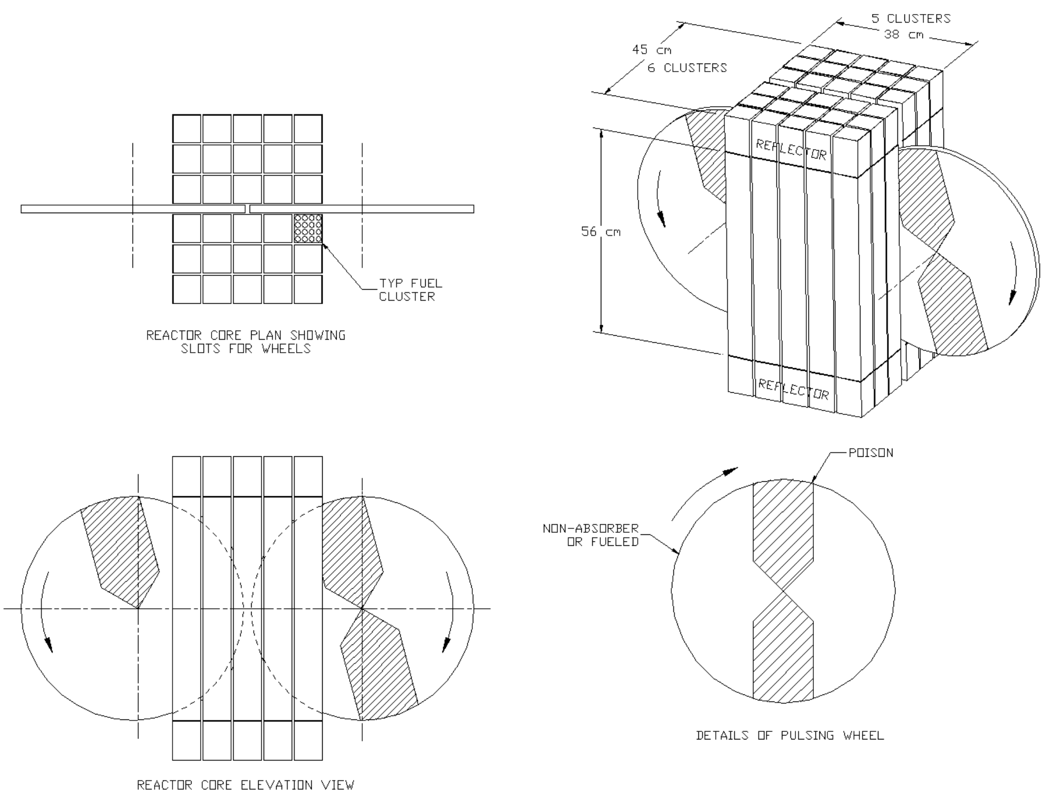

Figure 1: A sketch showing the relation of a pulsing wheel and core. The arrangement of poison and non-poison is also shown for the prime pulsing wheel and a possible auxiliary "clipping" wheel.

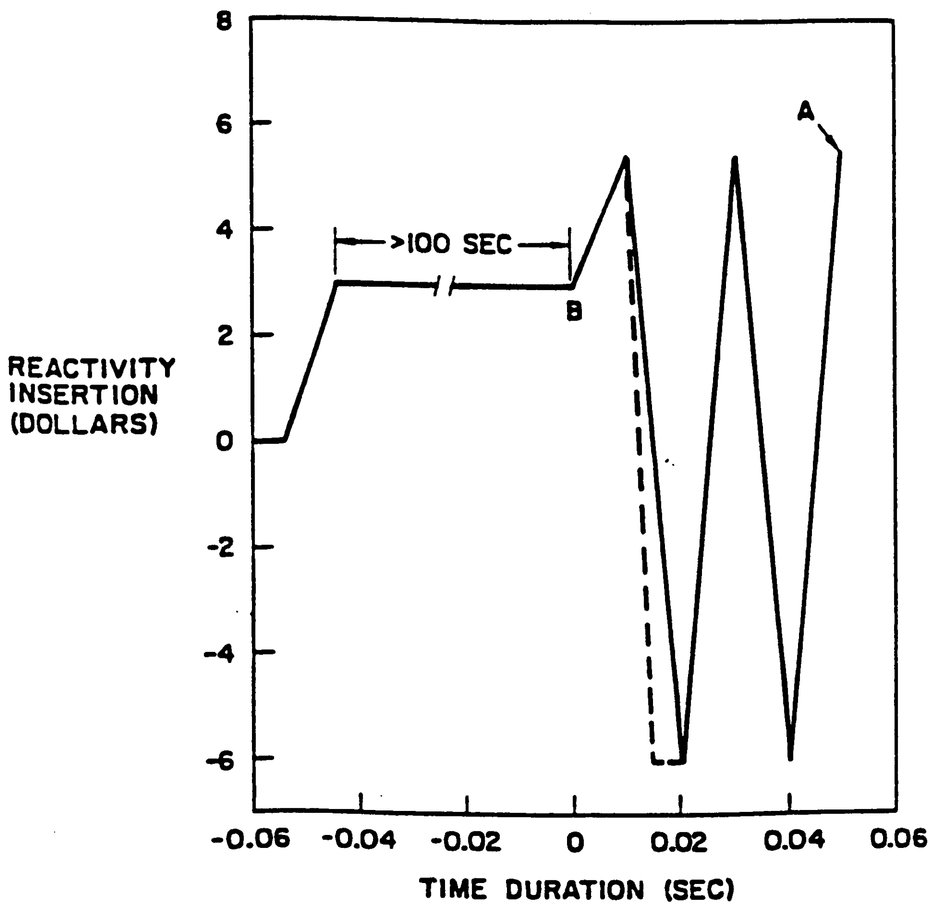

Figure 2: A sketch showing the time dependence of reactivity insertions. Normally the oscillatory behavior is continued indefinitely. For accident analysis, the insertion is assumed to be halted at point A.

An additional benefit accrues from the postulated use of a wheel which provides two Pulses for each revolution. For 50 pulses per second, its rotational speed would be 25 rps or 1500 rpm, a relatively low speed. There should be no difficulty in obtaining the necessary mechanical strength of the rotating members which might have a diameter as large as 60 cm. Of course, an auxiliary wheel of about the same size used as described above would rotate at twice this speed.

3.3 **TRIGA LEU Characteristics**

The heat removal rate and coolant flow characteristics for the TRIGA reactor calculations summarized in Table 1 are very similar to those for the Romanian 14 MW TRIGA reactor[7)]. The Romanian reactor has demonstrated the robustness of the 12.95-mm diameter fuel. In operation for 20 years with more than 13000 MWD not one fuel rod released any fission products. This operation included two unplanned reactivity excursions[7)] also with no fuel rod damage. Since the multiple pulsed TRIGA reactor as proposed will have essentially steady state characteristics (the fuel temperature varies only 1°C during pulsing), the performance of this fuel for multiple pulsing is expected to provide the same excellent, long term performance.

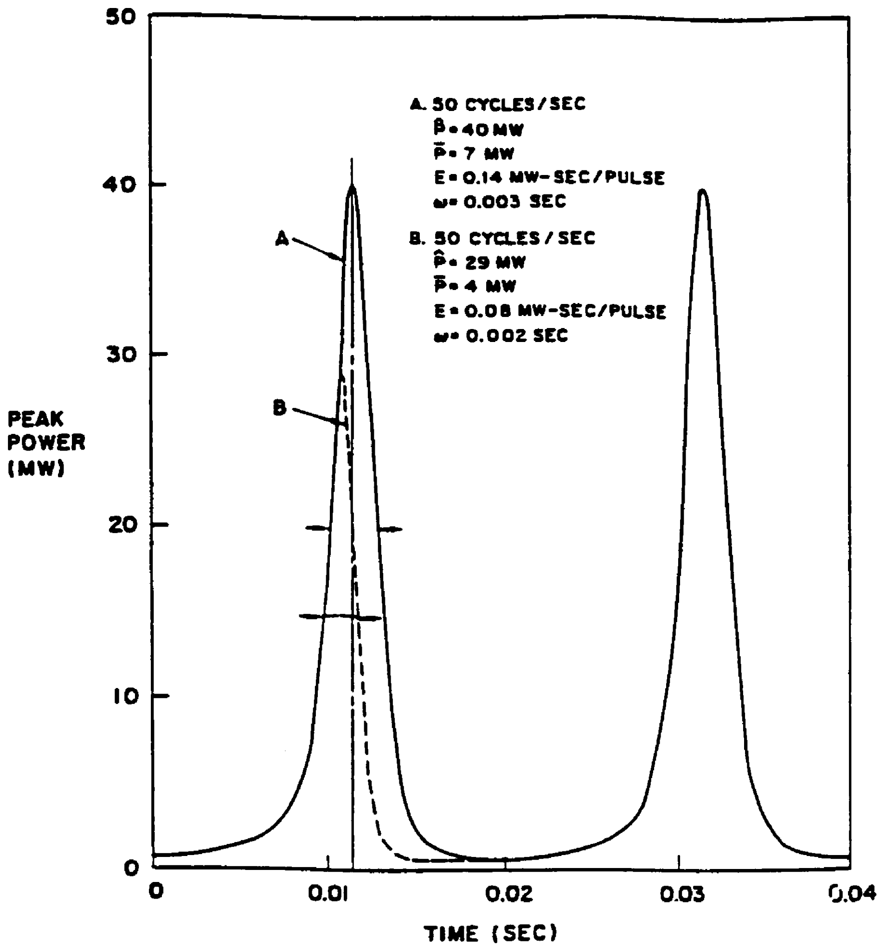

Figure 3: The time dependence of the equilibrium pulses for a uniform rate of inserting positive and negative reactivity. The dotted curve results if the insertion of negative reactivity is accelerated.

While considering temperature effects, it is worthwhile noting that the temperature coefficient does not provide the shutdown mechanism on a time scale suitable for the rapid pulsing rate. Before the temperature rise becomes significant for this purpose, a shutdown mechanism is provided by the mechanical addition of negative reactivity. However, the prompt negative temperature coefficient is still available as an inherent safety feature. For the small diameter fuel the prompt neutron lifetime is assumed to be 17 μsec and the prompt negative temperature coefficient is assumed to be 6×10^{-5} k/k °C. In order that the small diameter fuel with its different kinetic parameters shall have the same safety, the positive reactivity insertion is reduced. It is adjusted downward (to $4.25) to assure that the peak energy insertion per pulse ($E_p = 2C\frac{\Delta k}{\alpha}$) shall be the same as for the well demonstrated performance of the large diameter fuel. These values are included in Table 1.

The core life for the multiple pulsed TRIGA reactor will depend on the fuel type selected; that is, 30 wt-% or 45 wt-% uranium loading. Depending on the fuel type selected and the quantity of erbium burnable poison used, the core life can equal or exceed 5000 MWD before additional fuel will be required.

3.4 Safety Considerations

Safety of the proposed system has been partially demonstrated by the performance of standard pulsed TRIGA reactors in which single reactivity insertions of +$5.00 have been safely made in a cold core. The resulting peak energy release of ≤ 1.0 megawatt-sec per fuel element caused no indication of fuel element distress. In additional pulsing tests of fuel elements, the calculated peak temperature in some elements has safely reached as high as 1170°C with a hydrogen-to-zirconium ratio of about 1.65. Thus, a fuel-moderator element having a lower hydrogen-to-zirconium ratio of 1.58 to 1.60 can safely reach peak temperatures of ~1250°C. Additional demonstration of the safety of the core during pulsing is provided by the two unplanned reactivity excursions[7] in the 14 MW Romanian core with the 12.95-mm diameter fuel rods.

Since calculations have agreed well with the observed reactor parameters for the pulsed standard TRIGA, it is reasonable to place confidence in the same calculational techniques to compute the pulsing characteristics of the proposed system for a maximum credible insertion. The worst accident for the various systems of pulsing proposed above occurs when $5.50 positive reactivity (for the large diameter fuel or $4.25 for the small diameter fuel) is inserted in the warm core (point A in Figure 2) and no subsequent negative reactivity is provided. Such a case would occur if the rotating wheel were to stop rather abruptly or to fly out of the core. A transient analysis indicates that the peak power and energy released in such an event would be 11,300 megawatt and 52 megawatt-sec, respectively, with a resulting momentary peak temperature in the hottest fuel element of about 1250°C which falls quickly to a lower temperature. With a hydrogen-to-zirconium ratio of 1.58-1.6 for the proposed system, the equilibrium pressure corresponding to a peak temperature of 1250°C for the maximum credible reactivity insertion is no higher than already experienced in deliberate pulse tests. For comparison purposes, it may be further noted that the NSRR TRIGA reactor routinely produces peak power pulses of more than 20,000 MW with energy release of more than 100 MW-sec.[9].

Appropriate design parameters, including the hydrogen-to-zirconium ratio and the heat transfer characteristics of the core, can thus be selected to assure complete safety for the reactor system in this maximum contingency.

4. SUMMARY

Calculations have verified that a thermal neutron reactor of the TRIGA type using U-ZrH fuel elements and light water coolant can be operated to give routinely many pulses per second. Peak pulses up to about 100 megawatts and peak thermal neutron leakage fluxes up to $\sim 10^{15}$ n/cm^2.s can be achieved. Pulsing can be accomplished with a wheel with relative ease since there is no requirement on precise mechanical location of the wheel within the core slot. It is envisioned that the proposed system would be constructed within a normal, above-ground concrete shield and would appear quite similar in appearance to a normal 10 MW TRIGA reactor. To achieve the best signal-to-noise ratio for some neutron experiments as discussed earlier, a heavy water reflector could replace a part of the light water core reflector and be used to feed the core-end of tangential beam tubes. In addition, a cryogenic source of “cold” neutrons could be incorporated as desired for experiments. The reverse time-of-flight neutron scattering analysis system based on the Fourier chopper would be able to make singularly efficient use of the long duration pulses from the rapidly pulsed TRIGA reactor. Using the rapidly pulsed TRIGA reactor concept with its important elements of inherent safety and economy, it is possible to produce an intense source of neutrons for neutron beam research that is remarkably competitive with a long pulse spallation source.

ACKNOWLEDGMENTS

The writer acknowleges with gratitude the helpful discussions with G. B. West and R. L. Sherman.

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