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2011

EMERGENCY PREPAREDNESS AND RESPONSE

Generic Procedures for Response to a Nuclear or Radiological Emergency at Triga Research Reactors

PUBLICATION DATE: SEPTEMBER 2011

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GENERIC PROCEDURES FOR RESPONSE TO A NUCLEAR OR RADIOLOGICAL EMERGENCY AT TRIGA RESEARCH REACTORS

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2011

Emergency Preparedness
and Response

GENERIC PROCEDURES FOR RESPONSE TO A NUCLEAR OR RADIOLOGICAL EMERGENCY AT TRIGA RESEARCH REACTORS

The development of this publication has been supported by a grant from Norway through the IAEA extra budgetary programme on safe nuclear energy in Romania

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NUCLEAR OR RADIOLOGICAL EMERGENCY
AT TRIGA RESEARCH REACTORS
ATTACHMENT 1 (2011)
IAEA, VIENNA, 2011
IAEA-EPR

Printed by the IAEA in Austria
September 2011

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EDITORIAL NOTE

1. INTRODUCTION

1.1. BACKGROUND

In addition to the generic procedures for response to emergencies at research reactors provided in Ref. [1], the benefit of developing a dedicated attachment for TRIGA research reactors was identified as TRIGA[1] is the most common type of research reactor. There are currently 38 TRIGA research reactors operating in the world, which represents some 16% of all operating research reactors [2].

TRIGA research reactors are designed to be inherently safe, primarily due to the prompt negative temperature coefficient of Uranium-Zirconium Hydride (U-ZrH) fuel. This distinguishes the TRIGA research reactor from many other research reactors with respect to the potential consequences from design basis accidents where damage to TRIGA fuel is extremely unlikely due to fuel melting. Only mechanical damage to fuel is considered credible as part of the Design Basis Analysis [3].

Credible accidents for TRIGA research reactors were evaluated in the light of contemporary knowledge and considered the long operation history of this type of reactors [3]. Considering all TRIGA research reactors and other research reactors modified for TRIGA fuel utilization, the accumulated operational experience is 2700 reactor-years. During this operational experience none of these research reactors has experienced an accident as severe as those analysed in their final safety report. Credible accidents from excess reactivity insertions, metal-water reactions, lost, misplaced, or inadvertent experiments, core rearrangements, and changes in fuel morphology and ZrH_x composition were also evaluated, and suggestions for further study provided [3]. The only potential for off-site exposure was determined to be from a fuel handling accident.

Development of this attachment was supported by a grant from Norway [4].

1.2. OBJECTIVE

The objective of this publication is to provide specific guidance in developing arrangements for preparedness and response to emergencies at TRIGA research reactors [5, 6, 7].

1.3. SCOPE

The publication provides guidance for response to emergencies at TRIGA research reactors in Threat Category[2] II and III [6]. It contains information on the unique behaviour of TRIGA fuel during accident conditions; it describes design characteristics of TRIGA research reactors and provides specific symptom-based emergency classification for this type of research reactor. The information in the attachment compliments that provided in Ref. [1].

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[1] The term ‘TRIGA research reactor’ is meant to include those reactor designs that use TRIGA fuel as well as the specific TRIGA models.

[2] The term “threat category” is used here as described in Ref. [6] and only for the purposes of emergency preparedness and response; this usage does not imply that any threat, in the sense of an intention and capability to cause harm, has been made in relation to facilities, activities or sources.

This publication covers the determination of the appropriate emergency class and protective actions for a nuclear or radiological emergency at TRIGA research reactors. It does not cover nuclear security at TRIGA research reactors. The term “threat category” is used in this publication as described in Ref. [6] and for the purposes of emergency preparedness and response only; this usage does not imply that any threat, in the sense of an intention and capability to cause harm, has been made in relation to facilities, activities or sources. The threat category is determined by an analysis of potential nuclear and radiological emergencies and the associated radiation hazard that could arise as a consequence of those emergencies.

1.4. STRUCTURE

The attachment consists of an introduction which defines the background, objective, scope and structure, two sections covering technical aspects and appendices.

Section 2 describes the characteristics of TRIGA fuel in normal and accident conditions.

Section 3 contains TRIGA research reactor specific emergency classification tables for Threat Category II and III. These tables should be used instead of the corresponding emergency classification tables presented in Ref. [1] while developing the emergency response arrangements at TRIGA research reactors.

The appendices present some historical overview and typical general data for TRIGA research reactor projects (Appendix I) and the list of TRIGA installations around the world (Appendix II).

The terms used in this document are defined in the IAEA Safety Glossary [8] and the IAEA Code of Conduct on the Safety of Research Reactors [9].

2. TRIGA FUEL CHARACTERISTICS

2.1. THE TRIGA FUEL

The use of U-ZrH fuels for the TRIGA research reactor has been under continuous development at General Atomics since 1957. Over 11 000 fuel elements of 7 distinct types have been fabricated for 68 TRIGA research reactors [2].

The standard TRIGA fuel [10, 11] contains 8.5 to 12 wt % uranium (20% enriched) as a fine metallic dispersion in a zirconium hydride matrix (Figure 1).

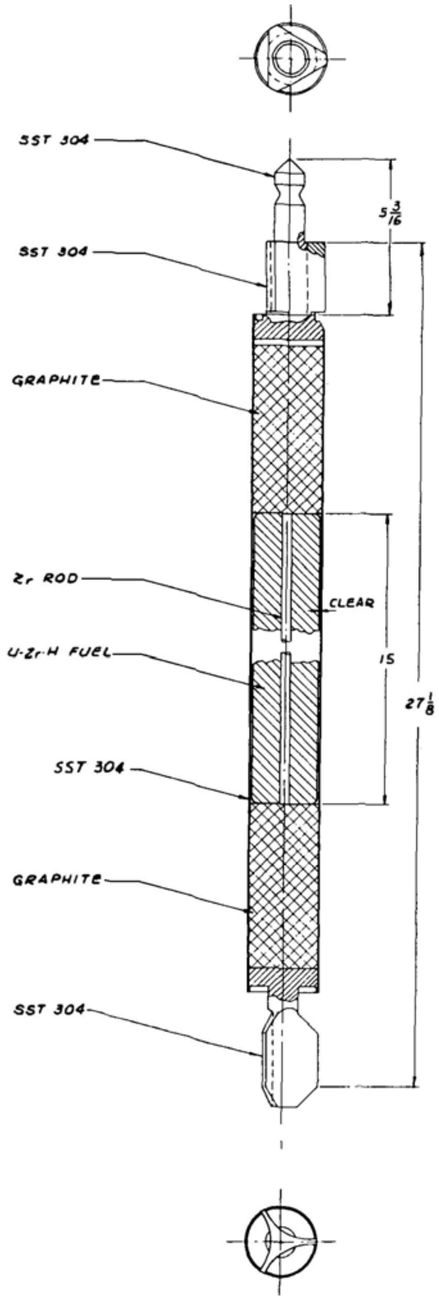

FIG. 1. Typical TRIGA fuel element (dimensions in inches).

The H/Zr ratio is nominally 1.6 (in the face-centred cubic delta phase). The equilibrium hydrogen dissociation pressure is governed by the composition and temperature. For $ZrH_{1.6}$, the equilibrium hydrogen pressure is 1 atm at about 760°C. The single-phase, high-hydride composition eliminates the problems of density changes associated with phase changes and with thermal diffusion of the hydrogen. Highly enriched uranium (HEU) versions of TRIGA fuels contained up to about 3 % erbium as a burnable poison to increase the core lifetime and contribute to the prompt negative temperature coefficient in the higher power (1 to 14 MW) TRIGA research reactors [12].

TRIGA fuel was developed based on the concept of inherent safety. A core composition was sought which had large prompt negative temperature coefficient of reactivity such that, if all the available excess reactivity were suddenly inserted into the core, the resulting fuel temperature would automatically cause the power excursion to terminate before any core damage resulted. Experimental results demonstrate that zirconium hydride possesses a basic mechanism to produce this desired characteristic. Additional advantages are that ZrH has a good heat capacity, results in relatively small core sizes and high flux values due to the high hydrogen content.

The 14 MW TRIGA research reactor [13], due to requirements of high specific power level and high neutron flux, uses a fuel geometry different from the typical TRIGA fuel element.

This reactor was built and is operated at the Institute for Nuclear Research in Pitesti, Romania. The 14 MW TRIGA research reactor operates with 29 fuel assemblies. A fuel assembly consists of a mechanical structure which contains the low enriched uranium LEU fuel elements. The mechanical structure is a square aluminium tube with the lower fitting made from cast aluminium to hold the fuel assembly in the core grid. The upper fitting allows the handling of the entire fuel assembly with a remote handling tool. The fuel elements are cladded with Incoloy 800 and have an external diameter of 13 mm. The fuel elements are positioned inside the fuel assembly in a square 5x5 lattice supported by three Inconel grid spacers. The fuel elements can be removed, rotated or replaced individually with a fuel element handling tool. This allows fuel element inspection, fuel burnup management and replacement of a single fuel element if necessary. Several fuel elements with exactly the same geometry are instrumented with thermocouples. Installation of those elements in the highest flux regions of the core allows continuous supervision of power peaking factors and maximum fuel temperature during operation.

2.2. ADDITION OF ERBIUM TO THE FUEL-MODERATOR MATRIX

The addition of erbium to the fuel-moderator matrix in no way compromises the chemical, mechanical or nuclear characteristics of the fuel compared to the extensively studied characteristics of standard TRIGA fuel. Erbium has a high boiling point and a relatively low vapour pressure so that it can be melted into the uranium-zirconium uniformly. All analyses that have been made on the alloy show that the erbium is dispersed uniformly, as is the uranium. Erbium is a metal and forms a metallic solution with the uranium-zirconium, thus there is no mechanism that would lead to segregation of the erbium. Erbium forms a hydride as stable as zirconium hydride which also suggests that the erbium remains uniformly dispersed through the alloy. Also, because neutron capture in erbium is an n-γ reaction, there are no recoil products.

The major changes and effects resulting from the addition of the erbium are:

(a) Allowance of higher content of fissile material, to produce a much longer-burning core than standard TRIGA fuel;

(b) A shortened prompt neutron lifetime compared with a standard core (~19 μs vs. 39 μs). This results from the heavier core loading of uranium and the erbium, but has no direct effect on steady state operation. The reduced lifetime of prompt neutrons does give shorter periods and higher peak powers during a transient when compared with a core with standard fuel (assuming equal reactivity insertions and an equivalent temperature coefficient). However, the reduced lifetime of prompt neutrons has no influence on the energy release or on fuel temperatures produced during a pulse. Since the operational limits of the system are based on thermal capacity of the fuel and this change in neutron lifetime does not affect fuel temperatures, there is no resulting compromise in the safety of the system.

2.3. LIMITING DESIGN BASIS PARAMETER AND VALUES

2.3.1. Fuel-moderator temperature

Fuel-moderator temperature defines the limits of TRIGA research reactor operation [11]. These limits stem from the out-gassing of hydrogen from the ZrH_x and the subsequent stress produced in the fuel element clad material. The mechanical properties of the clad material as a function of temperature dictate the upper limit on the fuel temperature. A fuel temperature safety limit of 1150°C for pulsing and stainless steel clad U-$ZrH_{1.65}$ or Er-U-$ZrH_{1.65}$ fuel is used as a design value to preclude the loss of clad integrity when the clad temperature is below 500°C. When clad temperatures equal the fuel temperature, the fuel temperature limit is 950°C. There is also a steady state operational fuel temperature design limit of 750°C based on consideration of irradiation- and fission-product-induced fuel growth and deformation. A maximum temperature of 750°C has been used as the operational design basis temperature because resulting average fuel temperatures result in insignificant calculated fuel growth from temperature-dependent irradiation effects. For the Annular Core Pulse Reactor (ACPR) fuel, where burnup is extremely low, the steady state operational fuel temperature design criterion is 800°C.

2.3.2. The dissociation pressure of the zirconium-hydrogen system

The dissociation pressure of the zirconium-hydrogen system is the principal contributor to the fuel element internal pressure at fuel temperatures above ~ 800°C [11]. Below ~ 800°C, trapped air and fission-product gases can be the major contributors to the internal pressure. At equilibrium condition, this pressure is a strong function not only of temperature but also the ratio of hydrogen to zirconium atoms and the carbon content of the material. The current upper limit for the hydrogen-to-zirconium ratio is about 1.65. The carbon content is important for ZrH as well as for organic iodine release. This content is about 0.2% (2000 ppm).

The equilibrium condition defined above never occurs, however, because the fuel is not at a constant temperature over the whole volume. Consequently, hydrogen pressure will be much lower.

2.4. FISSION PRODUCT RETENTION/RELEASE

The following general considerations apply to all TRIGA type fuel. Many experiments have been performed to determine the fraction of fission products retained by U-ZrH fuel including the following [11]:

- The measurement of a single fission product isotope quantity released from a full-size TRIGA element during irradiation (conducted in 1960).
- The measurement of the fractional release of several isotopes from small specimens of TRIGA fuel material during and after irradiation at temperatures ranging from ~25°C to 1100°C (conducted in 1966).
- The measurement of the quantities of several fission product isotopes released from a full-size TRIGA fuel element during irradiation in a duplication of the 1960 experiment (conducted in 1971).
    - (a) Post-irradiation annealing measurements of the release from small fuel samples heated to 400°C.
    - (b) Post-irradiation annealing release measurements from a small previously irradiated fuel sample that had experienced fuel burnup to ~5.5% of the ^{235}U.
- Measurements made as part of the Space Nuclear Auxiliary Power (SNAP) reactor programme.

The experiments included both low and high uranium loaded fuel samples [14].

The fractional release, φ, of fission product gases into the gap between fuel and clad from a full-size standard TRIGA fuel element is given by [11]:

$$\varphi = 1.5 \cdot 10^{-5} + 3.6 \cdot 10^{3} \exp\left(-\frac{1.34 \cdot 10^{4}}{T + 273} \right)$$

where:

T is fuel temperature, °C.

This function is plotted in Figure 2.

The first term of this function is a constant for low-temperature release; the second term is the high temperature portion. The release fractions are all normalized to a standard ratio of fuel-clad gap to fuel diameter. The curve in Figure 2 corresponds to a fuel element that has been irradiated for a sufficiently long time that all fission product activity is at equilibrium and the release fraction is at its theoretical maximum. This curve gives very conservative values for the high-temperature release from TRIGA fuel.

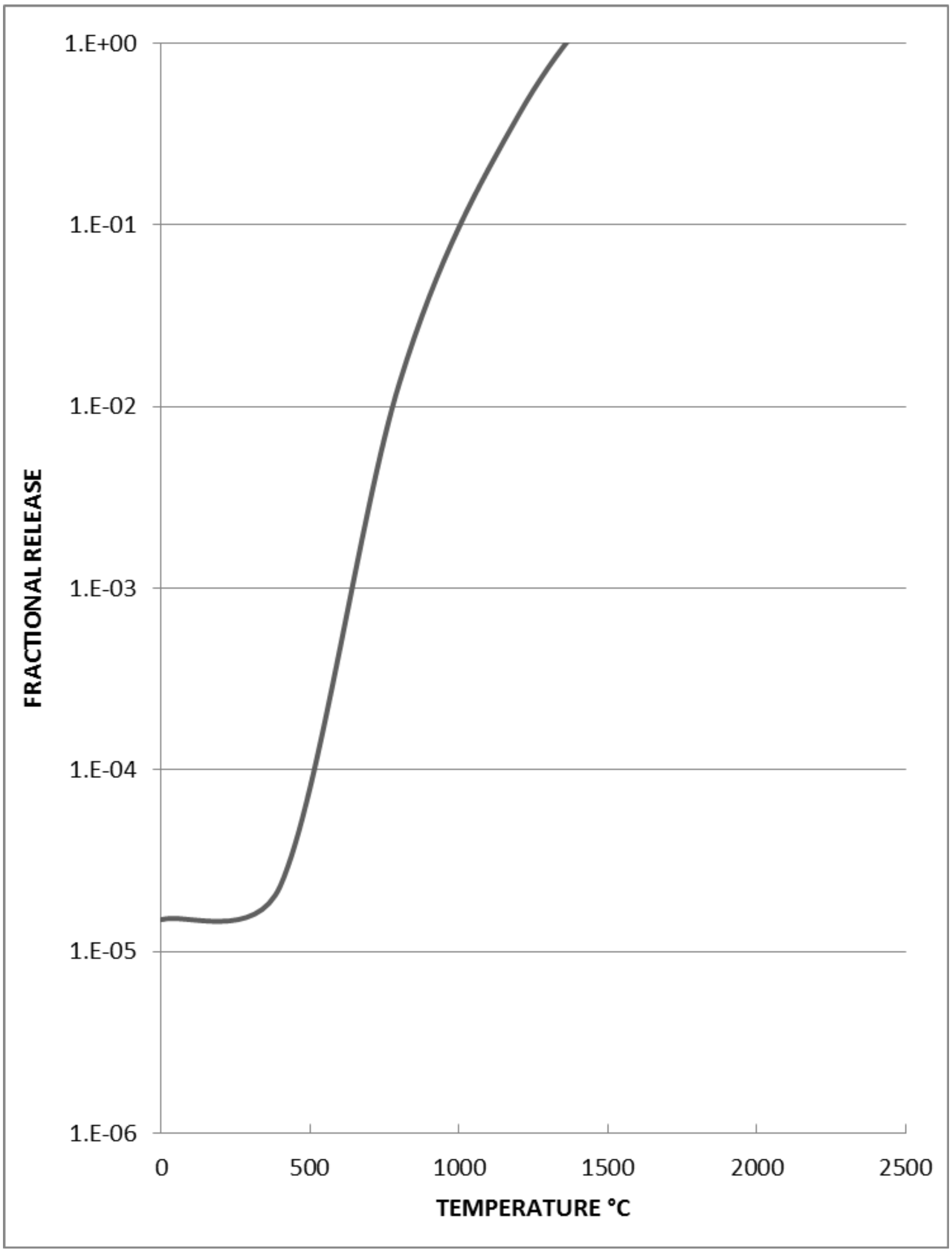

FIG. 2. Fractional release of gaseous fission products from TRIGA fuel showing theoretical values above 400°C corrected to infinite irradiation.

2.5. REACTIVITY PROPERTIES

U-ZrH TRIGA fuel has intrinsic properties designed to prevent nuclear accidents in the event of human error or mechanical malfunction. Research reactors not using U-ZrH fuel depend partially or entirely on electronic circuits, mechanical moving parts, and the delayed negative temperature coefficients of the fuel and moderator to protect the core from large positive reactivity insertions. Because this delayed feedback mechanism depends on the transfer of heat from the fuel to the water, the insertion of negative reactivity responds relatively slowly to a sudden power increases. Thus, if the reactivity additions were large, the power level could rise to a point that vaporizes the water, resulting in dangerously high fuel temperatures and the potential for destruction of the core from the energy release.

On the other hand, TRIGA fuel intrinsically has a large, prompt negative coefficient of reactivity that effectively controls large, positive reactivity insertions including super prompt critical insertions [15, 16]. Any sudden reactivity addition causes an increase in power that heats the fuel-moderator material (ZrH) instantaneously, causing the number of fissions to promptly decrease because of neutron energy spectrum hardening within the fuel element. As a result, the reactor temperature automatically and instantaneously compensates for the reactivity addition and limits the power increase. This prompt feedback effect has been demonstrated in pulse tests using 5.00$ reactivity insertions and more. Such control is fundamental to the TRIGA research reactor fuel and does not rely on mechanical or electrical control devices. This important property arises because the fuel elements are constructed of a solid homogenous alloy of uranium fuel and zirconium hydride moderator, making them 'fuel-moderator elements'.

In the United States Atomic Energy Commission USAEC's Special Power Excursion Reactor Test (SPERT), a core of uranium-aluminium plate-type research reactor fuel was explosively destroyed by a sudden insertion of reactivity equal in magnitude to that which most TRIGA's are pulsed repetitively, routinely, and with complete safety [3, 11].

2.6. MECHANICAL PROPERTIES

In all emergency scenarios analysed in Ref. [3] that resulted in fission product release, this release was produced by mechanical damage of the fuel only and was not from the melting of the fuel. The design basis accident analyses consider a single fuel element failure or a multiple fuel elements failure (with different release rates from fuel) due to mechanical damage of the fuel. The release of the fission products starts instantaneously after fuel clad integrity is compromised by mechanical damage.

This mechanical damage of the cladding will lead to a gap release of gaseous fission products, the balance of the fission products are retained in the U-ZrH matrix. Most scenarios assume that 100 % of the noble gases and volatile halogens, such as iodine, in the fuel-clad gap are released from each damaged fuel element and subsequently are transferred directly to the reactor confinement[3].

The delayed fractional release is not considered because the fuel does not melt. The temperature remains below the safety limit even at full power, so only noble gases and halogens are released from the fuel. The release rate for halogens is very small, and if the reactor confinement filtration system is available, less than 0.1 % of the iodine inventory in the reactor confinement will be released to the atmosphere.

[3] The term confinement is used to refer to either containment structure or confinement structure.

3. SYMPTOM BASED EMERGENCY CLASSIFICATION FOR THREAT CATEGORY II AND III TRIGA RESEARCH REACTORS

Each TRIGA research reactor facility should evaluate the consequences of potential reactor emergencies, including events with low probability, and determine the appropriate Threat Category for that reactor [6, 7, 17]. The assessment should include analysis of potential consequences for off-site population. The analyses performed for the reactor Safety Analysis Report may contain the necessary information.

The characteristics of the fuel in TRIGA research reactors lead to differences in the classification of emergencies when compared to other research reactors. Emergency conditions that may affect the integrity of the fuel in other research reactors are extremely unlikely to affect the fuel in TRIGA research reactors, resulting in lower emergency classifications for the TRIGA research reactors under similar conditions. While the classification of emergencies may differ between TRIGA and other types of research reactors, the response to a particular class of emergency is the same for TRIGA as for other research reactors.

The symptoms and the levels of severity used to define the emergency class for TRIGA research reactor accident conditions may differ from those for other research reactors. The emergency classification tables on the following pages — Table A.1-1 and Table A.1-2 — have been prepared specifically for Threat Category II and Threat Category III TRIGA research reactors respectively. When developing emergency response arrangements for TRIGA research reactors, Table A.1-1 should be used instead of Part 1, Table A.1 of Ref. [1] and Table A.1-2 should be used instead of Part 2, Table A.1 of Ref. [1].

There are no additional modifications for TRIGA research reactors to the guidance provided in Ref. [1].

TABLE A.1-1. SYMPTOM BASED EMERGENCY CLASSIFICATION FOR THREAT CATEGORY II TRIGA RESEARCH REACTORS

Review this table and compare to the existing emergency conditions. Classification is based on the more severe emergency class for the conditions.
Facility Emergency is more severe than Alert
(Revise as necessary to reflect reactor site conditions)

For the following entry conditions:	**Declare a General Emergency if:**	**Declare a Site Area Emergency if:**	**Declare a Facility Emergency if:**	**Declare an Alert if:**
CRITICAL SAFETY FUNCTION IMPAIRMENT				
Failure to stop nuclear chain reaction[4]	Failure to scram when above 5% *[or insert site specific power level]*[5] power **and** any of the following: •Pool/tank water level below top of active fuel **or** •Abnormal increase (100 - 1000x)*[or insert site specific increase above normal or a specific radiation level]* in multiple radiation monitors e.g. Reactor Confinement[6], Pool top, Primary Coolant System Piping, Ventilation System effluent, Purification System **or** •other indication of actual or imminent core damage	Failure to scram when above 5% *[or insert site specific power level]* power, abnormal conditions indicate automatic or manual scram is necessary and unable to maintain normal tank/pool water level	Failure to scram when above 5% *[or insert site specific power level]* power and abnormal conditions indicate automatic or manual scram is necessary	Failure to fully shut down (increasing neutron flux)[7] as part of normal shutdown with sufficient heat removal available

4 Stop nuclear chain reaction is more general term that includes reactor scram, which is used only for insertion of control rods to the reactor.

5 Failure to scram reactor is usually evaluated if reactor power is greater than 5 % and conditions indicate that scram is necessary (safety systems are usually capable to remove heat rate less than 5 % of nominal power). For some plants different, plant specific value should be used.

6 The term confinement is used to refer to either containment structure or confinement structure.

7 Increasing neutron flux is an explicit symptom if the reactor is not fully shut down.

TABLE A.1-1. SYMPTOM BASED EMERGENCY CLASSIFICATION FOR THREAT CATEGORY II TRIGA RESEARCH REACTORS

Review this table and compare to the existing emergency conditions. Classification is based on the more severe emergency class for the conditions.
Facility Emergency is more severe than Alert
(Revise as necessary to reflect reactor site conditions)

For the following entry conditions:	**Declare a General Emergency if:**	**Declare a Site Area Emergency if:**	**Declare a Facility Emergency if:**	**Declare an Alert if:**
Inadequate core cooling – Pool/tank level[8] or decay heat removal (considering the operations of piping, primary system pump, secondary system pump, primary-secondary heat exchanger, heat sinks, power supply, auxiliary fluid)	Pool/tank water level is, or is projected to be, below top of active fuel for greater than *[insert site specific time period to cause release of fission products from fuel elements]* minutes	Pool/tank water level is or is projected to be below top of active fuel		Pool/tank water level decreasing over a longer time period than expected while systems are responding as designed
	Pool/tank water level is or is projected to be below top of active fuel **and** any of the following: •Pool/tank water makeup rate is unable to recover the core **or** •Abnormal increases (100 - 1000x) in multiple radiation monitors **or** •other indications of imminent or actual core damage *Note: Consideration of imminent confinement boundary failure might be considered as further additional criteria* [9]	Actual or projected long term failure of the ability to remove decay heat to the environment potentially affecting the ability to protect the core	Unavailability of normal system for decay heat removal **and** Unavailability of Emergency Core Cooling System	Unavailability of normal system for decay heat removal

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8 Inadequate core cooling is characterized by two kinds of entry conditions – Pool/tank water level and decay heat removal capability.

9 In case of core damage, the status of the confinement barriers will affect the magnitude of fission product release.

TABLE A.1-1. SYMPTOM BASED EMERGENCY CLASSIFICATION FOR THREAT CATEGORY II TRIGA RESEARCH REACTORS

Review this table and compare to the existing emergency conditions. Classification is based on the more severe emergency class for the conditions.
Facility Emergency is more severe than Alert
(Revise as necessary to reflect reactor site conditions)

For the following entry conditions:	**Declare a General Emergency if:**	**Declare a Site Area Emergency if:**	**Declare a Facility Emergency if:**	**Declare an Alert if:**
Loss of AC or DC power sources				AC or DC power needed for safety systems and their supporting systems operation is lost or reduced to a single source
Loss of or degraded control of safety systems including post-accident instrumentation[10]	Unavailability of safety system instruments or controls in the control room and remote control locations and other indications of imminent or actual core damage	Unavailability of safety system instruments or controls in the control room and major transient in progress potentially affecting the ability to protect the core		Unavailability of safety system instruments or controls in the control room
LOSS OF FISSION PRODUCT BARRIERS DURING REACTOR OPERATION (combination of cladding failures and water pool unavailability, or cladding failures and reactor confinement emergency ventilation unavailability)[11]				
Abnormal I-131 in coolant or presence of elevated delayed neutrons in coolant[12] **or** Airborne activity in the Reactor Confinement			*[Determine a site specific airborne activity from fission products in the Reactor confinement such that the design basis release rate from confinement causes on-site radiation levels that exceed the evacuation OIL at any on-site area]*	Abnormal radiation level increase at the purification system **or** Long term trend indicating gradual increase of I-131 activity in coolant

10 Safety systems control capability can be either degraded or completely lost; both cases are reflected. Both unreliable functioning of several safety system instruments or alarms and unavailability of safety system instruments or controls are considered. Post-accident instrumentation provides the essential information to support safety system operation and control and is included.

11 The simultaneous loss of all three fission product barriers is unlikely, except for a terrorist attack or major natural disaster.

12 Conditions severe enough to warrant a Site Area Emergency or General Emergency are defined by radiological conditions defined elsewhere in this Table.

TABLE A.1-1. SYMPTOM BASED EMERGENCY CLASSIFICATION FOR THREAT CATEGORY II TRIGA RESEARCH REACTORS

Review this table and compare to the existing emergency conditions. Classification is based on the more severe emergency class for the conditions.
Facility Emergency is more severe than Alert
(Revise as necessary to reflect reactor site conditions)

For the following entry conditions:	**Declare a General Emergency if:**	**Declare a Site Area Emergency if:**	**Declare a Facility Emergency if:**	**Declare an Alert if:**
Confinement damaged	Confinement unable to perform the design function **and** a large release of fission products is in progress or is imminent	Confinement unable to perform the design function **and** a release of radiological materials is possible		Confinement unable to perform the design functions while the reactor is shutdown
RADIATION LEVELS				
Airborne effluent release rates exceed release limits	Effluent monitor readings for more than 15 minutes greater than ... *[insert site specific list of effluent monitors and readings indicating that in 1 hour the off-site doses will be greater than the intervention levels for urgent protective actions assuming average meteorological conditions]*[13]	Effluent monitor readings for more than 15 minutes greater than ...*[insert site specific list of effluent monitors and readings indicating that in 4 hours the off-site doses will be greater than 0.10 of the intervention levels for urgent protective actions assuming average meteorological conditions*][13]	Effluent monitor readings for more than 15 minutes greater than ...*[insert site specific list of effluent monitors and readings indicating that in 4 hours the on-site doses will be greater than 0.10 of the intervention levels for urgent protective actions assuming average meteorological conditions*]	Effluent monitor exceeds allowed release activity limit

[13] This decision should be based on evolution of the situation and interpretation of data from reactor systems.

TABLE A.1-1. SYMPTOM BASED EMERGENCY CLASSIFICATION FOR THREAT CATEGORY II TRIGA RESEARCH REACTORS

Review this table and compare to the existing emergency conditions. Classification is based on the more severe emergency class for the conditions. Facility Emergency is more severe than Alert

(Revise as necessary to reflect reactor site conditions)

For the following entry conditions:	**Declare a General Emergency if:**	**Declare a Site Area Emergency if:**	**Declare a Facility Emergency if:**	**Declare an Alert if:**
High radiation levels in control room or other areas requiring continuous access for safety system operation and maintenance *Note: Inconsistent monitor readings could result from incomplete mixing, a failed monitor or by seeing radiation from a contaminated system nearby. Monitors may show high, low or centre range if they fail*		Radiation levels greater than 10 mSv/h *[or insert site specific dose rate based on personnel exposure limits]* for more than 1h **or** Projected dose to operating personnel could exceed 100 mSv during necessary occupancy period	Radiation levels greater than 1 mSv/h *[or insert site specific dose rate based on personnel exposure limits]* potentially lasting several hours	Unexpected radiation levels greater than 0.10 mSv/h *[or insert site specific dose rate based on personnel exposure limits]* or 100x background potentially lasting several hours
High radiation levels in areas requiring occasional occupancy to maintain or control safety systems		Radiation levels greater than 100 mSv/h *[or insert site specific dose rate based on personnel exposure limits]* potentially lasting several hours	Radiation levels greater than 10 mSv/h *[or insert site specific dose rate based on personnel exposure limits]* potentially lasting several hours	Radiation levels greater than 1 mSv/h *[or insert site specific dose rate based on personnel exposure limits]* potentially lasting several hours
High radiation levels in non-critical occupied areas, for example, experimental facilities			Radiation level increase (>100x) detected on multiple instruments, or Abnormal radiation levels greater than 1 mSv/h *[or insert site specific dose rate]*	Radiation level increase (>10x) detected on multiple instruments, or Abnormal radiation levels greater than 0.1 mSv/h*[or insert site specific dose rate]*

TABLE A.1-1. SYMPTOM BASED EMERGENCY CLASSIFICATION FOR THREAT CATEGORY II TRIGA RESEARCH REACTORS

Review this table and compare to the existing emergency conditions. Classification is based on the more severe emergency class for the conditions.
Facility Emergency is more severe than Alert
(Revise as necessary to reflect reactor site conditions)

For the following entry conditions:	**Declare a General Emergency if:**	**Declare a Site Area Emergency if:**	**Declare a Facility Emergency if:**	**Declare an Alert if:**
Elevated Reactor Confinement radiation levels and evidence of fuel damage *Note: Inconsistent monitor readings could result from incomplete mixing or a failed monitor or by seeing radiation from a contaminated system nearby. Analog monitors may show high, low or centre range if they fail*	*[Determine a site specific radiation level from fission products in the confinement such that the design basis release rate from confinement requiring urgent protective action in the UPZ]*	*[Determine a site specific radiation level from fission products in the confinement such confinement failure requiring urgent protective action in the UPZ]*	*[Determine a site specific radiation level from fission products in the confinement such that the design basis release rate from confinement requiring urgent protective action in any on-site area]*	Radiation level increase greater than 0.10 mSv/h *[or insert site specific dose rate]*
Unplanned increase in reactor facility radiation levels	Multiple reactor facility radiation monitors show an unplanned or unpredicted increase by a factor of 100 or more and any other indication of actual core damage	Multiple reactor facility radiation monitors show an unplanned or unpredicted increase by a factor of 100 or more and another major emergency is in progress potentially affecting the ability to protect the core		Multiple reactor facility radiation monitors show an unplanned or unpredicted increase by a factor of 100 or more
High dose rates at or beyond the site boundary	Dose rates at or beyond the site boundary greater than 1 mSv/h *[or insert the site specific operational intervention level for evacuation]*	Dose rates at or beyond the site boundary greater than 0.1 mSv/h. *[or insert 1/10 of the site specific operational intervention level for evacuation]*		Dose rates at or beyond the site boundary greater than 10μSv/h *[or insert site specific reading indicating 100 times background]*
SECURITY, FIRE, NATURAL AND OTHER EVENTS				
Security event (intruder or terrorist attack) (See entry conditions Loss of or degraded control of safety systems)	Security event causes *confinement* damage **and** Security event causes core damage	Security event causes *confinement* damage **or** Security event causes core damage	Security event , actual or threatened, that could result in damage to any safety system operation or the reactor	Credible security threat to the reactor or reactor safety systems

TABLE A.1-1. SYMPTOM BASED EMERGENCY CLASSIFICATION FOR THREAT CATEGORY II TRIGA RESEARCH REACTORS

Review this table and compare to the existing emergency conditions. Classification is based on the more severe emergency class for the conditions. Facility Emergency is more severe than Alert

(Revise as necessary to reflect reactor site conditions)

For the following entry conditions:	**Declare a General Emergency if:**	**Declare a Site Area Emergency if:**	**Declare a Facility Emergency if:**	**Declare an Alert if:**
Fire or explosion (See entry conditions Loss of or degraded control of safety systems)	Fire or explosion causes confinement damage **and** Fire or explosion causes core damage	Fire or explosion causes confinement damage **or** Fire or explosion causes core damage	Fire or explosion that has the potential to cause fuel damage affecting on-site locations	Fire or explosion potentially affecting areas containing safety systems
Unexpected media or public inquiry				Inquiry requests information on a perceived or real emergency
Toxic or flammable gases (See entry conditions Loss of or degraded control of safety systems)			Toxic or flammable gases that prevent control of reactor safety systems	Toxic or flammable gases in the facility
Major events such as: • Earthquake • Tornado • Floods • High winds • Vehicle or airplane[14] crash • Hurricane • Tsunami • Storm surge • Lightning strikes [15]	Major events resulting in fuel damage and *confinement* damage	Major events resulting in damage or impaired access to safety and/or decay heat removal systems or affecting their long term operation	Major events resulting in damage to reactor systems or building or causes fuel damage that affects the on-site population	Major events that threaten the plant such as : •Events beyond the design basis of the plant •Events resulting in actual or potential loss of access to the site for an extensive period of time
Flooding of reactor building				Flooding can affect the Safety and Control Systems

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[14] Airplane crash can also cause severe damage to plant and decrease the plant safety.

[15] Lightning strikes can also cause severe damage to plant and decrease the plant safety.

TABLE A.1-1. SYMPTOM BASED EMERGENCY CLASSIFICATION FOR THREAT CATEGORY II TRIGA RESEARCH REACTORS

Review this table and compare to the existing emergency conditions. Classification is based on the more severe emergency class for the conditions.
Facility Emergency is more severe than Alert
(Revise as necessary to reflect reactor site conditions)

For the following entry conditions:	**Declare a General Emergency if:**	**Declare a Site Area Emergency if:**	**Declare a Facility Emergency if:**	**Declare an Alert if:**
Loss of communications				Events resulting in actual or potential loss of communications to the site for an extensive period of time
Loss of control of Radioactive material			Loss of control of a dangerous source on the site[16]	Loss of control of or access to fuel not installed in the reactor **or** Loss of control of any radioactive material
Reactor Senior Operator opinion	Conditions that warrant taking urgent protective actions off-site	Conditions that warrant preparing the public to implement urgent protective actions	Conditions that warrant taking protective actions on-site	Abnormal conditions warranting obtaining immediate additional assistance for the on-site operations staff **or** Abnormal conditions warranting increased preparedness of off-site officials

[16] A dangerous source is one that meets certain criteria, nuclide and quantity, established in Ref. [10].

TABLE A.1-1. SYMPTOM BASED EMERGENCY CLASSIFICATION FOR THREAT CATEGORY II TRIGA RESEARCH REACTORS

Review this table and compare to the existing emergency conditions. Classification is based on the more severe emergency class for the conditions.
Facility Emergency is more severe than Alert
(Revise as necessary to reflect reactor site conditions)

For the following entry conditions:	**Declare a General Emergency if:**	**Declare a Site Area Emergency if:**	**Declare a Facility Emergency if:**	**Declare an Alert if:**
Human Error[17]				Error results in violation of reactor operating limits and conditions or damages an experimental apparatus **and** Has the potential to cause overexposure to personnel on-site, or a release to the environment
Injured Person(s)				Individual(s) injured and/or contaminated with off-site treatment and/or decontamination required
FUEL HANDLING AND SPENT FUEL POOL EVENTS				
Abnormal refueling or spent fuel conditions Fuel handling abnormality			Loss of ability to maintain water level above spent fuel Abnormal radiation level increase on multiple monitors during fuel transfers or movements	Damage to spent fuel but fuel remains covered Damage to fuel element or control rod

[17] Human error resulting in a Facility Emergency would be expected to create conditions included in another set of entry conditions.

TABLE A.1-1. SYMPTOM BASED EMERGENCY CLASSIFICATION FOR THREAT CATEGORY II TRIGA RESEARCH REACTORS

Review this table and compare to the existing emergency conditions. Classification is based on the more severe emergency class for the conditions. Facility Emergency is more severe than Alert

(Revise as necessary to reflect reactor site conditions)

For the following entry conditions:	**Declare a General Emergency if:**	**Declare a Site Area Emergency if:**	**Declare a Facility Emergency if:**	**Declare an Alert if:**
Abnormal fuel follower control rod condition			Radiation level at the top of pool area 10x higher than normal condition	Damage to the fuel follower control rod **or** •Abnormal radiation level increase at the purification system **or** •Abnormal radiation level increase on multiple monitors during control rod inspection
Bowed or distorted fuel element				Bowing allows contact with adjacent fuel elements
EXPERIMENTAL EQUIPMENT AND SYSTEMS EVENTS				
Radioactive material released from an irradiation device		*[Determine a site specific airborne activity from an irradiation device such that confinement failure requires urgent protective action in the UPZ]*	*[Determine a site specific airborne activity from an irradiation device such that the design basis release rate from confinement requires urgent protective action at any on-site area]*	Any indication of failure of a irradiation device
Unplanned reactor scram				Reactor scram, unknown cause
Experimental equipment abnormality				Damage to experimental assembly

TABLE A.1-2. SYMPTOM BASED EMERGENCY CLASSIFICATION FOR THREAT CATEGORY III TRIGA RESEARCH REACTORS

Review this table and compare to the existing emergency conditions. Classification is based on the more severe emergency class for the conditions. Facility Emergency is more severe than Alert

(Revise as necessary to reflect reactor site conditions)

For the following entry condition:	**Declare a Facility Emergency if:**	**Declare an Alert if:**
CRITICAL SAFETY FUNCTION IMPAIRMENT		
Failure to stop nuclear chain reaction	Failure to scram when above 5% *[or insert site specific power level]* power and abnormal conditions indicate automatic or manual scram is necessary	Failure to fully shut down (increasing neutron flux)[18] as part of normal shutdown with sufficient heat removal available
Inadequate Decay Heat Removal[19]	Unavailability of normal system for decay heat removal. **and** Unavailability of Emergency Core Cooling System	Unavailability of normal system for decay heat removal
Loss of AC or DC power[20] sources		AC or DC power needed for safety systems and their supporting systems operation is lost or reduced to a single source
Loss of or degraded control of safety systems including post-accident instrumentation[21]		Safety system was inoperative when the reactor was operating and design limits possibly were exceeded

[18] Increasing neutron flux is an explicit symptom if the reactor is not fully shut down.

[19] Facilities that do not require active decay heat removal because passive losses to ambient air or coolant are sufficient to avoid fuel damage should consider deleting this emergency.

[20] This is intended to apply to a loss of all power sources needed to control and monitor the reactor as well as prevent discharges of radioactive materials from the facility. Site specific power sources should be provided here to clarify what situation constitutes a loss of facility power.

[21] Safety systems control capability can be either degraded or completely lost; both cases are reflected. Both unreliable functioning of several safety system instruments or alarms and unavailability of safety system instruments or controls are considered. Post-accident instrumentation provides the essential information to support safety system operation and control and is included.

TABLE A.1-2. SYMPTOM BASED EMERGENCY CLASSIFICATION FOR THREAT CATEGORY III TRIGA RESEARCH REACTORS

Review this table and compare to the existing emergency conditions. Classification is based on the more severe emergency class for the conditions. Facility Emergency is more severe than Alert

(Revise as necessary to reflect reactor site conditions)

For the following entry condition:	Declare a Facility Emergency if:	Declare an Alert if:
LOSS OF FISSION PRODUCT BARRIERS DURING REACTOR OPERATION (combination of cladding failures and water pool unavailability, or cladding failures and reactor confinement [22] emergency ventilation unavailability)[23]		
Abnormal I-131 in coolant or presence of elevated delayed neutrons in coolant **or** Airborne activity in Reactor Confinement	*[Determine a site specific airborne activity from fission products in the Reactor Confinement such that the design basis release rate from confinement causes on-site radiation levels that exceed the evacuation OIL at any on-site area]*	Abnormal radiation level increase at the purification system **or** Long term trend indicating gradual increase of I-131 activity in coolant
Confinement barrier damaged	Confinement unable to perform the design function and a release of radiological materials is possible	Confinement unable to perform the design function while the reactor is shutdown
RADIATION LEVELS		
Unplanned reactor power excursion	Power transient exceeds fuel limits	Power transient exceeds operating limits
Airborne effluent release rates exceed release limits	Effluent monitor readings for more than 15 minutes greater than ...*[insert site specific list of effluent monitors and readings indicating that in 4 hours the on-site doses will be greater than 0.10 of the intervention levels for urgent protective actions assuming average meteorological conditions*]	Effluent monitor exceeds allowed release activity limit
High radiation levels[24]	Abnormal radiation level increase (>500X) detected on multiple instruments, **or** Abnormal radiation levels greater than 1 mSv/h in occupied spaces such as the control room	Abnormal radiation level increase (>100X) detected on multiple instruments, **or** Abnormal radiation levels greater than 0.1 mSv/h

[22] The term confinement is used to refer to either containment structure or confinement structure.

[23] The simultaneous loss of all three fission product barriers is unlikely, except for a terrorist attack or major natural disaster.

[24] The facility may choose a different increase multiple and/or list specific instruments.

TABLE A.1-2. SYMPTOM BASED EMERGENCY CLASSIFICATION FOR THREAT CATEGORY III TRIGA RESEARCH REACTORS

Review this table and compare to the existing emergency conditions. Classification is based on the more severe emergency class for the conditions. Facility Emergency is more severe than Alert

(Revise as necessary to reflect reactor site conditions)

For the following entry condition:	**Declare a Facility Emergency if:**	**Declare an Alert if:**
Elevated Reactor Confinement radiation levels and evidence of fuel damage *Note: Inconsistent monitor readings could result from incomplete mixing or a failed monitor or by seeing radiation from a contaminated system nearby. Analog monitors may show high, low or centre range if they fail*	*[Determine a site specific radiation level from fission products in the confinement such that the design basis release rate from confinement causes on-site radiation levels that exceed the evacuation OIL in any on-site area]*	Radiation level increase greater than 0.10 mSv/h *[or insert site specific dose rate]*
High dose rates at the site boundary	Dose rates at the site boundary greater than 100μSv/h *[or insert site specific dose rate]*	Dose rates at or beyond the site boundary greater than 10μSv/h *[or insert site specific dose rate or 100 times background]*
Inadvertent release of radioactive material or unplanned overexposure of personnel	Event causes or has the potential to cause individual personal exposures in excess of 50 mSv in a short period of time *(or lesser site-specific value denoting an unplanned exposure in excess of the permissible annual dose limit)*	Event causes or has the potential to cause individual personal exposures in excess of 20 mSv in a short period of time *(or lesser site-specific value denoting an unplanned exposure in excess of the permissible average annual dose limit)*
SECURITY, FIRE, NATURAL AND OTHER EVENTS		
Security event (intruder or terrorist attack)	Security event, actual or threatened, that could result in damage to any safety system or the reactor	Credible security threat to the reactor or reactor safety systems
Fire or explosion (See entry conditions Loss of or degraded control of safety systems)	Occurs in a facility building and has the potential to release radioactive material or damage fuel	Fire or explosion potentially affecting areas containing safety systems
Unexpected media or public inquiry		Inquiry requests information on a perceived or real emergency
Toxic or flammable gases (See entry conditions Loss of or degraded control of safety systems)	Toxic or flammable gases that prevent control of reactor safety systems	Toxic or flammable gas detected in the facility

TABLE A.1-2. SYMPTOM BASED EMERGENCY CLASSIFICATION FOR THREAT CATEGORY III TRIGA RESEARCH REACTORS

Review this table and compare to the existing emergency conditions. Classification is based on the more severe emergency class for the conditions. Facility Emergency is more severe than Alert

(Revise as necessary to reflect reactor site conditions)

For the following entry condition:	Declare a Facility Emergency if:	Declare an Alert if:
Major natural or external disaster such as: • Earthquake • Tornado • Flood • High winds • Vehicle or airplane crash • Hurricane • Tsunami • Storm surge • Lightening Strike	Major events resulting in damage to reactor systems or building or causes fuel damage that affects the on-site population	Major events that threaten the plant such as: • Events beyond the design basis of the facility • Events resulting in actual or potential loss of access to the facility for an extensive period of time
Flooding of reactor building		Flooding that can affect the safety and control systems
Loss of Communication		Events resulting in actual or potential loss of communication with the facility for an extensive period of time
Loss of control of Radioactive material	Loss of control of a dangerous source on the site[25]	Loss of control of or access to fuel not installed in the reactor **or** Loss of control of any radioactive material
Reactor Senior Operator opinion	Conditions that warrant taking protective actions on-site	Abnormal conditions warranting obtaining immediate additional assistance for the on-site operations staff
Human Error[26]		Error results in violation of reactor operating limits and conditions or damages an experimental apparatus **and** Has the potential to cause overexposure to personnel on-site, or a release to the environment

[25] Appendix 8 of Ref. (17) provides the information to determine the amount considered dangerous for selected nuclides.

[26] Human error resulting in a Facility Emergency would be expected to create conditions defined by another set of entry conditions.

TABLE A.1-2. SYMPTOM BASED EMERGENCY CLASSIFICATION FOR THREAT CATEGORY III TRIGA RESEARCH REACTORS

Review this table and compare to the existing emergency conditions. Classification is based on the more severe emergency class for the conditions. Facility Emergency is more severe than Alert

(Revise as necessary to reflect reactor site conditions)

For the following entry condition:	**Declare a Facility Emergency if:**	**Declare an Alert if:**
Injured Person(s)		Individual(s) injured and/or contaminated with off-site treatment and/or decontamination required
FUEL HANDLING AND SPENT FUEL POOL EVENTS		
Abnormal fuel follower control rod condition		Damage to the fuel follower control rod **or** •Abnormal radiation level increase at the purification system **or** •Abnormal radiation level increase on multiple monitors during control rod inspection
Fuel handling or experiment abnormality[27]	Abnormal radiation level increase on multiple monitors during fuel transfers or movements	Damage to fuel element, control rod, or experiment assembly
EXPERIMENTAL EQUIPMENT AND SYSTEMS EVENTS		
Radioactive material released from an irradiation device	*[Determine a site specific airborne activity from an irradiation device such that the design basis release rate from confinement causes on-site radiation levels that exceed the evacuation OIL at any on-site area]*	Any indication of failure of a irradiation device
Bowed or distorted fuel element in the core		Bowing allows contact with adjacent fuel elements

[27] The intent is to define emergencies that involve moving fuel or operating experiment devices without reactor operation and subsequently cause an unsafe condition or an emergency to occur. An inadvertent criticality or damage that releases radioactive material from an experiment are possible emergencies that would meet these conditions.

APPENDICES

APPENDIX I

TRIGA CHARACTERISTICS

HISTORICAL OVERVIEW

At the International Conference on Peaceful Uses of Atomic Energy in 1955, the need for a reactor 'fuse' that was "…self-contained and wholly automatic… activated by changes in power level…" was presented [18]. Subsequently, General Atomics (GA) a US company located in San Diego, California, developed a small research reactor that:

- Would be inherently safe;
- Was operationally flexible and relatively inexpensive;
- Allowed a large variety of experiments.

The first TRIGA research reactor achieved initial criticality on 3 May 1958 at the General Atomics site, John Hay Hopkins Laboratory for Pure and Applied Science, in San Diego, and operated until 1997. The achievement was announced at the Second United Nations Conference on the Peaceful Uses of Atomic Energy in 1958 and a TRIGA research reactor was demonstrated at the Conference [19]. During the following decades, more than 60 TRIGA research reactors were constructed all over the world. Three basic TRIGA research reactor models have been produced:

- Mark-I: underground pool;
- Mark-II: above ground tank;
- Mark-III: above ground oval tank with movable core.

Some other type of existing research reactors were subsequently replaced with TRIGA research reactors or were converted to use TRIGA fuel. A short description of the three TRIGA research reactor types is presented in this appendix and a list of all worldwide TRIGA research reactors that were put into operation (some of which are now decommissioned) is given in Appendix II.

TECHNICAL CHARACTERISTICS OF TRIGA MARK I RESEARCH REACTOR

Typical General Data

- Below ground; fixed core; graphite reflector;
- 100 kW to 2000 kW steady state power level;
- Up to 6 400 000 kW pulsing power level;
- $8.0x10^{13}$ n/cm^{2}s maximum thermal flux (<0.21 eV) at 2000 kW;
- $UZrH_{1.6}$ fuel elements using uranium enriched to 20 %.

The below-ground TRIGA Mark I research reactor is extremely simple in physical design (Figure AI-1).

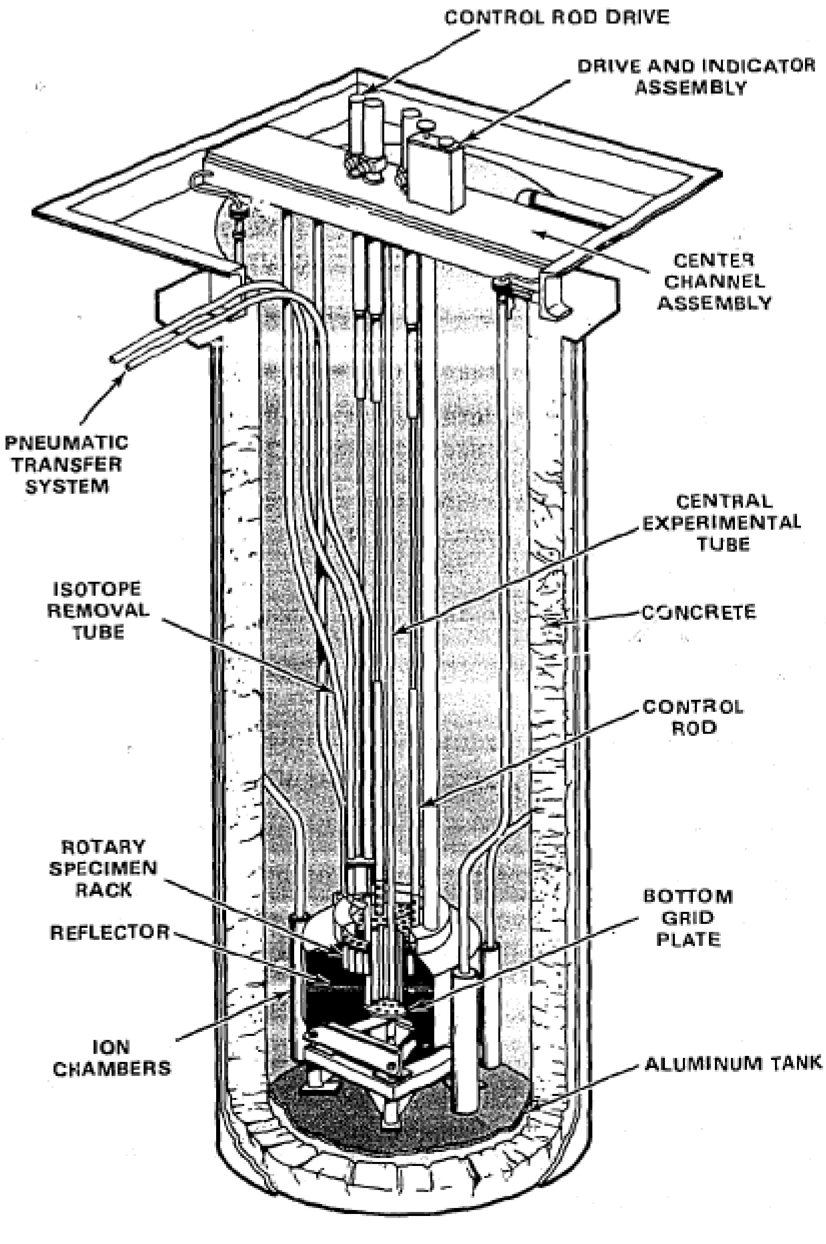

FIG. AI-1. Schematic View of a TRIGA Mark I Research Reactor [3].

It is a graphite-reflected core capable of operating up to 2000 kW steady state and pulsing routinely and reproducibly with reactivity insertions up to 3.2 % δk/k. The reactor core rests at the bottom of a reactor pool. Surrounding earth and demineralized water provide the required radial and vertical shielding. No special confinement building is necessary and installation in existing buildings is often feasible. The Mark I TRIGA research reactor can be installed in a circular pool or in a large, oblong pool for greater experimental access to the reactor core. Core cooling is achieved through natural convection, eliminating the need for an expensive and restrictive forced cooling system [20].

TECHNICAL CHARACTERISTICS OF TRIGA MARK II RESEARCH REACTOR

Typical General Data

- Above ground; fixed core; graphite reflector; 4 beam tubes; thermal column;
- 250 kW to 2000 kW steady state power level with natural convection cooling of the core and with forced cooling of pool water via separate heat exchanger;
- Up to 6 400 000 kW pulsing power level;
- $8.0x10^{13}$ n/cm^2 s maximum thermal flux (<0.21 eV) at 2000 kW;
- $UZrH_{1.6}$ fuel elements using uranium enriched to 20%.

The TRIGA Mark II research reactor provides experimental capabilities greater than the TRIGA Mark I research reactor. It is an above-ground fixed-core research reactor (Figure A1-II).

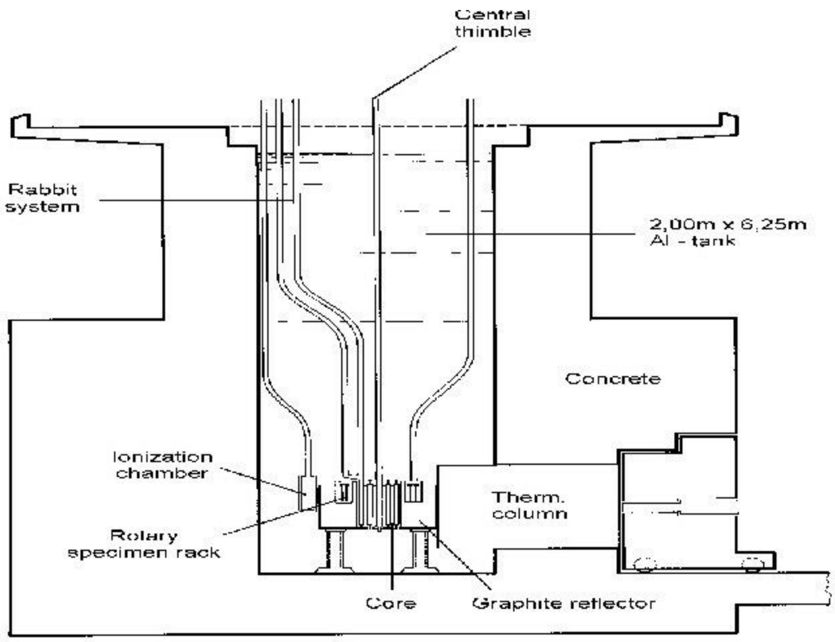

FIG. A1-II. Schematic View of a TRIGA Mark II Research Reactor [21].

Its core, similar to that of the TRIGA Mark I research reactor, is located in a pool surrounded by a concrete shield structure which is above the reactor room floor. The pool water provides natural convection cooling up to 2000 kW, with forced cooling of the pool water via separate heat exchanger. The Mark II features include [20]:

- Thermal Column: a graphite thermal column, 1.2 m by 1.2 m by 1.65 m, extending from the reflector through the concrete structure, provides a source of well-thermalized neutrons suitable for physical research or biological irradiation. A movable high-density concrete door with a removable 20 cm concrete plug shields the outer face of the column.
- Beam Ports: four (15 cm diameter horizontal beam ports, extending through the concrete shield to the face of the reflector) permit the extraction of core radiations, or the insertion of specimens for irradiation. Two of the beam tubes extend radially to the reflector, a third penetrates the reflector to the core's edge, and the fourth is tangent to the core.

Typical General Data

- Above ground; movable core; beam tubes; thermal columns;
- Exposure room; removable core-irradiation facilities;
- 1000 kW to 3000 kW steady state power level with forced cooling of the core;
- Up to 6 400 000 kW pulsing power level;
- $6.6x10^{13}$ n/cm2 s maximum thermal flux (<0.21 eV) at 2000 kW;
- $UZrH_{1.6}$ fuel elements using uranium enriched to 20 %.

The TRIGA Mark III research reactor, the most versatile of the standard TRIGA series, is available in either above- or below-ground configurations (Figure AI-3).

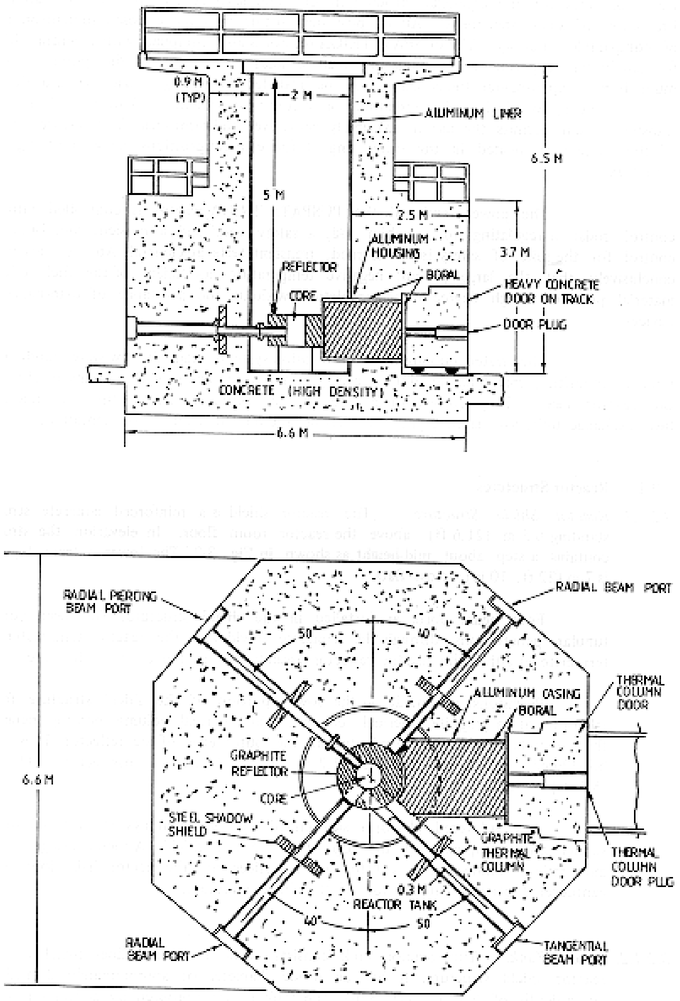

FIG. AI-3. Schematic View of TRIGA Mark III Research Reactor [22].

Its water-reflected movable core greatly increases the reactor's flexibility. The core can be moved to one end of the pool for experiments in an adjacent dry, walk-in exposure room, or to the opposite end for experiments involving the thermal column and beam ports. The ability to move the radioactive core away from the experimental facilities greatly eases set-up of experiments.

The reactor tank is approximately 7.5 m long by 7.5 m deep, with a maximum width of 3 m at the center. Because it is natural convection cooled up to 3000 kW, the reactor can be operated anywhere in the pool. Reactor facilities include [20]:

- Two thermal columns with internal void — a graphite thermal column, 1.2 m by 1.2 m by 3 m, extends from the periphery of the reactor core through the concrete shield structure. A 0.9 m by 0.9 m by 1.0 m Hohlraum space is provided in this horizontal thermal column with a vertical thermal column directly above. Four ports through the concrete shielding allow access to the two thermal columns.
- Beam Ports — four 15-cm-diameter horizontal beam ports penetrate the concrete shield and the reactor pool water to the edge of the core shroud, and two 20-cm-diameter through beam ports intersect in the thermal column adjacent to the core.
- Walk-in exposure room — this room is 3 m wide by 3.6 m long by 2.9 m high and easily accommodates very large experiments. Access to the room is provided by several 15-cm-diameter conduits and a motor-driven concrete door.

Below are presented some main characteristics for different TRIGA research reactor projects (Tables A1-I to A1-III).

TABLE AI-1. EXAMPLE OF 1 MW TRIGA RESEARCH REACTOR MAIN CHARACTERISTICS [23]

Steady State			
Steady State Power		1 MW	
Fuel Assemblies	Type	19.75 wt% Er-U-ZrH	
	Number	90	
	Number of fuel element bundles	24	
	Cladding material	304 stainless steel	
	Cladding Thickness	0.508 mm	
	Diameters	Zirconium Rod Outer Diameter	6.35 mm
		Fuel meat outer diameter	34.823 mm
	Fuel Meat Length	381 mm	
Control Rods	Material	Boron carbide (B_4C) clad in 304 SS	
	Number	6 total 4 with fuel followers	
	Drive	Electrical motor drive Electromagnet connection Compressed air against piston Physical coupling	
Reflectors	Material	Graphite	
	Number	11	
Pool		10 m depth, stainless steel lining, light water, 400 m^3	
Maximum Thermal Flux		1.12x1013 $n/cm^2 s$	
Pulse Operation			
Maximum Pulse Amount		$1.91	

TABLE AI-2. EXAMPLE OF 14 MW TRIGA STEADY STATE REACTOR (SSR) MAIN CHARACTERISTICS [13]

Steady State		
Steady State Power		14 MW
Fuel Assemblies	Type	LEU U-ZrH fuel
	Number	29; 8.9 cm^2 cross section
	Number of fuel element / fuel assembly	25
Control Rods	Material	Hot pressed compacts of boron carbide (B_4C) pellets, clad in Zy-4 tubes. 16 absorber elements installed in square cross section identical with fuel assembly dimensions
	Number	8
	Drive	Electrical motor with rack and pinion Electromagnetic connection with the control rod
Reflectors	Material	Beryllium square cross section identical with fuel assembly
	Number	20 with 3.3 cm central hole 24 without holes
Pool		10m depth, 4.5 in width, 9m length, aluminium tank, light water (300 m^3)
Maximum Thermal Flux Peak		2.9x10^{14} n/cm^{2}s
Maximum Fast Flux Peak		3.6x10^{13} n/cm^{2}s
Pulse Operation		
Maximum Pulse Power		20 000 MW
Minimum Period		1.2 ms
Pulse Width		4.6 ms, 1/2 pulse

TABLE AI-3. EXAMPLE OF TRIGA ACPR MAIN CHARACTERISTICS [13]

Steady State		
Steady State Power		Up to 500 kW Wide steady state power range (from mW). Suitable for tests and calibration measurements for very low power levels
Fuel	Type	12wt%U-ZrH fuel
	Enrichment	20wt% 235U
	Cladding material	stainless steel with dimples
	Diameter	3.56 cm
	Fuel elements number	146+6 fuel followers
	Type	Fuel follower type
	Poison material	natural B_4C
Control Rods	Number	6
	Drive	rack and pinion, electromagnetic connection with the control rod
	Number	2 fast transient rods and 1 adjustable transient rod
Transient Control Rods	Type	air follower
	Poison material	B_4C
	Rod drive	Fast; pneumatic adjustable; rack and pinion drive
Pool		10m depth, 4.5 in width, 9m length, aluminium tank, light water (300 m^3)
Maximum Thermal Flux Peak		$1.0x10^{15}$ n/cm^2s
Maximum Fast Flux Peak		$1.0x10^{14}$ n/cm^2s
Pulse Operation		
Maximum Pulse Power		20 000 MW
Minimum Period		1.2 ms
Pulse Width		4.6 ms, 1/2 pulse

APPENDIX II

TRIGA RESEARCH REACTORS AROUND THE WORLD [2]

Country	Facility Name	Steady State Thermal Power (kW)	Type	Status	Criticality Date
Austria	TRIGA II VIENNA	250	TRIGA MARK II	Operating	07 Mar. 1962
Bangladesh	TRIGA MARK II	3000	TRIGA MARK II	Operating	14 Sep. 1986
Brazil	IPR-RI	100	TRIGA MARK I	Operating	06 Nov. 1960
Democratic Rep. of the Congo	TRICO I	50	TRIGA MARK I	Shutdown	06 Jun. 959
Democratic Rep. of the Congo	TRICO II	1000	TRIGA MARK II	TMSD	24 Mar. 1972
Finland	FIR-1	250	TRIGA MARK II	Operating	27 Mar. 1962
Germany	FRF-2	1000	TRIGA CONV	Decommissioned	01 Oct. 1977
Germany	FRH	250	TRIGA MARK I	Shutdown	31 Jan. 1973
Germany	TRIGA HD I	250	TRIGA MARK I	Shutdown	01 Aug. 1966
Germany	TRIGA HD II	250	TRIGA MARK I	Shutdown	28 Feb. 1978
Germany	FRMZ	100	TRIGA MARK II	Operating	03 Aug. 1965
Germany	FRN	1000	TRIGA MARK III	Decommissioned	23 Aug. 1972
Indonesia	KARTINI-PTAPB	100	TRIGA MARK II	Operating	25 Jan. 1979
Indonesia	TRIGA MARK II, BANDUNG	2000	TRIGA MARK II	Operating	19 Oct. 1964
Italy	LENA, TRIGA II PAVIA	250	TRIGA MARK II	Operating	15 Nov. 1965
Italy	TRIGA RC-1	1000	TRIGA MARK II	Operating	11 Jun. 1960
Japan	NSRR	300	TRIGA ACPR	Operating	30 Jun. 1975
Japan	MUSASHI REACTOR	100	TRIGA MARK II	Shutdown	30 Jan. 1963
Japan	TRIGA-II RIKKYO	100	TRIGA MARK II	Shutdown	08 Dec. 1961
Republic of Korea	TRIGA MK II-SEOUL	250	TRIGA MARK II	Shutdown	19 Mar. 1962
Republic of Korea	TRIGA MK III-SEOUL	2000	TRIGA MARK III	Shutdown	10 Apr. 1972
Malaysia	TRIGA PUSPATI (RTP)	1000	TRIGA MARK II	Operating	28 Jun. 1982
Mexico	TRIGA MARK III	1000	TRIGA MARK III	Operating	08 Nov. 1968
Morocco	MA-R1	2000	TRIGA MARK II	Operating	02 May 2007
Philippines	PRR-1	3000	TRIGA CONV	Shutdown	26 Aug. 1963
Romania	TRIGA II PITESTI - PULSED	500	TRIGA Dual Core	Operating	02 Feb. 1980
Romania	TRIGA II PITESTI - SS CORE	14000	TRIGA Dual Core	Operating	02 Feb. 1980
Slovenia	TRIGA- MARK II LJUBLJANA	250	TRIGA MARK II	Operating	31 May 1966
Taiwan, China	THOR	2000	TRIGA CONV	Operating	13 Apr. 1961

Country	Facility Name	Steady State Thermal Power (kW)	Type	Status	Criticality Date
Thailand	TRR-1/M1	2000	TRIGA MARK III	Operating	07 Nov. 1977
Turkey	ITU-TRR, TECH UNIV	250	TRIGA MARK II	Operating	11 Mar. 1979
United Kingdom	ICI TRIGA REACTOR	250	TRIGA MARK I	Decommissioned	01 Aug. 1971
United States of America	UI-LOPRA UNIV ILLINOIS	10	TRIGA	Decommissioned	28 Dec. 1971
USA	ANN. CORE RES. REACTOR (ACRR)	4000	TRIGA ACPR	Operating	01 Jun. 1967
USA	ARRR	250	TRIGA CONV	Operating	09 Jul. 1964
USA	NSCR TEXAS A&M UNIV.	1000	TRIGA CONV	Operating	01 Jan. 1962
USA	TRIGA PUERTO RICO NUC CTR	2000	TRIGA CONV	Shutdown	01 Aug. 1960
USA	UWNR UNIV. WISCONSIN	1000	TRIGA CONV	Operating	26 Mar. 1961
USA	WSUR WASHINGTON ST. UNIV.	1000	TRIGA CONV	Operating	13 Mar. 1961
USA	PSBR PENN ST. UNIV.	1000	TRIGA MARK CONV	Operating	15 Aug. 1955
USA	AFRRI TRIGA	1000	TRIGA MARK F	Operating	01 Jan. 1962
USA	DORF TRIGA MARK F	250	TRIGA MARK F	Shutdown	01 Jan. 1961
USA	TRIGA MK F, NORTHRUP	1000	TRIGA MARK F	Decommissioned	01 Jan. 1963
USA	ATUTR	250	TRIGA MARK I	Shutdown	01 Jan. 1989
USA	DOW TRIGA	300	TRIGA MARK I	Operating	06 Jul. 1967
USA	GA-TRIGA F	250	TRIGA MARK I	Shutdown	01 Jul. 1960
USA	GA-TRIGA I	250	TRIGA MARK I	Shutdown	03 May 1958
USA	GSTR GEOLOGICAL SURVEY	1000	TRIGA MARK I	Operating	26 Feb. 1969
USA	NRF NEUTRON RAD FACILITY	1000	TRIGA MARK I	Shutdown	01 Mar. 1977
USA	RRF REED COLLEGE	250	TRIGA MARK I	Operating	02 Jul. 1968
USA	TRIGA MK I MICH ST UNIV	250	TRIGA MARK I	Decommissioned	21 Mar. 1969
USA	TRIGA UNIV. UTAH	100	TRIGA MARK I	Operating	25 Oct. 1975
USA	TRIGA, VET. ADMIN.	20	TRIGA MARK I	Shutdown	26 Jun. 1959
USA	UCI, IRVINE	250	TRIGA MARK I	Operating	25 Nov. 1969
USA	UI-TRIGA MK I	100	TRIGA MARK I	Shutdown	01 Aug. 1960
USA	UNIV. ARIZONA TRIGA	100	TRIGA MARK I	Operating	06 Dec. 1958
USA	UT TRIGA UNIV TEXAS	1000	TRIGA MARK I	Decommissioned	01 Jan. 1963
USA	KSU TRIGA MK II	250	TRIGA MARK II	Operating	16 Oct. 1962

Country	Facility Name	Steady State Thermal Power (kW)	Type	Status	Criticality Date
USA	NRAD	250	TRIGA MARK II	Operating	12 Oct. 1977
USA	OSTR, OREGON STATE UNIV.	1100	TRIGA MARK II	Operating	08 Mar. 1967
USA	TRIGA COLUMBIA UNIV	250	TRIGA MARK II	Decommissioned	01 Jan. 1977
USA	TRIGA CORNELL	500	TRIGA MARK II	Shutdown	01 Jan. 1962
USA	TRIGA II UNIV. TEXAS	1100	TRIGA MARK II	Operating	12 Mar. 1992
USA	UC DAVIS/MCCLELLAN N. RESEARCH CENTER	2000	TRIGA MARK II	Operating	20 Jan. 1990
USA	UI-TRIGA UNIV. ILLINOIS	1500	TRIGA MARK II	Shutdown	23 Jul. 1969
USA	BRR UC BERKELEY	1000	TRIGA MARK III	Decommissioned	10 Aug. 1966
USA	GA-TRIGA III	1500	TRIGA MARK III	Decommissioned	01 Jan.1966
USA	MUTR UNIV. MARYLAND	250	TRIGA Modified	Operating	01 Dec. 1960

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