TRIGA® REACTORS

ORIGINS, HISTORY AND PRESENT

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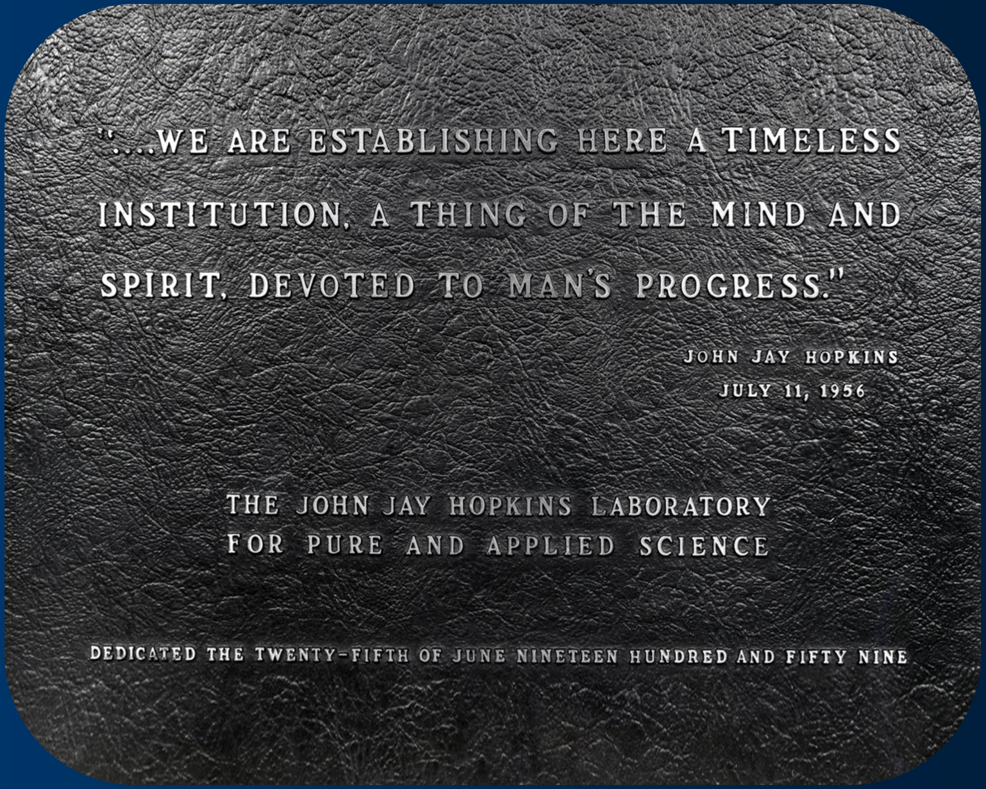
FOR: GA RETIREES ASSOCIATION

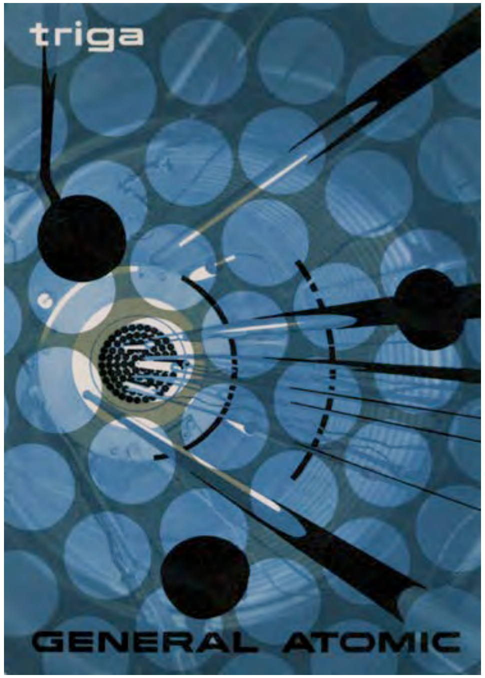
19TH SEPTEMBER 2019



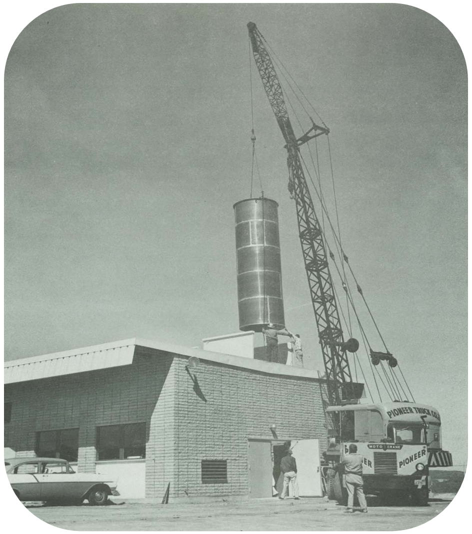
GENERAL ATOMICS

OUTLINE

- **TRIGA Development**
  - Historical Perspective
  - Key technology evolutions
  - Key installations worldwide
- **TRIGA Reactor Installations at GA**
  - Key Characteristics, Operating History and Utilization
  - Decommissioning Activities and current status
- **TRIGA Fuel Development & Fabrication**
- **Open Discussion**

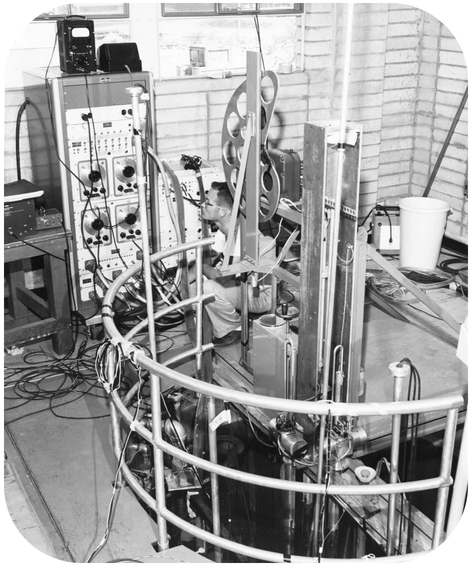


THE FIRST TRIGA: 10 kW PROTOTYPE INITIAL CRITICALITY MAY 3, 1958

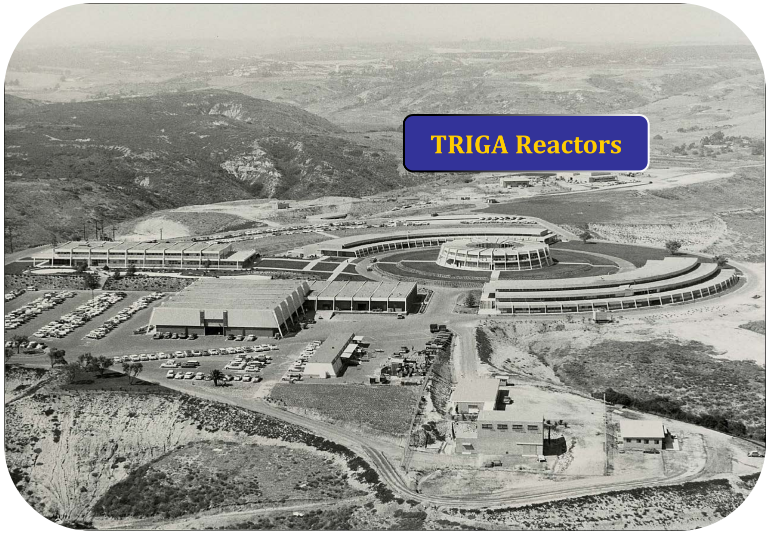


THREE REACTORS WERE CONSTRUCTED ON THE TORREY PINES SITE

250 kW MARK I
1.5 MW MARK F (1960)
2.0 MW MARK III (1968)




1959 – Niels Bohr speaks at GA site dedication



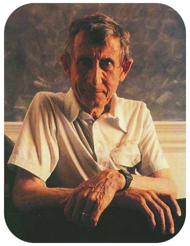
TRIGA: THE "SAFE" REACTOR

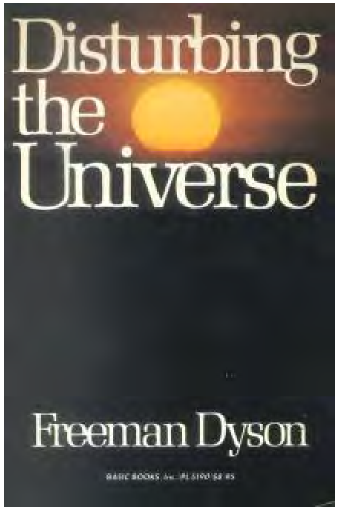
- **The so-called Safe Reactor was originally Edward Teller's idea (1955-'56).**

  "... a reactor so safe that it could be given to a bunch of high school children to play with without any fear that they would get hurt ..."

  "... inherent safety means that its safety must be guaranteed by the laws of nature and not merely by the details of engineering ..."

- **The governing law of nature is the fundamental behavior of homogeneous reactor fuel**
  - *Fission of U-235 heats the homogeneous mixture of fuel and moderator ($UZrH_x$) and results in neutrons in thermal equilibrium with the mixture at temperature T*

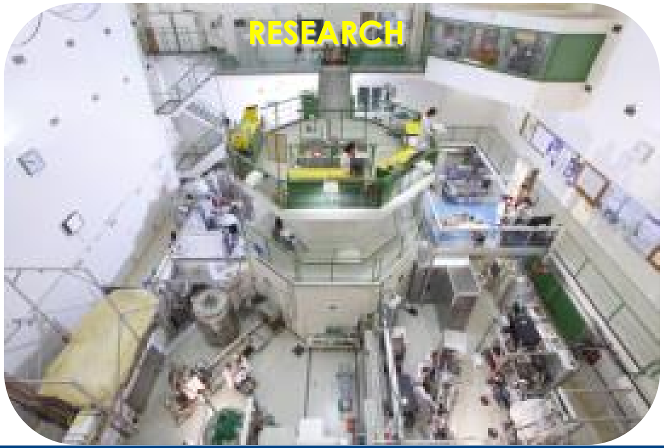


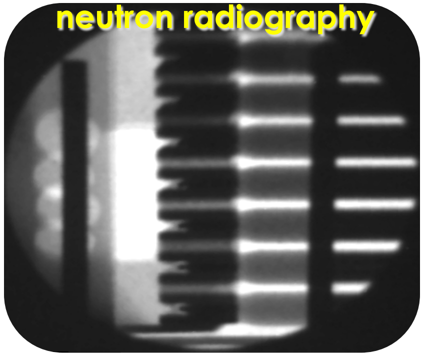


66 TRIGA® Reactors Worldwide . . .

Training
Research
Isotope Production
General
Atomics

- Inherently safe
- Pool-type, light water-cooled
- SS or Incoloy-clad, $UZrH_x$ or $UZrH_x$-Er fuel
- 20 kWt to 16 MWt
- Designs to 25 MWt





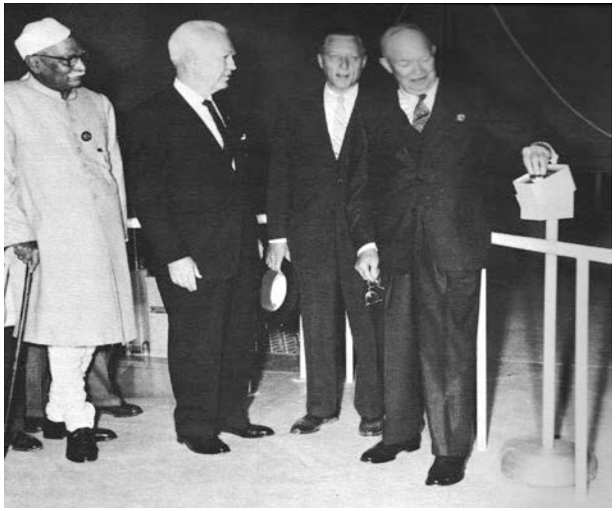
. . . IN 23 COUNTRIES

- 13 ARE CONVERSIONS FROM ALUMINIDE PLATE TO $UZrH_X$ CORES
- FOUR OTHER PROJECTS NOT COMPLETED
- >1100 REACTOR YEARS AND >50,000 TRANSIENTS

EARLY DEMONSTRATIONS OF TRIGA TECHNOLOGY

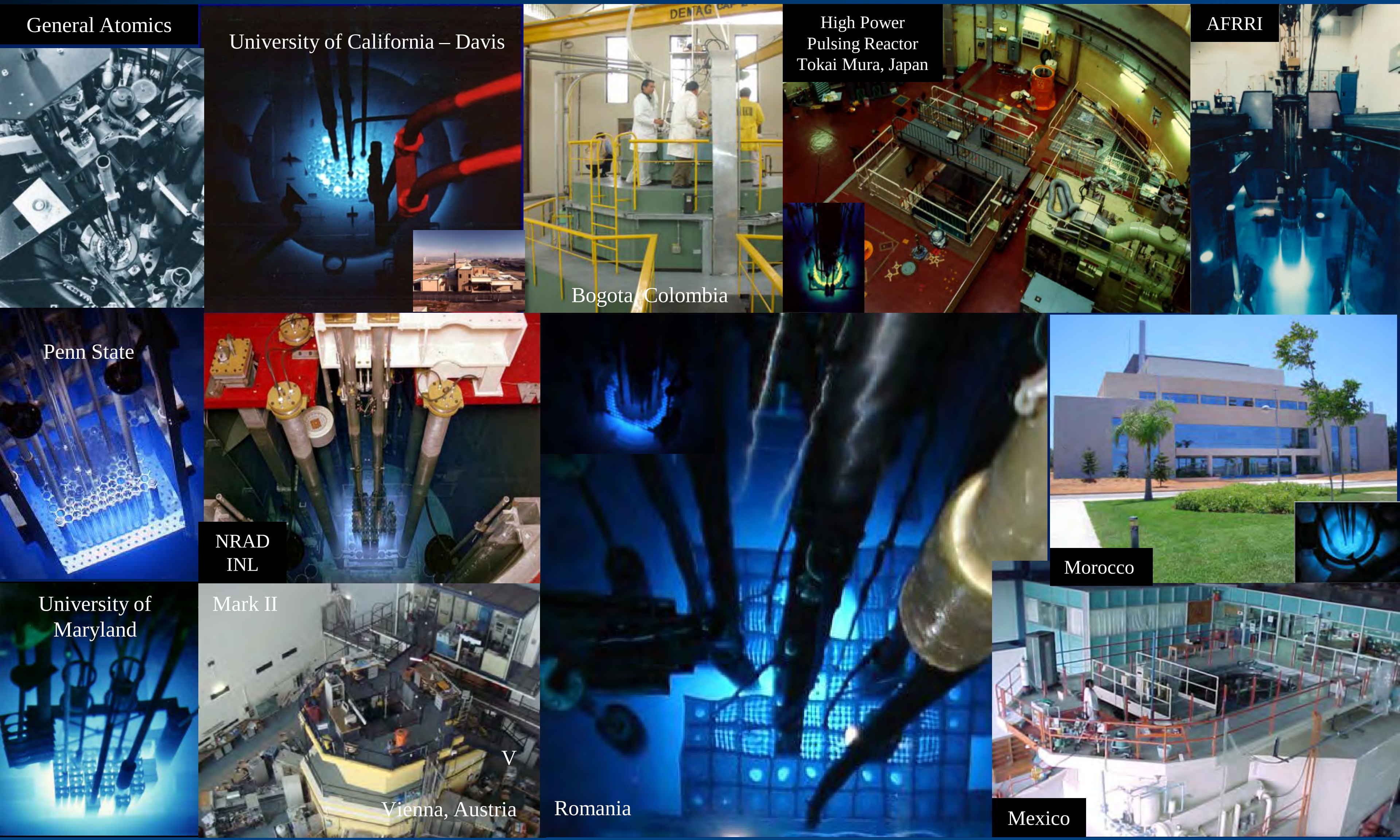
2ND GENEVA CONFERENCE ON PEACEFUL USES
OF ATOMIC ENERGY
SEPTEMBER 1958

WORLD AGRICULTURAL FAIR
NEW DELHI
LATE 1959



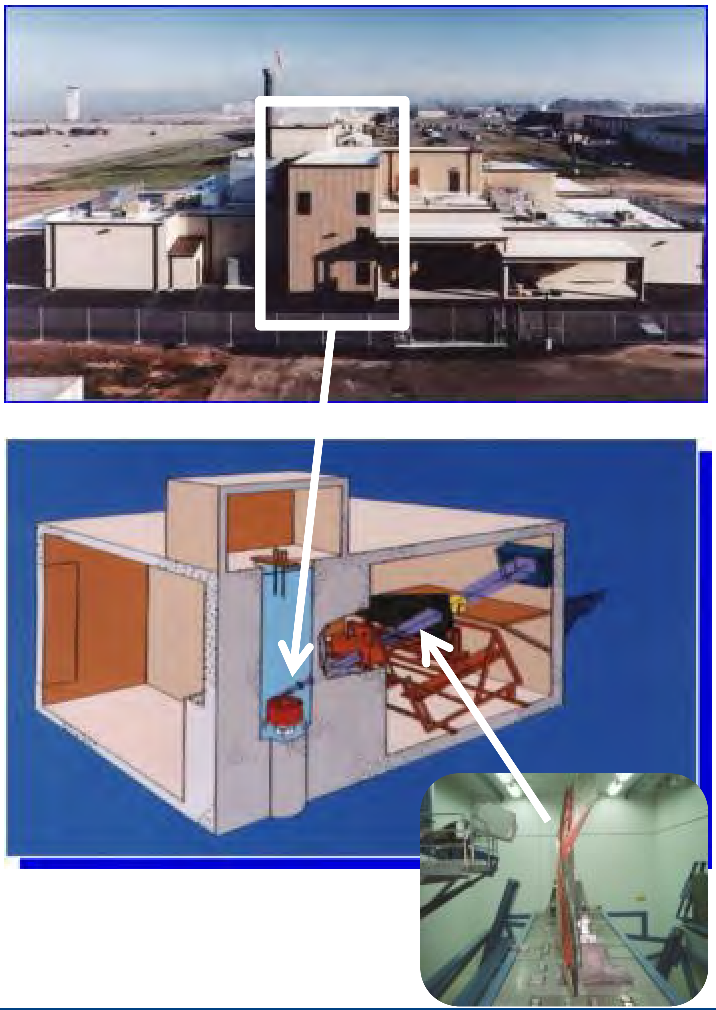
ACQUIRED BY CONGO AND BECAME THE FIRST REACTOR
TO OPERATE ON THE AFRICAN CONTINENT

TRIGA : 1958 - Present

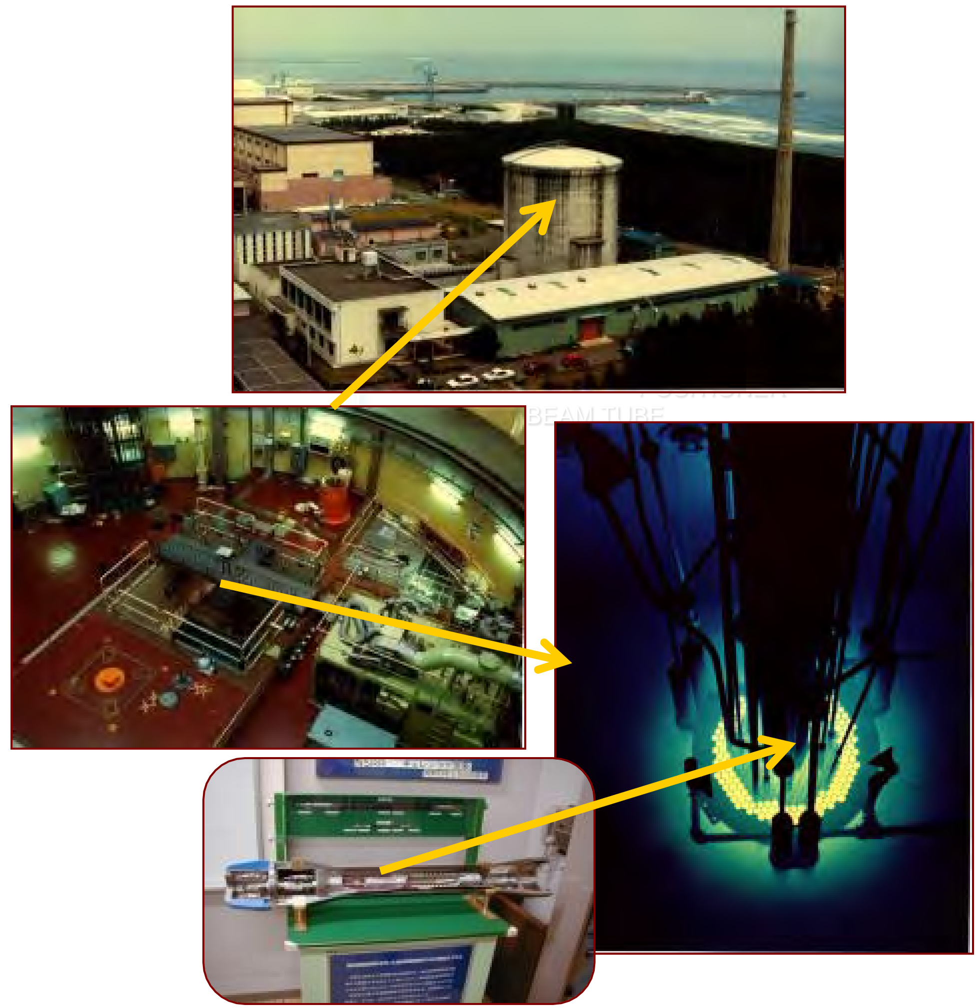


SPECIAL PURPOSE TRIGA REACTORS

University of California - Davis
McClellan Nuclear Radiation Center

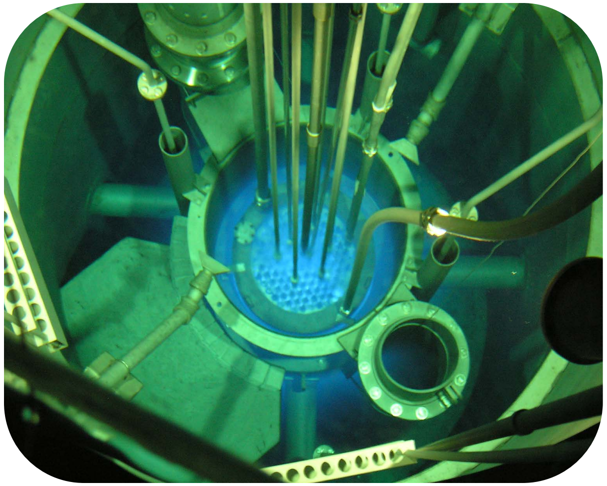


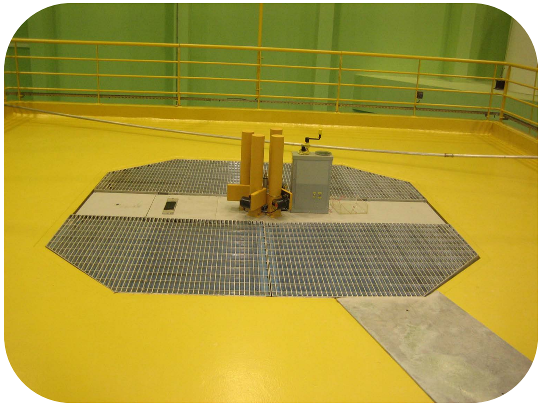
High Power [22 GW(t)] Annular Pulsing Reactor
Tokai Mura, Japan



2 MW UPGRADABLE TRIGA REACTOR MOROCCO

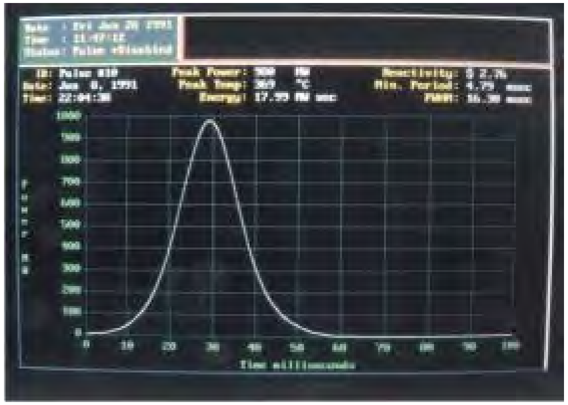
COMMISSIONED 2007

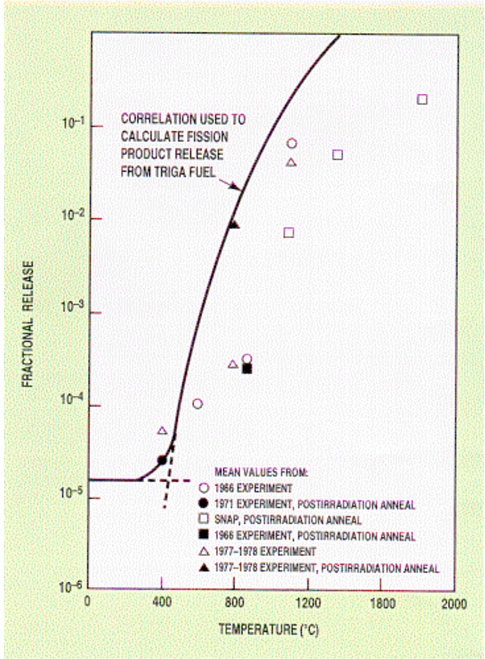




SAFETY COMES FROM FUEL CHARACTERISTICS

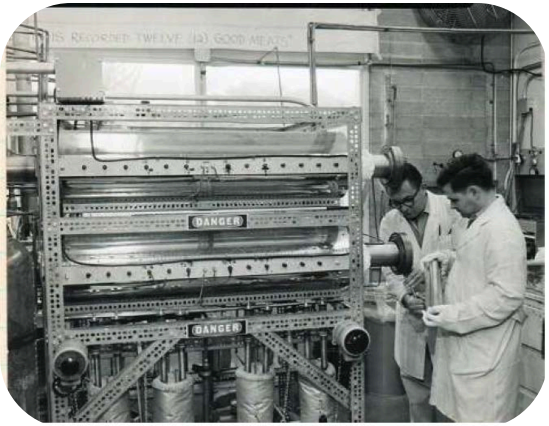
- **LARGE *PROMPT* NEGATIVE TEMPERATURE COEFFICIENT**
  - *limits peak fuel temperatures*
  - *Safety of large reactivity insertions has been demonstrated*
- **CHEMICAL STABILITY**
  - *$UZrH_x$ metal fuel matrix demonstrated to be chemically stable & corrosion resistance in water*
- **CLADDING STRENGTH**
  - *High strength cladding maintains integrity at high temperatures and high fuel burnup*
- **FISSION PRODUCT RETENTION**
  - *The fuel matrix provides high retention of fission products*

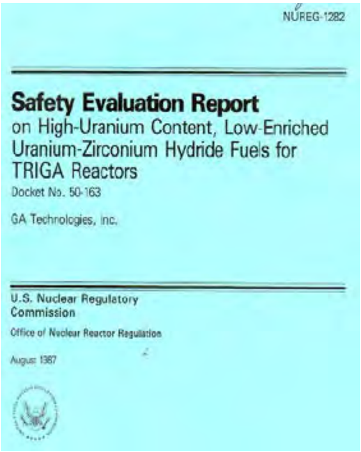




URANIUM-ZIRCONIUM HYDRIDE FUEL TECHNOLOGY EVOLVED

- **Early 1950s: $UZrH_{1.0}$ metallic alloy fuels first developed for satellite use.**
- **Late 1950s-early 60s: Development continued at GA.**
- **Early fuels were LEU (<1.0 gU/cm^3). HEU with burnable poisons used for extended core life.**
- **1987: High density LEU fuels (> 8.0 gU/cm^3) for medium to high power regimes with long core life approved by NRC:**
  - *10 TRIGAs converted from HEU to high density LEU fuels.*

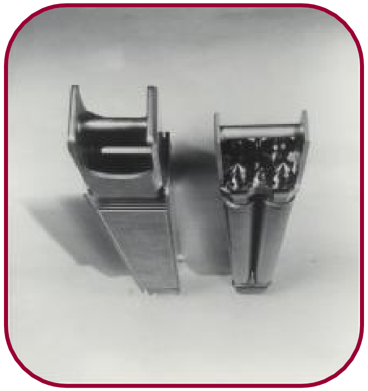


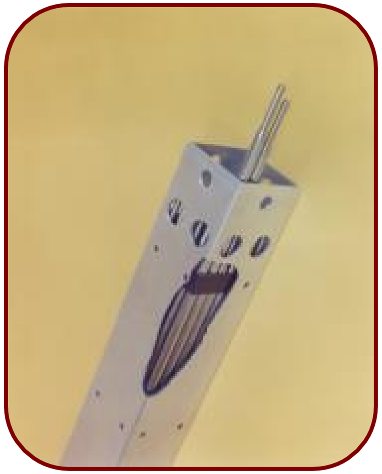

NUREG-1282

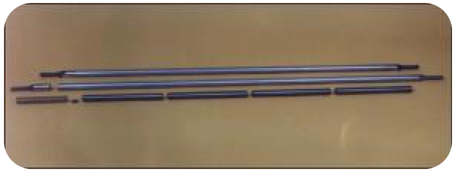
Safety Evaluation Report
on High-Uranium Content, Low-Enriched Uranium-Zirconium Hydride Fuels for TRIGA Reactors
Docket No. 50-163
GA Technologies, Inc.

U.S. Nuclear Regulatory Commission
Office of Nuclear Reactor Regulation

August 1987

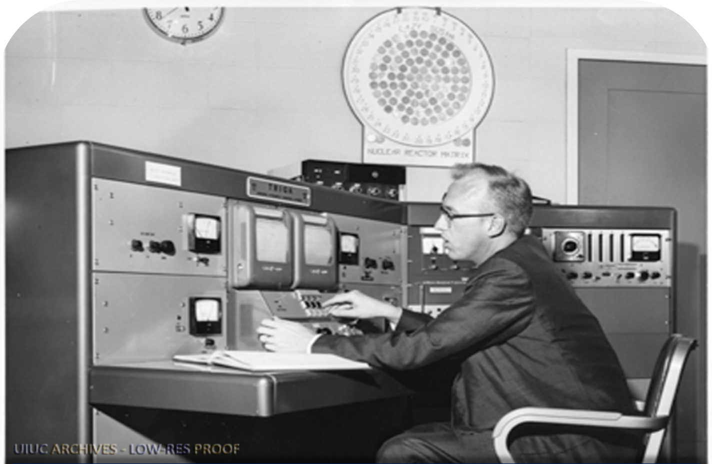




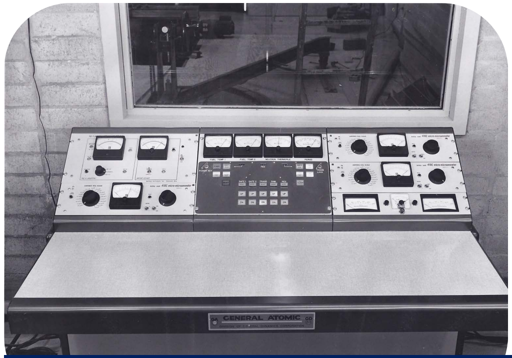


INSTRUMENTATION & CONTROL SYSTEMS EVOLVED

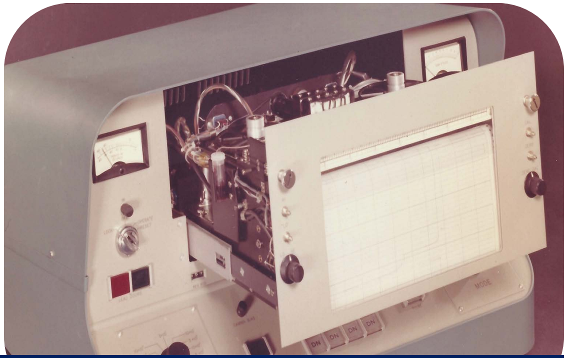
GENERATION I
VACUUM TUBE AND TRANSISTORIZED



U of Illinois: Original Vacuum Tube (1958)

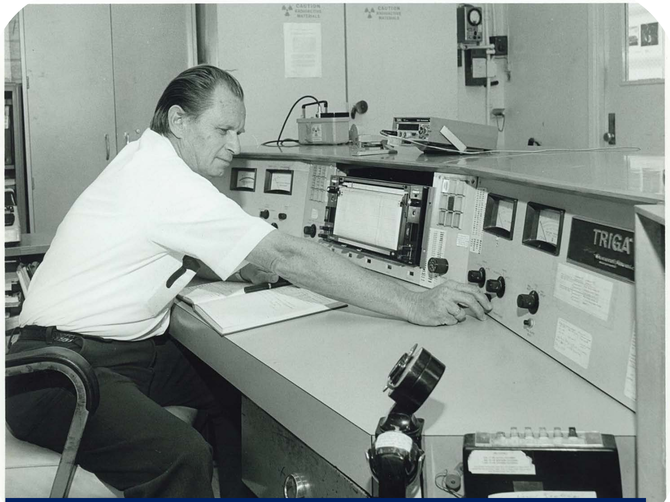


GA TRIGA 1.5 MW Mark F (1960)



Desktop Version

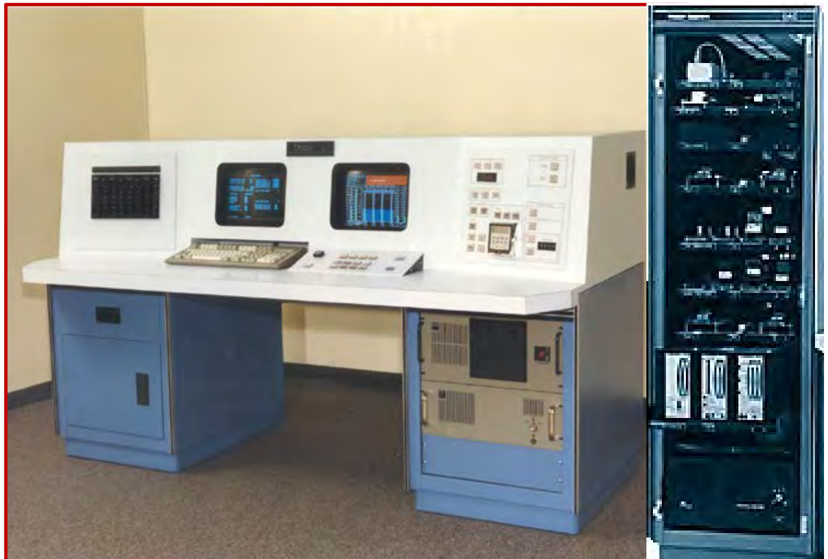
GENERATION II
SOLID STATE



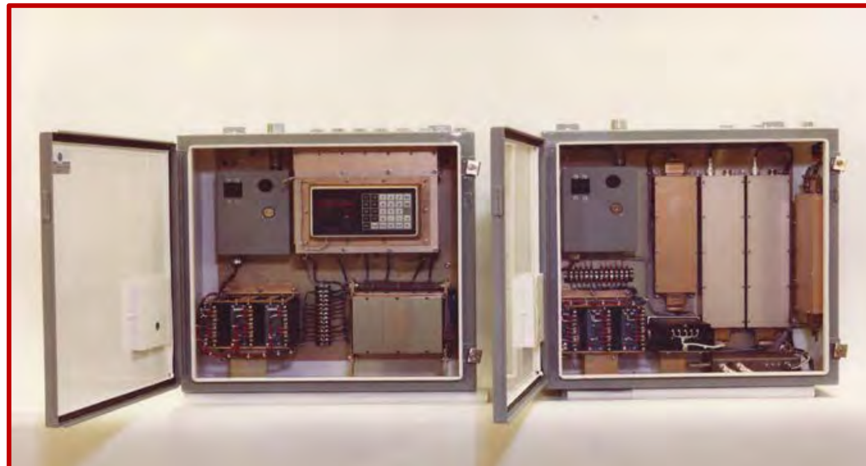
GA TRIGA MARK I (Early 1970s)

BANGLADESH 3 MW TRIGA MARK II (1987)

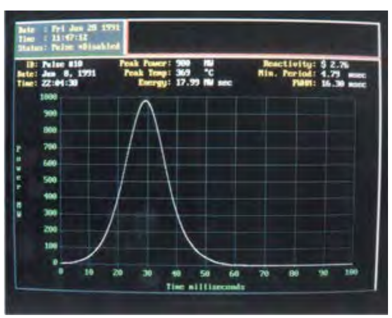
The Switch from Solid State Analog to Analog-Digital (1987)

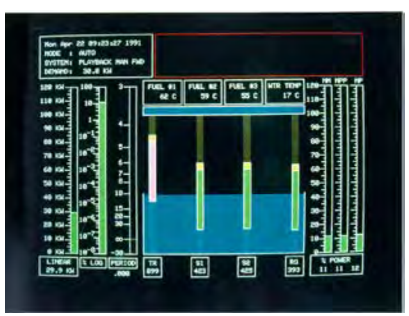


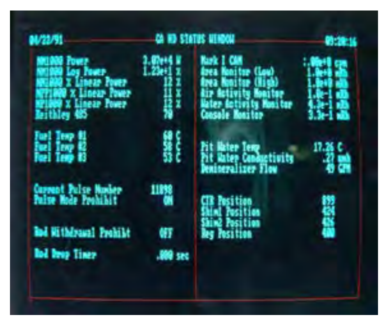
Prototype Operator Console

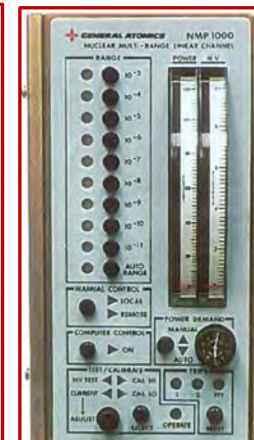


Prototype NM-1000 Wide Range Channel







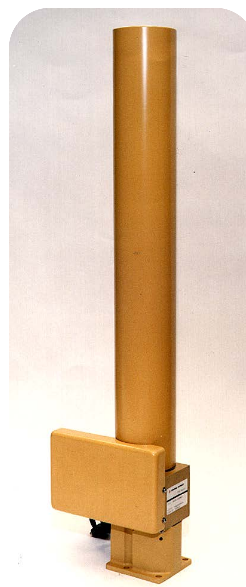


Earlier Versions of Compact, Modularized NI Channels

CURRENT GENERATION III TRIGA I&C INSTALLATIONS

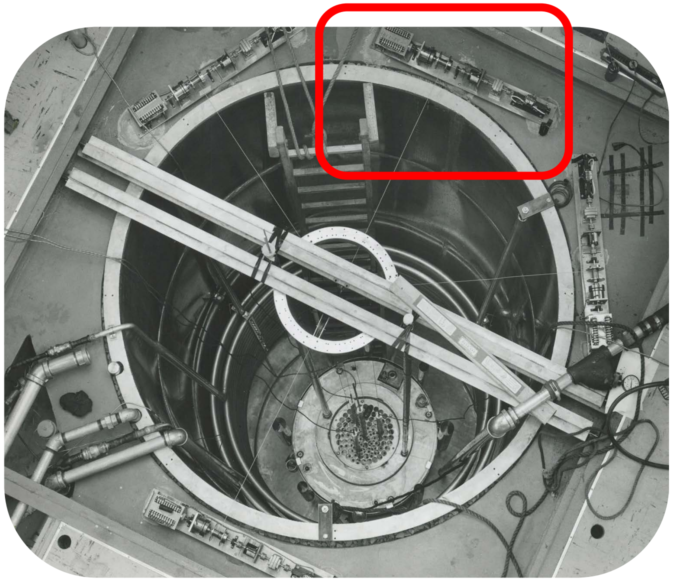
Idaho National Lab

Bangladesh

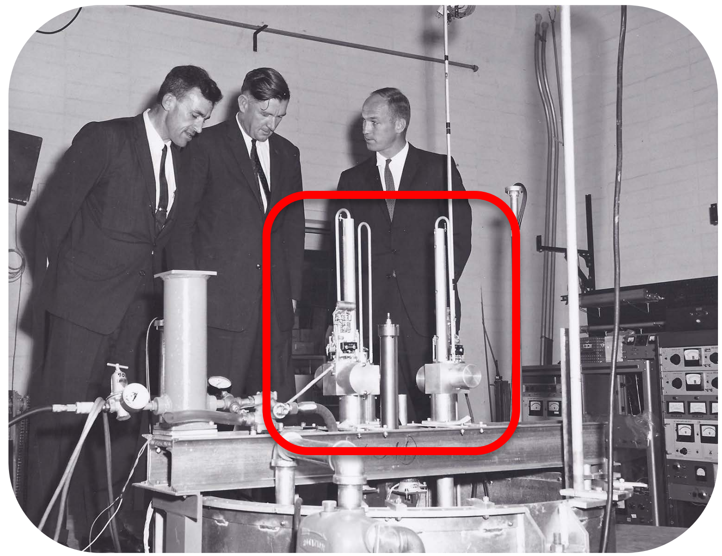


AFRRI

EVOLUTION OF CONTROL ROD DRIVE TECHNOLOGY



GA TRIGA Mark I (1958)
Pulley Driven



GA TRIGA Mark F (1960)
Rack & Pinion

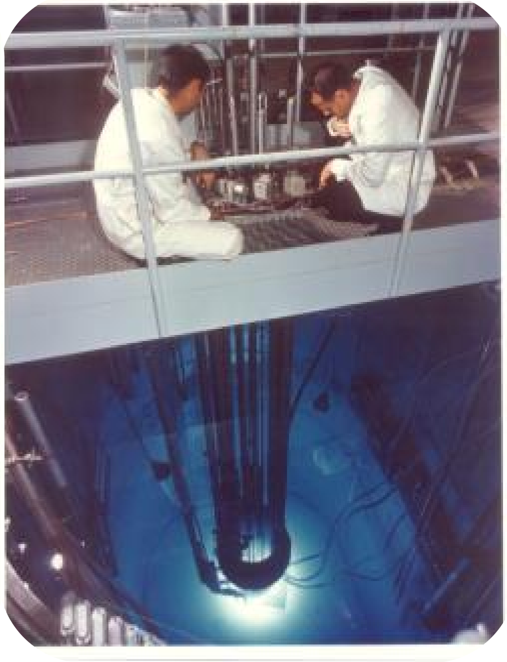
1988 - Present
Stepping Motors

GENERAL ATOMICS' TRIGA REACTORS FACILITY TORREY PINES MESA

THREE OF THE EARLIER TRIGA REACTORS WERE BUILT AT GA OPERATED FROM 1958 – 1997

- **MARK I**
  - ✓ Originally 10 kW
  - ✓ 250 kW Steady State
  - ✓ $3.00 Transients

- **MARK F**
  - ✓ 1,500 kW Steady State
  - ✓ $5.50 Transients
  - ✓ Movable core



- **MARK III**
  - ✓ 2,000 kW
  - ✓ No pulsing
  - ✓ Movable core

GENERAL ATOMICS MARK I: KEY CHARACTERISTICS

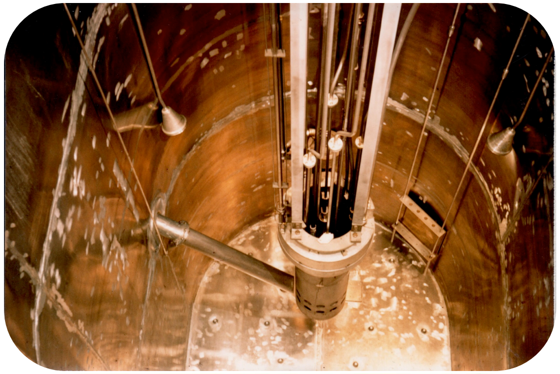
INITIAL CRITICALITY	MAY 3, 1958
SHUTDOWN	1997
NPUF LICENSE/DOCKET	R-38/50-89
POWER (SS/TRANSIENT)	250 kW / $3.00 (~ 1 GW)
TYPE	BELOW GROUND OPEN POOL, LIGHT WATER NATURAL CONVECTION COOLED
FUEL	$UZrH_{1.0-1.6}$ Al and SS clad 8.5 wt% U 19.7% U-235
MODERATOR/REFLECTOR	ZrH_X/GRAPHITE
CONTROL	3 - B_4C MOTOR DRIVEN 1 – B_4C AIR DRIVEN (TRANSIENTS)
KEY UTILIZATION FEATURES	ROTARY RACK, RABBIT, HIGH TEMP FURNACES, RADIOGRAPHY, IN-CORE IRRADIATION FACILITIES

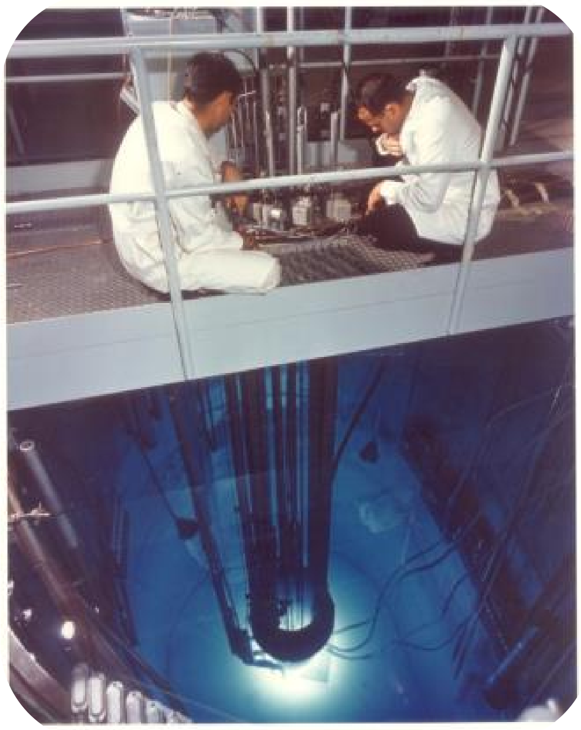
GENERAL ATOMICS MARK F: KEY CHARACTERISTICS

INITIAL CRITICALITY	JULY 2, 1960
SHUTDOWN & SECURED	MARCH 22, 1995
NPUF LICENSE/DOCKET	R-67/50-163
POWER (SS/TRANSIENT)	1,500 kW / $5.50 (~ 6.4 GW)
TYPE	BELOW GROUND OPEN POOL, LIGHT WATER NATURAL CONVECTION COOLED
FUEL	$UZrH_{1.6}$ SS clad 8.5 – 30 wt% U 70% and 19.7% U-235
MODERATOR/REFLECTOR	ZrH_X H_2O
CONTROL	5 - B_4C FUEL FOLLOWERS 1 – B_4C AIR DRIVEN TRANSIENT[1]
KEY UTILIZATION FEATURES	HIGH TEMP FURNACES, NEUTRON RADIOGRAPHY, LARGE IN-CORE & EX-CORE IRRADIATION FACILITIES

[1] REMOVED DURING 24/7 STEADY STATE OPERATIONS

GENERAL ATOMICS MARK III: KEY CHARACTERISTICS

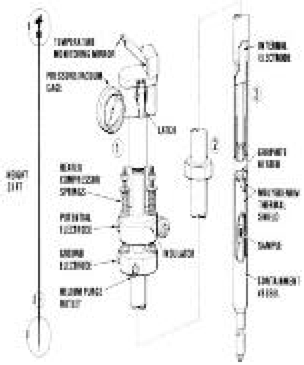




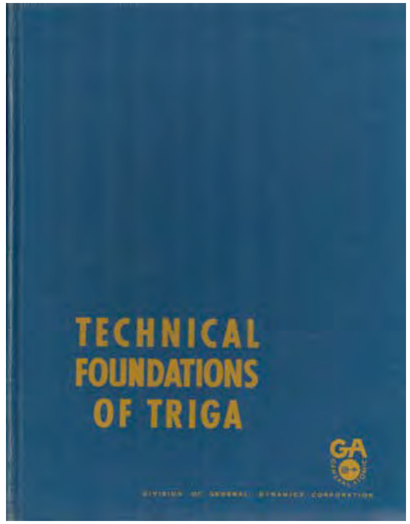
INITIAL CRITICALITY	JAN 17, 1966
SHUTDOWN & SECURED	SEPT 26, 1973
NPUF LICENSE/DOCKET	R-100/50-227
POWER (SS/TRANSIENT)	2,000 kW / SS only
TYPE	OPEN POOL, LIGHT WATER NATURAL CONVECTION COOLED
FUEL	$UZrH_{1.6}$ SS clad 8.5 wt% U 70% U-235
MODERATOR/REFLECTOR	ZrH_X/H_2O
CONTROL	4 - B_4C FUEL FOLLOWERS
KEY UTILIZATION FEATURES	LARGE IN-CORE IRRADIATION FACILITIES, BEAM PORTS

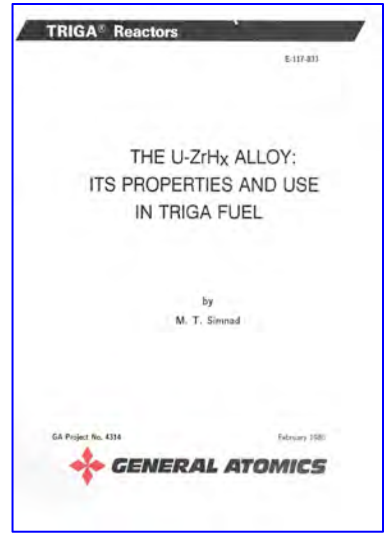
UTILIZATION OF GA'S THREE RESEARCH REACTORS OVER THEIR LIFETIMES

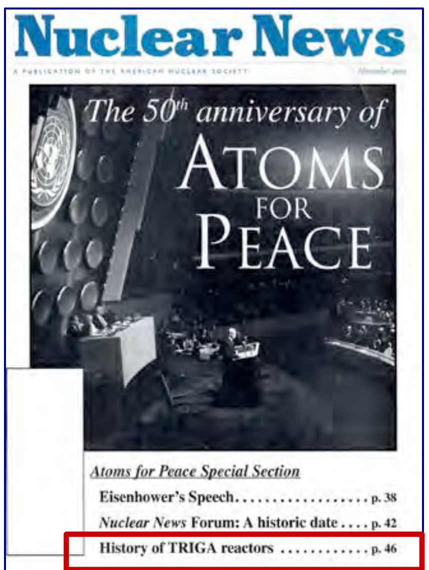
- **Testing of SP-100 Thermionic Fuel Elements**
  - 24/7 operations (Mark F and Mark III) with only 1-week maintenance shutdown per year.
- **Neutron activation analysis**
- **Neutron radiography**
  - Vertical beam (Mark I) and underwater (Mark F)
- **Production of short-lived isotopes**
  - F-18 in Mark F
  - R&D on others
- **Semiconductor radiation hardness testing**
- **Operator training**
- **Fuel Testing and qualification: $UZrH_x$ and TRISO**
  - In-core high-temperature furnaces operated in both Mark I and Mark F.
- **Reactor Instrumentation Testing &Qualification**
  - Mark I first Part 50 license with full digital I&C
- **Gemstone Irradiations**
  - Blue topaz

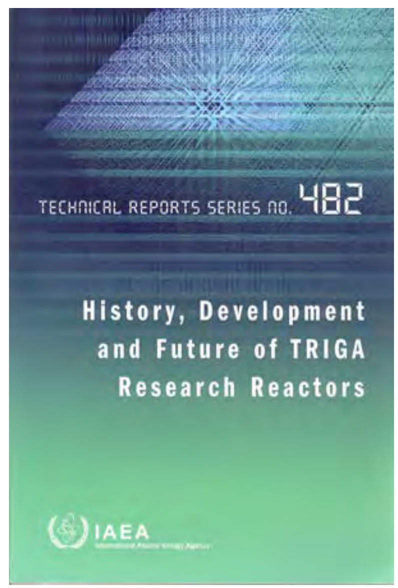


HISTORICAL AND RECENT TRIGA RELATED PUBLICATIONS





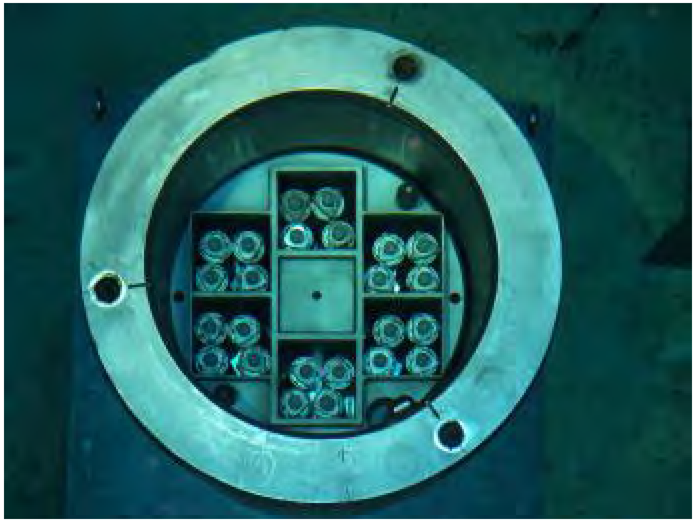




GENERAL ATOMICS TRIGA REACTORS FACILITY SHUTDOWN TO FUEL REMOVAL (1995-2010)

- **TRANSFER MARK I FUEL TO MARK F REACTOR POOL**
- **REMOVE MARK I REACTOR INTERNALS AND TANK**
- **MARK I BIOSHIELD CORE DRILLING & ACTIVATION ANALYSIS**
- **IMPLEMENT POST-9/11 COMPENSATORY MEASURES**
  - Install Physical Barriers
  - Enhance Surveillance & Monitoring
- **CHACTERIZE FUEL & PLAN FOR TRANSFER TO DOE**
  - Negotiations with DOE, INL, and others

REMOVAL OF SPENT FUEL SEPTEMBER 2010 TO IDAHO NATIONAL LAB



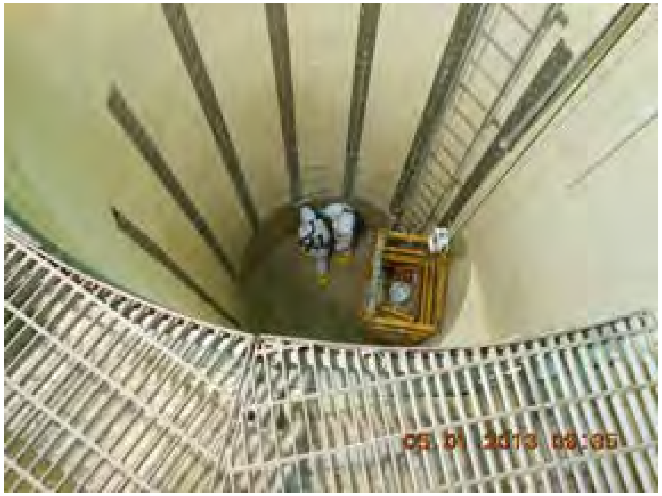
REMOVAL OF SPENT FUEL
SEPTEMBER 2010 TO IDAHO NATIONAL LAB

REMOVAL OF IRRADIATED HARDWARE FROM MARK F UNDERWATER STORAGE CANAL

- **NOVEMBER 2010 - MAY 2012**
  - PLANNING, RADIOLOGICAL CHARACTERIZATION AND RAD SURVEYS OF HIGHLY-RADIOACTIVE NEUTRON-ACTIVATED HARDWARE
  - LOADING AND GROUTING OF NEUTRON ACTIVATED ITEMS IN FOUR TYPE A CONTAINERS
  - SHIPMENT OF ~35 Ci OF ACTIVATED MATERIAL TO NEVADA NATIONAL SECURITY SITE (NNSS)

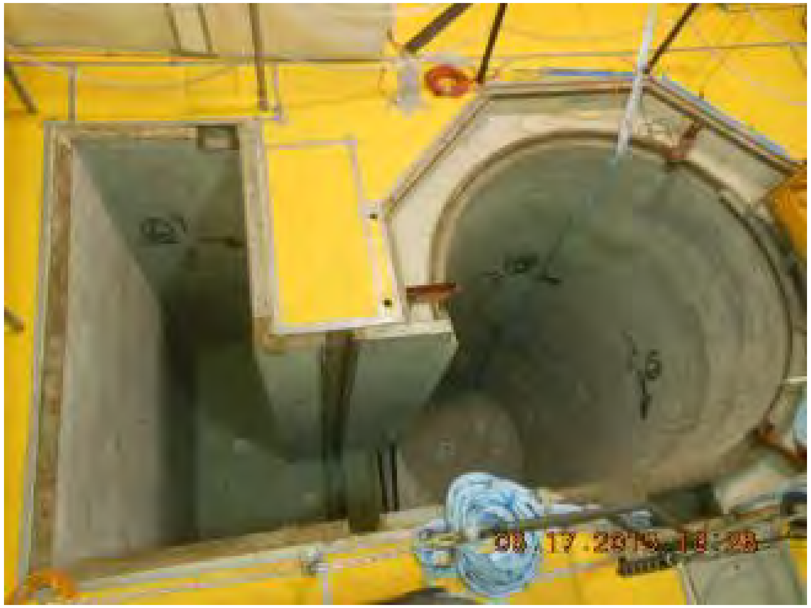
PUMPOUT OF MARK F POOL & REMOVAL OF REMAINING LOW LEVEL HARDWARE

- **JUNE 2012 - JUNE 2013**
  - PUMPOUT MARK F POOL (~18K GALLONS)
  - REMOVE UNDERWATER BARRIERS & FUEL STORAGE RACKS
  - PACKAGE & SHIP LLW FOR DISPOSAL



CHARACTERIZATION & REMOVAL OF SURFACE Cd & Pb CONTAMINATION IN MARK F PIT

- **JULY 2013 - MAY 2015**
  - CHARACTERIZE MLLW (Cd & Pb) ON SURFACE OF MARK F PIT
  - REMOVE SURFACE LAYER OF EPOCAST & GUNITE IN PIT & CANAL

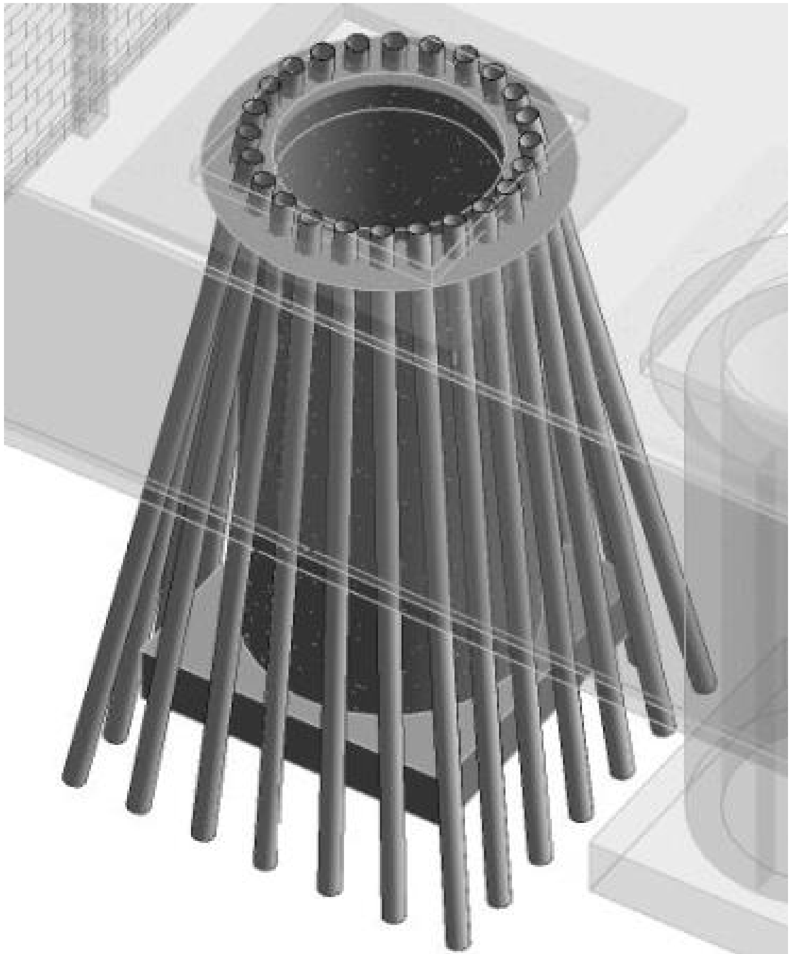


CHARACTERIZATION AND EXCAVATION OF MARK F REACTOR PIT

- **JUNE 2015 - DECEMBER 2018**
  - CORE DRILLING & SAMPLE ACTIVATION ANALYSIS
  - REMOVE GUNITE & STEEL LINER UP TO 6.5 FT (REACTOR PIT ONLY)
  - REMOVE PORTION OF WALL & FLOOR CONCRETE (NO SOIL REMOVAL REQUIRED)

CHARACTERIZATION AND EXCAVATION OF MARK I REACTOR PIT

- **MARK I MICROPILE INSTALLATION – SEPT 2018**
  - BORING TO 28 FT. DEPTH TO CHARACTERIZE SOIL
  - 24 MICROPILES INSTALLED TO BELOW FOUNDATION TO STABILIZE SOIL
  - SECURED TO INSIDE CYLINDER WITH TOW HOOKS & CHAINS



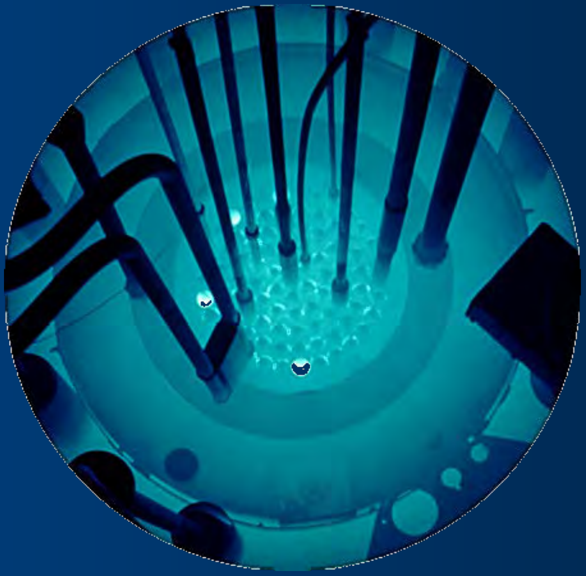
CHARACTERIZATION AND EXCAVATION OF MARK I REACTOR PIT

- **JANUARY 2017 - MARCH 2019**
  - CORE DRILLING & SAMPLE ACTIVATION ANALYSIS
  - REMOVED BOTTOM 6.5 FT OF CONCRETE CYLINDER
  - REMOVED ENTIRETY OF FLOOR
  - REMOVED UP TO 1FT OF SURROUNDING SOIL
  - SCREW JACKS INSTALLED FOR ADDITIONAL STABILIZATION

TRIGA REACTORS FACILITY CURRENT STATUS & FUTURE PLANS

- **APRIL 2019 – PRESENT**
  - SHIP 18 BOXES & 24 DRUMS OF WASTE FOR DISPOSAL
  - COLLECT POST REMEDIATION SOIL/CONCRETE SAMPLES FROM EXCAVATED PITS
  - FINAL STATUS SURVEYS UNDERWAY
  - EXPECT LICENSE TERMINATION BY NRC IN 2020
  - PROPERTY TO BE RELEASED FOR UNRESTRICTED USE BY GA

TRIGA FUEL DEVELOPMENT & FABRICATION



19 September 2019

TRIGA INTERNATIONAL

WORLDWIDE TRIGA REACTORS

Training, Research, Isotopes, General Atomics (TRIGA)

- First reactor critical May 3, 1958 in San Diego, California
- 66 TRIGA facilities have been constructed to date
- Steady-state operating power levels to 14 MW(t)*
- Pulsing to 22,000 MW(t)

TRIGA WIDE RANGE CAPACITY

Veteran Administration Hospital TRIGA
18 Kw Reactor Facility

Romania 14 MW TRIGA Reactor Facility

TRIGA INTERNATIONAL

TRIGA FUEL DEVELOPMENT

TRIGA Fuel
Fabrication Facility

- **TRIGA fuel fabrication carried out at GA's San Diego Campus from1958 through 1995**
- **Fuel element design**
  - Low power design
  - High power design
- **Fuel development**
  - U content
  - U-235 enrichment

TRIGA INTERNATIONAL

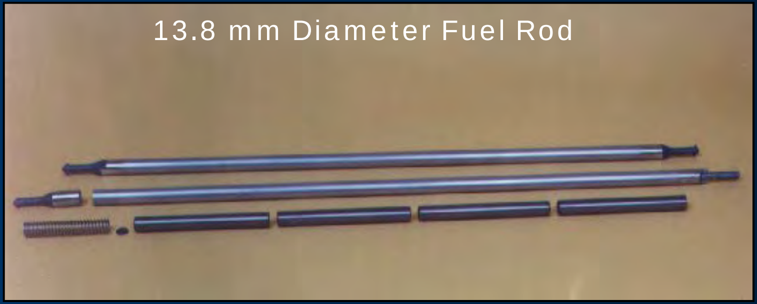
TRIGA FUEL ELEMENT DESIGNS

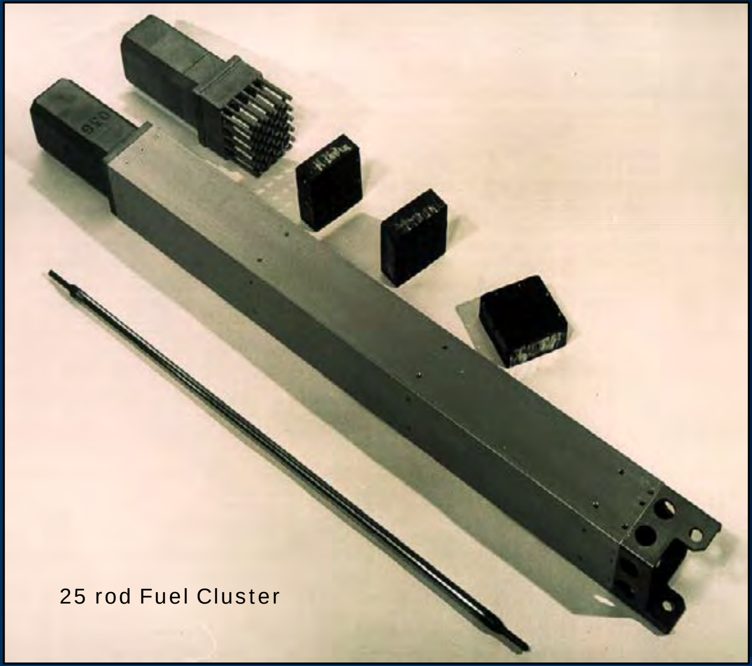
Low Power Design ≤ 3 MW

Standard Fuel Element

Plate Conversion
4 Rod Cluster Design

High Power/High Performance Design ≥ 5 MW





TRIGA FUEL FABRICATION FACILITY – CHANGE IN VENUE

Problem:

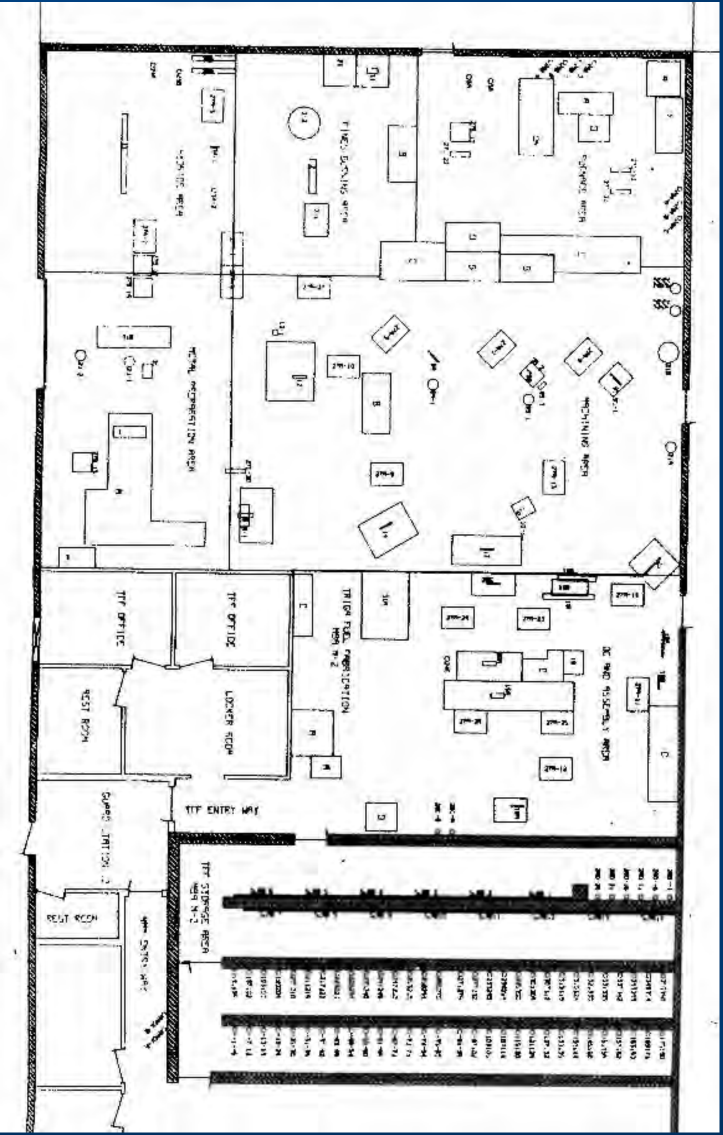
- In the early 90's, licensing TRIGA fuel fabrication in a single purpose facility for operation in San Diego/USA became very expensive and economically impractical

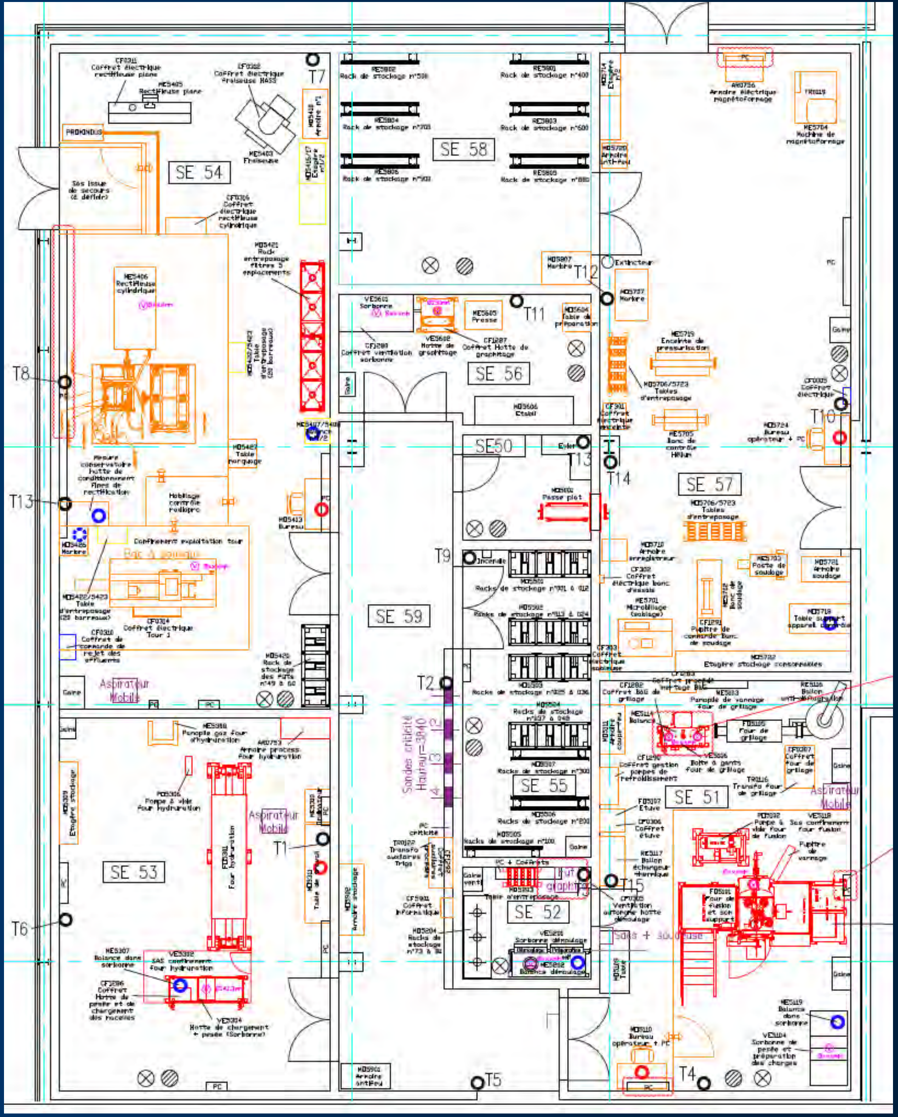
Solution:

- GA investigated relocating the fuel fabrication facility to reduce the escalating costs
- TRIGA International, SAS (TI) was founded
    - A 50 / 50 Joint Venture between General Atomics and CERCA (AREVA/Framatome)
    - A French company with headquarter in Paris, Fabrication facility in Romans sur Isere

TRIGA INTERNATIONAL

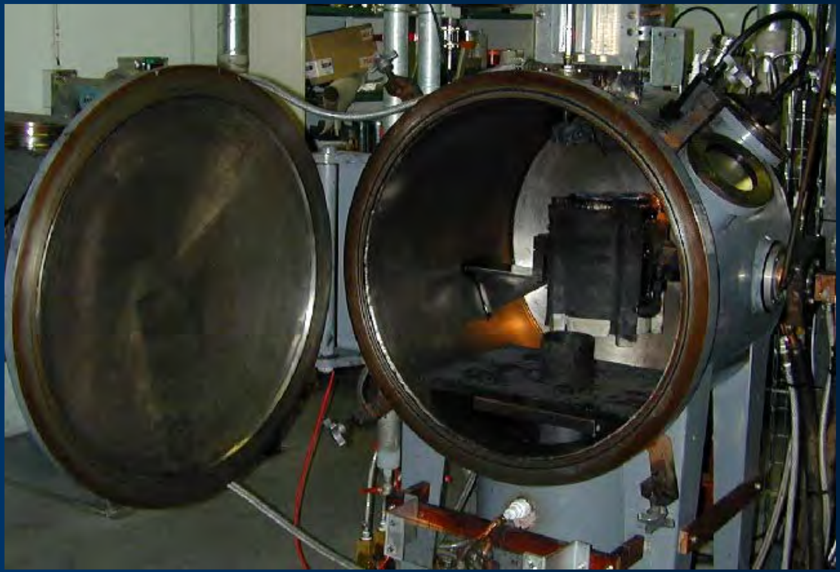
COMPARISON OF TRIGA FUEL FABRICATION FACILITIES





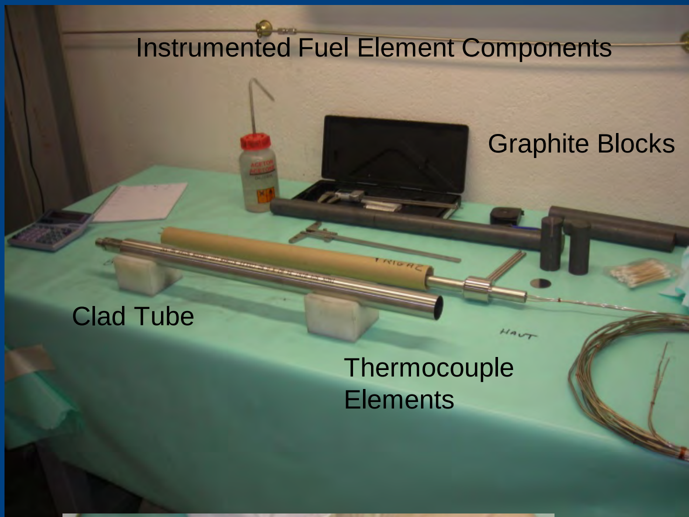
TRIGA INTERNATIONAL

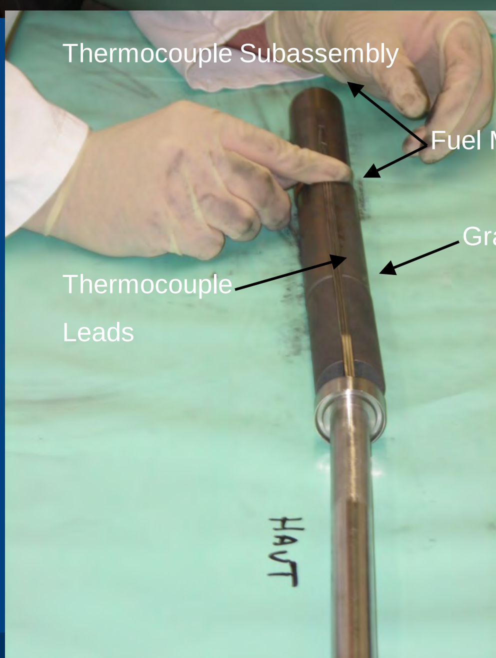
FUSION / CASTING FURNACE



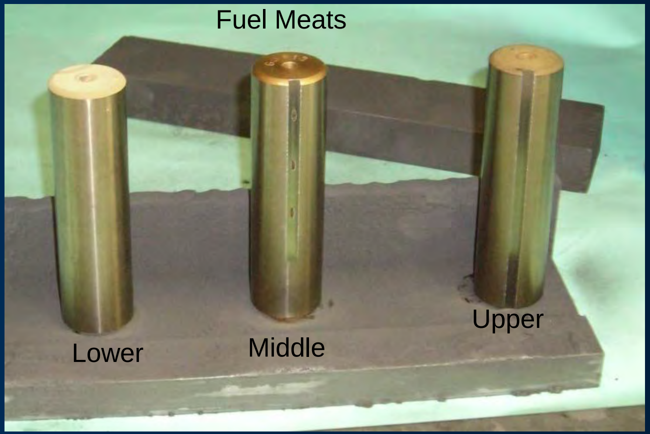
HYDRIDE FURNACE

FUEL ELEMENT ASSEMBLY





Manual Assembly of Subassembly



Assembled Instrumented Fuel Elements

Boiling Water
Bath

TRIGA INTERNATIONAL EXPERIENCE

- The TI joint venture has been very successful
- Fabricated more than 1000 fuel elements
- Converted 7 TRIGA reactors from the use of HEU to LEU

Reactor	Contract	Commissioning	Fuel Elements
Romania - Initial 1/2 Core (San Diego)	1993	1994	400
Romania - Final 1/2 Core (TRIGA International)	2003	2006	400
Texas A&M University	2005	2006	66
Washington State University	2006	2008	62
Oregon State University	2007	2008	96
University of Wisconsin	2008	2009	106
Neutron Radiography (NRAD), INL	2009	2009	55
ININ, Mexico City	2010	2012	125

- Provides replacement fuel for TRIGA reactors as part of the US-DOE University Program
- Provides replacement fuel for other worldwide TRIGA REACTORS

TRIGA INTERNATIONAL

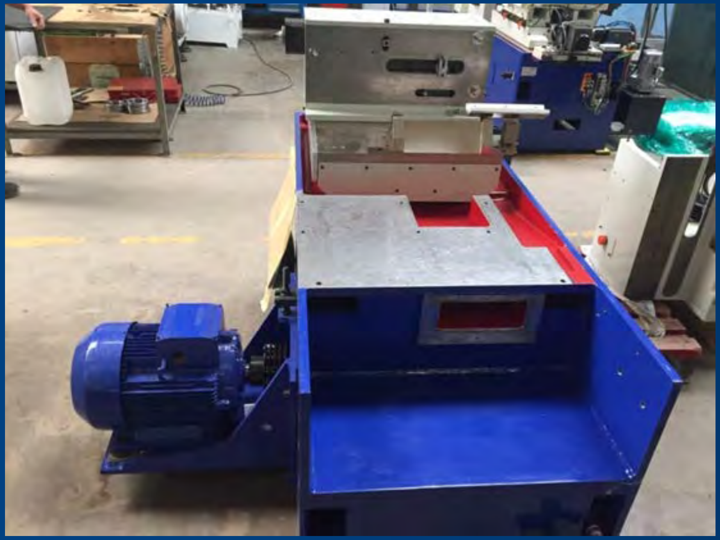
NEW EQUIPMENT

Fusion/Casting Furnace

New Hydride Furnace

TRIGA INTERNATIONAL

NEW EQUIPMENT CONTINUED



Centerless Grinder

Lathe

TRIGA INTERNATIONAL

MOST RECENT PROJECT

Morocco

2 MW TRIGA Reactor

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