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A CONTINUOUSLY PULSED TRIGA REACTOR: AN INTENSE SOURCE FOR NEUTRON SCATTERING EXPERIMENTS

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ABSTRACT

A variety of configurations of TRIGA reactor cores has been used to demonstrate various pulsing applications, including pulses repeated much more frequently than the more normal six pulses per hour. Because of the renewed interest in sources for neutron beams with intensities ranging up to 10^{16} n/cm.s, the continuously pulsed TRIGA reactor has been reexamined. The TRIGA reactor fuel ($U\text{-}ZrH_x$) has been demonstrated to be very robust especially for pulsing applications. To produce 25 to 50 pulses per second, additional features are available which also have been demonstrated individually. These include the availability of small diameter fuel rods capable of producing high power but with manageable peak fuel temperatures and control features adequately efficient to provide the required rapidly changing reactivity. The TRIGA fuel has been subjected to very great burnup (>65%) with no problem of fuel stability and with all the safety features of TRIGA fuel intact. It appears that an average power of 10 to 16 MW will be sufficient to provide the desired intensities of neutrons. The availability of these additional features makes the rapidly pulsed TRIGA reactor an important candidate for thermal neutron scattering experiments.

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1. INTRODUCTION

Because of the demise of the Advanced Neutron Source (ANS) project and the continued interest in constructing even larger spallation sources for neutron scattering research, it appears useful to reexamine the concept of a continuously pulsed TRIGA reactor. Kursted and Miley[1] reported early work (1971) on a rapidly pulsed TRIGA reactor which they pulsed at rates up to 3 per minute. Considerable experimental research has been devoted to efforts to pulse a TRIGA reactor at rates up to at least 10 per minute and perhaps 30 per minute.

The successful development of a TRIGA reactor core specifically designed to produce peak power pulses of 100 MW or more at rates of up to 50 per second can provide a thermal neutron source intensity of up to 10^{16} n/cm^{2}·s that is competitive with multiple pulsed fast reactors and the pulsed spallation sources. The relative simplicity of the pulsed TRIGA system contrasts strongly with the complexity of the typical BeV proton synchrocyclotron used with the various spallation sources for neutron production.

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[3] 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 (9.4 mm) has been used in the high power steady state TRIGA reactor in Romania (14 MW) with great success[4] 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[5] 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 9.4 mm diameter TRIGA LEU fuel rods were tested in the large pulsing reactor at General Atomics[6] 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 requiring up to 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[7] for the continuously pulsed TRIGA reactor. Since the TRIGA fuel now proposed for the multiple pulsing reactor will use 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 operating cycle can be extended to several months if desired.

2.2. New Type of Pulsing Mechanism

The use of standard control rods in single or banked configuration with stepping motor driving mechanism is well established for steady state operation. For pulsing TRIGA reactors even as rapidly as 10 per minute, the standard pneumatically operated pulsing mechanism is sufficient. For the production of pulses at rates up to 50 per second, the use of a rotating wheel that alternately introduces poison and fuel or poison and non-poison can be considered. This would be similar in some degree to that used successfully with the IBR-2 fast reactor facility in Dubna, Russia.

A new type of pulsing mechanism for fission reactors that does not involve mechanical motion has been proposed by Bowman[8,9]. This system of reactor control depends on the demonstrated property of ^{3}He polarization by laser light. The reduction in reactivity control results from application of laser light to ^{3}He inside a control rod. Since the very large $1/v$ absorption cross section of ^{3}He is associated with only one of the two spin states that can be formed when S-wave neutrons are absorbed, the absorption cross section decreases by a factor of two for fully polarized ^{3}He. When the laser light is turned off, the polarization of ^{3}He decays thus increasing the resulting reactivity effects. Unfortunately, the normal half life for polarization decay in this system would be long, about 12 hours. However, application of a small pulsed magnetic field produced by means of a coil surrounding the control rod can depolarize the ^{3}He is less than a millisecond. Thus the increase in reactivity insertion can be very rapid for this system and could be of significant value in the rapidly pulsed TRIGA system.

If the ^{3}He reactivity control system could be developed to produce a rapid enough polarization, this control system would contribute significantly to the safety of the overall system since the need for the rotating wheel would disappear.

2.3 Improved Instrumentation for Neutron Scattering Measurements with a Pulsed Neutron Source

The traditional methods to perform thermal neutron elastic and inelastic scattering measurements are based on either some form of neutron diffractometer or time-of-flight techniques. Both of these general approaches are used with steady state neutron sources such as the high power reactor (ILL) at Grenoble, France. For the time-of-flight applications, it has usually been necessary to use a beam chopper to provide the initial narrow pulse widths required for high resolution scattering measurements.

In more recent times, a high energy accelerator ($\sim$1 BeV protons) has been used with a spallation target to produce the short pulses of thermal neutrons required for neutron scattering measurements. For many applications it has also been necessary to use *"poisoned"* moderators to achieve the required narrow pulses especially with cold neutron sources. Such a poisoning technique does indeed achieve the required narrow source pulses of neutrons but at the cost of reduced neutron source intensities.

In the mid-1960s, Whittemore and associates developed the high efficiency Fourier Chopper[10] and obtained a U.S. patent[11]. At about the same time, Dr. Hiismaki and associates in Finland developed a modified approach based on a similar Fourier Chopper concept. In a practical manifestation of the Finnish approach, the so-called Reverse Time-of-Flight (RTOF) technique has been applied to scattering studies using a steady state reactor source[12]. The Geesthacht and Finnish group have close cooperation[13] with the Russian group in Leningrad and with the IBR-2 group at Dubna. A great advantage of the RTOF method with the Fourier Chopper is that it can be used without an additional phased chopper for the broad pulses produced by IBR-2 and possibly by the multiple pulsed TRIGA system. Elimination of the additional chopper greatly enhances the efficiency with which the pulsed neutron sources are used since source neutrons in the entire broad pulse (or at least most of the broad pulse) are accepted for the RTOF technique.

3. THE CONTINUOUSLY PULSED TRIGA REACTOR FOR NEUTRON BEAM EXPERIMENTS

3.1 Principle of Continuously Pulsed TRIGA Reactor.

A modification of the pulsing mechanism traditionally used with pulsed TRIGA reactors is suggested which will permit the reactor to be pulsed repetitively many times per second to a peak power level in the 40 to 400-megawatt range with the power between pulses of the order 0.5 megawatt. All of the inherent safety features associated with the large negative prompt 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 then relying on the prompt negative temperature coefficient to limit the peak power since the resulting pulse will be quite wide ($>$ 0.010 sec) with a *"tail"* which contains a significant amount of unwanted energy and of limited repetition rate. 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 overall pulse width. It is also 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 positive and negative reactivity, as proposed here, serves both these purposes.

For slow neutron beam research using time-of-flight techniques, 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} to 10^{16} n/cm^2·s. Further improvement of the signal-to-noise ratio is possible with additional gain of neutron beam intensity through the use of a D_2O reflector tank and tangential beam tubes.

The pulse width at half-height will probably be on the order of 3 to 6 milliseconds. This is considerably wider than desired for neutron beam research where pulse widths of the order 5 to 10 μsec are desired. However, the broad source pulses can be efficiently used for the RTOF technique based on the Fourier Chopper, as discussed in Section 2.3 above. Alternately, Fermi choppers can be used to provide the desired narrow pulses. 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 9.4-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 TRIGA 14-MW reactor[4] and the standard 10 MW TRIGA LEU reactor[14]. 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 D_2O surrounding at least part of 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

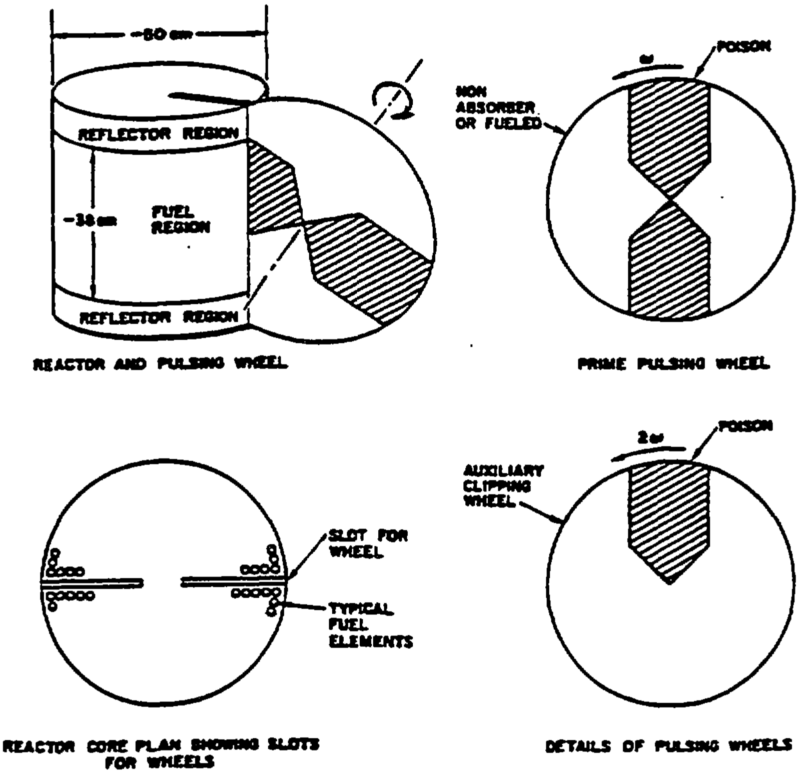

Figure 1: *A sketch showing the relation of a pulsing wheel and core. The arrangement of poison and non-poison is also shown for the prime pulsing wheel and a possible auxiliary "clipping" wheel.*

average power and pulse frequency. Although other selections have been made, the early study was aimed at providing a suitable system with an average power in the range of 4 to 7 megawatts with a pulse rate of 50 per second. Table 1 is a summary of the results of two different sets of calculations made with the General Atomics kinetics code BLOOST[15]. More recent evaluations have considered fewer pulses per second but with much larger peak power levels.

Table 1

Summary of Operational Characteristics for an Unoptimized System

	Uniform Pulsing and Clipping	Accelerated Clipping
Pulses per Second	50	50
Peak Power (MW)	40	29
Average Power (MW)	7	4
Minimum Power between Pulses	0.6	0.5
Pulse Width at half power (sec)	3×10^{-3}	2×10^{-3}
Energy in Pulse, MW-sec	0.14	0.080
Peak Thermal Leakage Flux in reflector (n/cm^2-sec)	0.5×10^{15}	0.36×10^{15}
Prompt Neutron Lifetime, μsec	12	12
Prompt Negative Temperature Coefficient ($\delta k/k°C$)	6×10^{-5}	6×10^{-5}
Average Fuel Temperature in 38 mm (9.4 mm) diam. fuel rods (°C)	365 (300)	355 (275)
Temperature Variation in Fuel During Pulse (°C)	~1	~1

3.3 **Reactivity Sequence**

The schedule for reactivity (positive and negative) insertions needed to provide the results of Table 1 is shown in Figure 2. The reactor is brought to a steady-state power with the slow 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 (above zero reactivity) followed by the uniform rate of insertion of -\$11.50 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 300°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 still with acceptable fuel temperatures, a slight delay in the insertion of the -\$11.50 can increase the peak pulsed power levels to 100 MW or more. For larger peak powers (above ~100 MW), the average power would be increased to about 10 to 15 MW.

It may be noted that a calculation of the reactivity worth of the poison section of a rotating wheel has been made; its worth was calculated to be \$13.90, well in excess of the \$11.50 discussed above. A satisfactory design can be based on alternate sections of poison and non-poison. In this case, the reactor would have \$5.50 reactivity inserted with regular control rods. The rotation of the wheel would then produce the reactivity sequence shown by the solid curve in Fig. 2. If it is desired to clip the trailing edge of each pulse by accelerating the insertion of negative reactivity, this could be accomplished by the use of a second wheel with poison as shown in Fig. 1 and rotated at twice the speed.

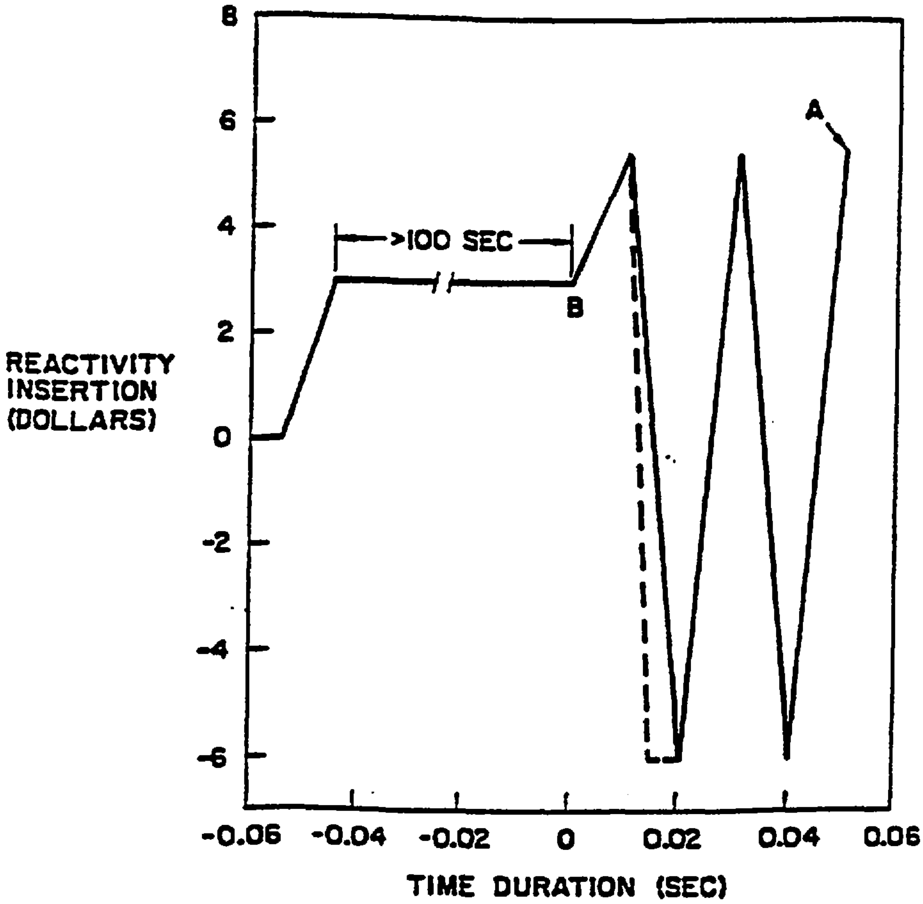

Figure 2: *A sketch showing the time dependence of reactivity insertions. Normally the oscillatory behavior is continued indefinitely. For accident analysis, the insertion is assumed to be halted at point A.*

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.

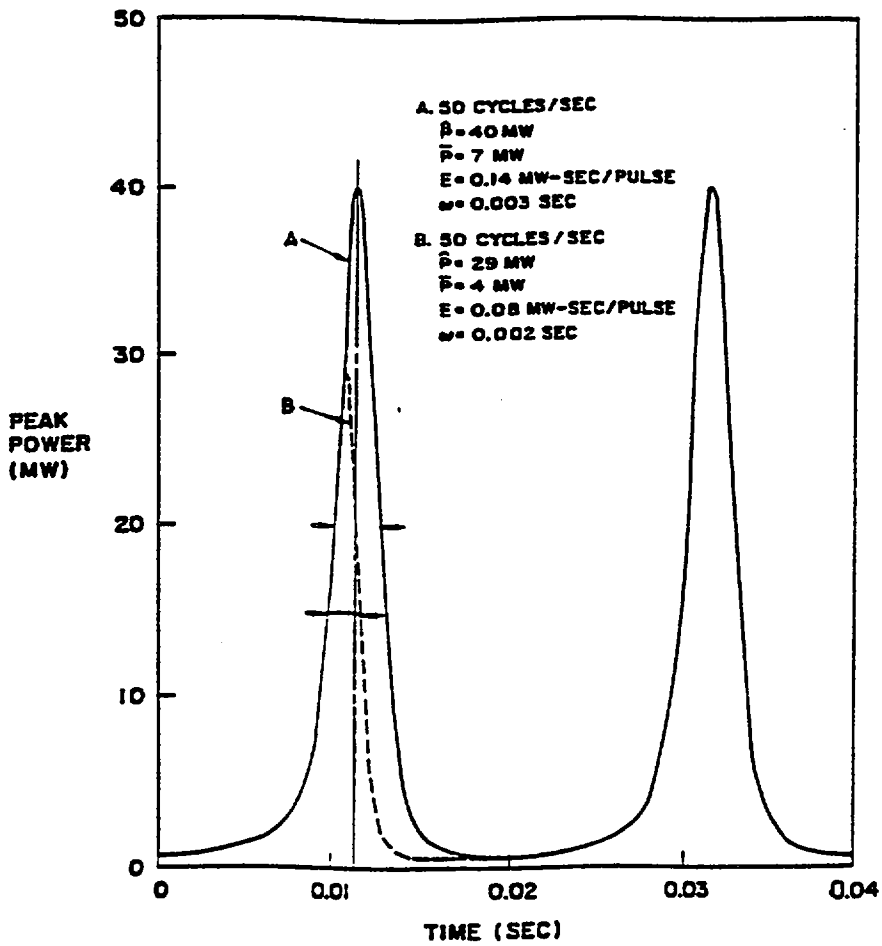

Figure 3: *The time dependence of the equilibrium pulses for a uniform rate of inserting positive and negative reactivity. The dotted curve results if the insertion of negative reactivity is accelerated.*

The potential for vibration and the hazards associated with a rotating wheel could be eliminated if the polarized ^3He control system with adequate reactivity and frequency response could be developed. At this time, the adequacy of a ^3He system has yet to be demonstrated for the proposed multiple pulsed TRIGA system.

Variations in the timing between the positive and negative reactivity sequence can increase the magnitude of the peak power. Decreasing the number of pulses per second and using the features provided by the second rotating wheel (as discussed above) can limit the average power level to about 10 MW. An average power level of about 10 to 15 MW is easy to cool and is well demonstrated for the TRIGA case[4]. The data in Table 2 give an idea of higher performance levels of the continuously pulsed TRIGA where the average power level is constrained to about 16 MW.

Table 2

Summary of Estimated Performance Levels for a Continuously Pulsed TRIGA Reactor

$\hat{P}$ (MW)	$\bar{P}$ (MW)	Flux at Core End of Beam Ports (n/cm^2.s)	Pulses per second
29	4	5.5×10^{14}	50
40	7	7.6×10^{14}	50
140	10	2.7×10^{15}	35
400	16	7.6×10^{15}	24

3.4 TRIGA LEU Characteristics.

The heat removal rate summarized in Table 1 and coolant flow characteristics for this TRIGA reactor are very similar to those for the Romanian 14 MW TRIGA reactor[4]. The Romanian reactor has demonstrated the robustness of the 9.4-mm diameter fuel. In operation for more than 13 years with more than 13000 MWD not one fuel rod released any fission products. This operation included two unplanned reactivity excursions[4], also with no fuel rod damage. Since the multiple pulsed TRIGA reactor as proposed herein will have essentially steady state characteristics (the fuel temperature varies only about 1 °C during pulsing), the performance of this fuel for multiple pulsing is expected to provide the same excellent, long term performance.

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.

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. The prompt neutron lifetime is calculated to be 12 μsec and the prompt negative temperature coefficient is calculated to be 6×10^{-5} $\Delta k/k/{}^\circ C$. These are characteristics computed for a core composed of the smaller diameter, more highly loaded fuel rods.

3.5 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 have 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[4] in the 14 MW Romanian core with the 9.4-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 reactivity insertion. The worst accident for the various systems of pulsing proposed above occurs when $5.50 positive reactivity 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 especially since the regular control rods would drop into the core to terminate the described event. 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 total energy release of more than 100 MW-sec[3].

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 reactor of the TRIGA type using U-ZrH fuel elements and light water coolant can be operated to give continuously many pulses per second. Peak pulses in the range 50 to more than 100 megawatts and peak thermal neutron leakage fluxes of nearly $\sim 10^{16}$ 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. A more simple pulsing system may be possible with a polarized ^{3}He control rod if adequate reactivity and frequency of polarization and depolarization can be developed. It is envisioned that the proposed reactor system would be constructed within a normal, above-ground concrete shield and would appear quite similar to a normal 5-10 MW

TRIGA reactor. To achieve the best signal-to-noise ratio for some neutron experiments as discussed earlier, a heavy water reflector would replace at least 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 few millisecond duration pulses from the rapidly pulsed TRIGA reactor. Using the rapidly pulsed TRIGA reactor concept, it becomes possible to produce a competitive and intense source of neutrons for neutron beam research purposes, based on a reactor which possesses important elements of inherent safety and economy. It should be noted that specified frequency of pulses and peak power levels were chosen for illustrative purposes. A wide variety of alternative operating conditions can be chosen to meet specific user requirements.

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