GT-MHR ADVISORY GROUP

Constellation Nuclear

WHO, WHAT & WHY

PSEG

Pre-application NRC Meeting

12/03/01

Dominion

Entergy

NMC

S-2

release

UTILITY ADVISORY MEMBERS--WHO

- **EntergyNuclear**
  - *– Dan Keuter, Utility Advisory Board Chairman*
- **Nuclear Management Company**
- **Dominion**
- **Omaha Public Power District**
- **PSE&G**
- **Constellation**
- **Other**

Current Support - > 30 % of Industry

UAG STRUCTURE

GT-MHR Advisory Group

Licensing

- Development of Licensing Plan
  - Design Certification
  - Prototype Testing
- Development of Safety Analyses
  - PRA
- Development of Regulatory Standard
  - Design Basis Events
  - General Design Criteria
  - Selection of Safety Related SSCs
  - Plant Parameters Envelope

Engineering

- Overall Plant Design Description
- System Design Description
- Adaptation of International Design
  - US Regulatory & Commercial Standards
  - Containment Design
  - Power Conversion System
  - Core Design
  - BOP Refit Issues (e.g., 50Hz v. 60Hz, etc.)

Construction & Operation

- Capital Cost
- O&M Cost
- Decommissioning Cost
- Economic Evaluatio
- Procurement
- Project Scheduling
- Project Financing

Fuels

- Fuel Fabrication
- Qualification of Fuel
- Fuel Cycle Costing

Near Term Deployment

- Government Relatio
- Coordination of DOE Activities
- Deployment within US Market
- Development of Overall Communications Pl
- NEI Interface
- Wall Street Acceptance

ACADEMIC ADVISORY GROUP (AAG)

Members

- University of California at Berkley
  - Per Peterson, Chair
- MIT
- University of Michigan
- Oregon State
- Texas A&M
- Wisconsin
- University of Florida
- Ohio State
- Purdue
- Penn State

UTILITY ADVISORY MEMBERS--WHAT

UAB Purpose

- Provide Industry Guidance on:
  - Development and Deployment of GT-MHR
  - Coordination with Industry (NEI, NRC, EPRI & DOE) Activities to Maximize Efficiency & Prudence of Efforts
- Facilitate Incorporation of Lesson Learned From Earlier Gas Reactor Licensing and Operational Experience

"SUPER-SAFE" DESIGN --WHY

- **Meltdown Proof**
  - –High Temperature Fuel Capacity
  - –Passive & Conductive Cooling
- **Low Security Risk**
  - –Below-Grade Construction Arrangement
  - –Silo
  - –No Power Required
- **No Active Safety Systems**
  - –No Emergency Core Cooling
  - –No Emergency Diesels
- **Proliferation Resistant**
  - –Ceramic Fuel Makes Retrieval Difficult
  - –Low Fissile Fuel Volume Fraction
  - –High Fuel Burn-up / Pu Degradation

GEN IV Benefits at CCGT Prices

Gas Turbine - Modular Helium Reactor Safety Approach

Presented to NRC Staff
3 December 2001

Laurence L Parme
Manager, Reactor Safety & Licensing
General Atomics

GENERAL ATOMICS

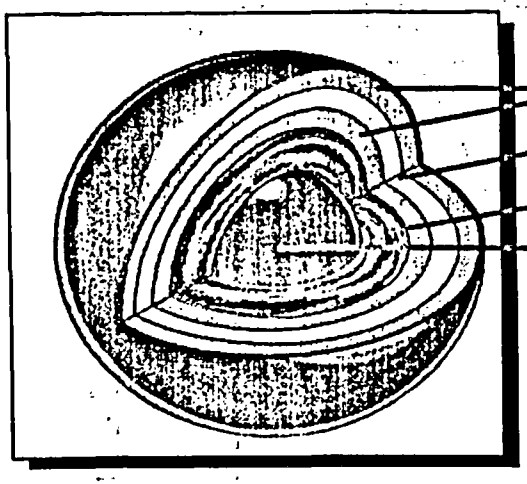
Modular Gas-Reactor Safety Approach Differs From Earlier Reactor Designs

- GT-MHR safety emphasizes
  - Keeping radionuclides at source during all accidents
  - Minimizing reliance on active/complex engineered systems
- Passive safety design based on reoptimized application of established HTGR technology
  - High temperature compatible fuel and core
  - Single phase, chemically & neutronically inert coolant
  - Specially tailored core power and geometry

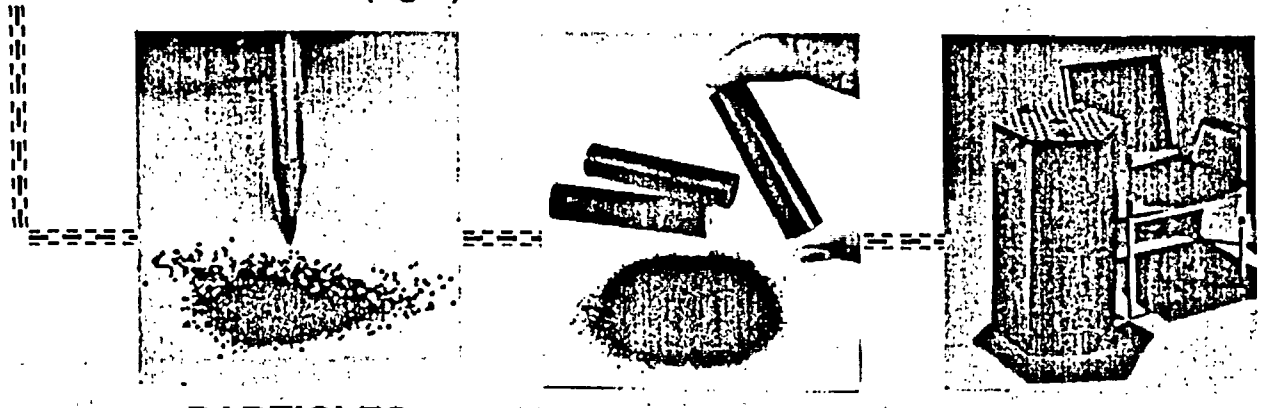
Conservative, robust design with defense-in-depth remain keystones of safety

GENERAL ATOMICS

Key to GT-MHR Safety
Multiple Ceramic Fuel Coatings



TRISO Coated fuel particles (left) are formed into fuel rods (center) and inserted into graphite fuel elements (right).

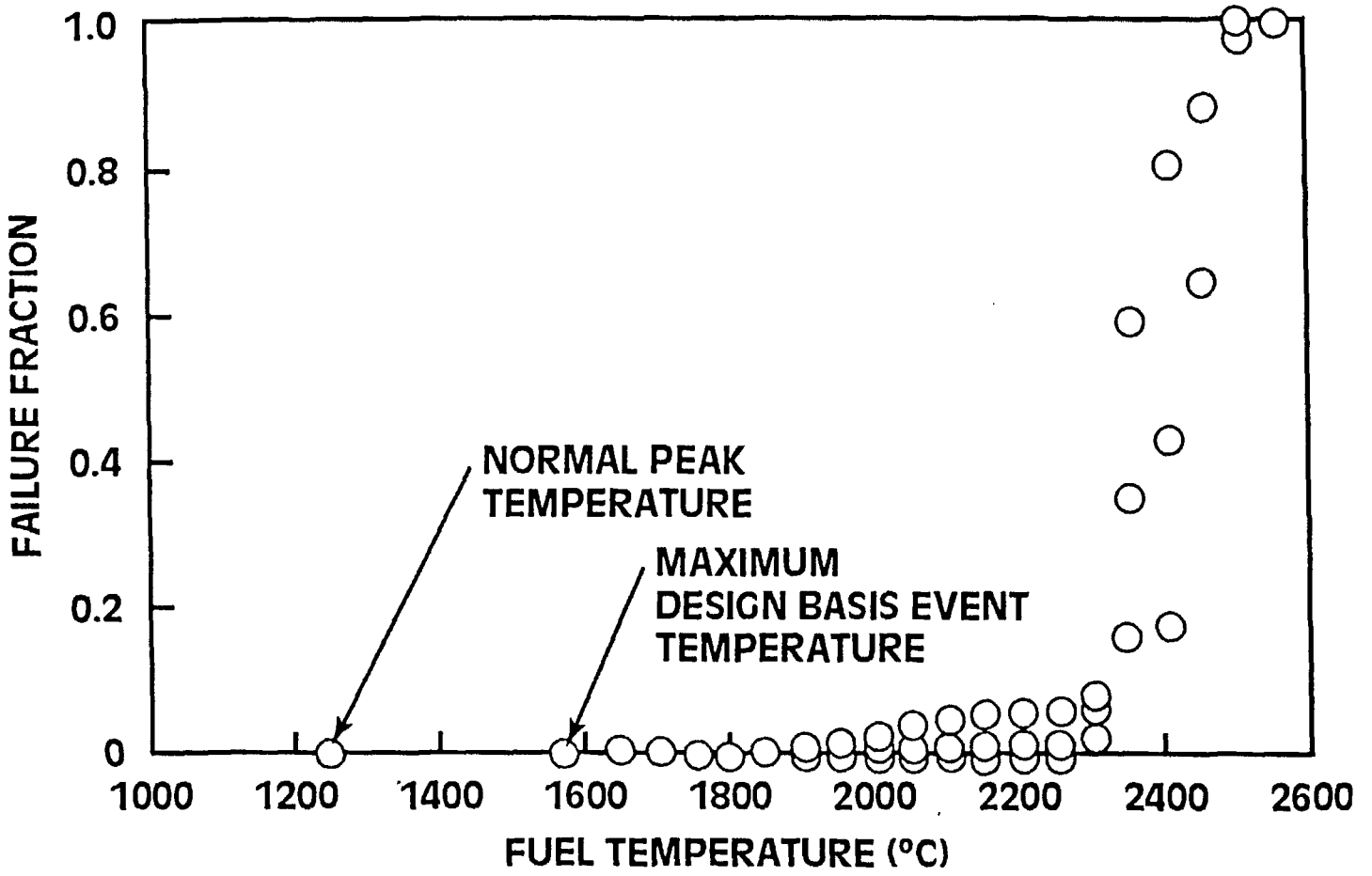


PARTICLES COMPACTS FUEL ELEMENTS

GENERAL ATOMICS

L-029(5)
4-14-94

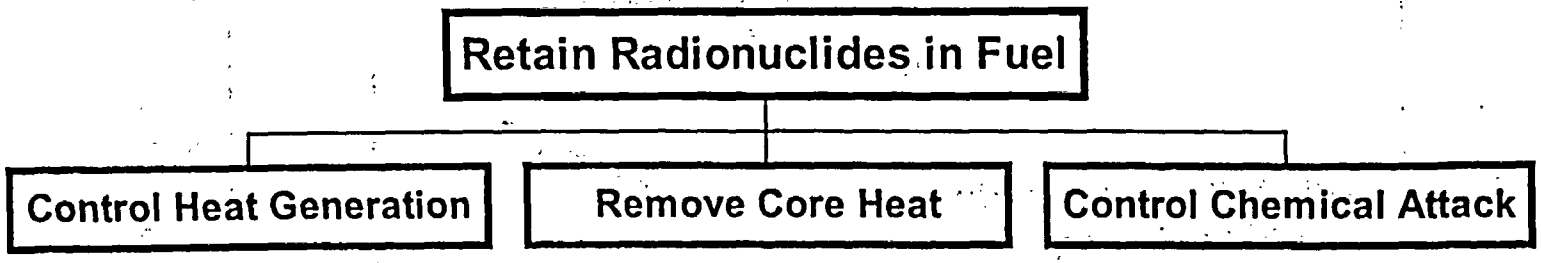
Coated Particles Remain Intact Even at Very High Temperatures



GENERAL ATOMICS

L-266(1)
7-28-94
W-9

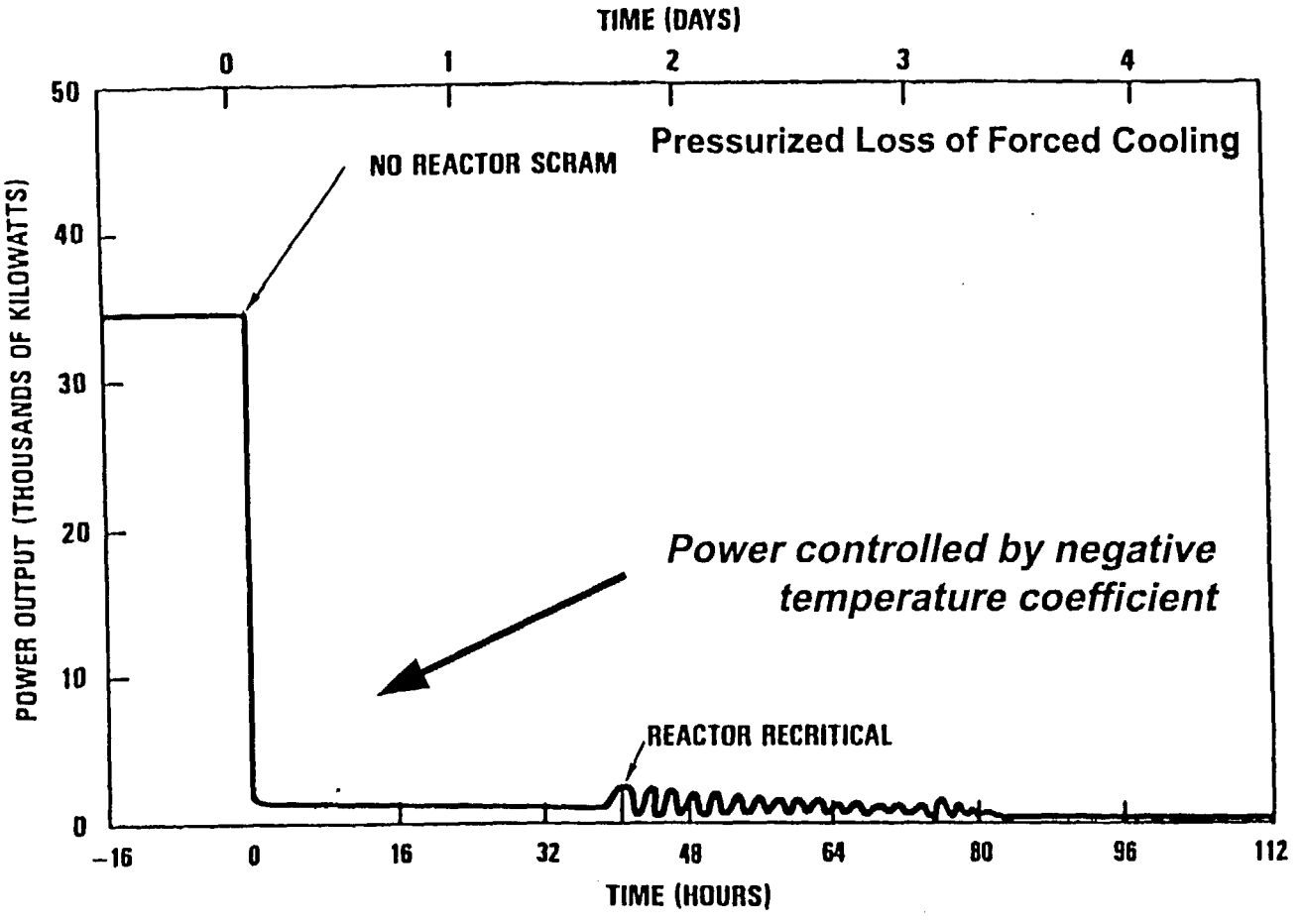
Safety Focused on Assured Fuel Particle Integrity



- Fission (heat generation) shut down without rod motion
- Heat removal assured by reactor design
  - *Low power density*
  - *Low thermal rating per module*
  - *Annular core and high L/D ratio*
- Chemical attack limited by design & materials
  - No high pressure water source in gas-turbine plant
  - Nuclear graphite, geometry, and limited air control potential oxidation

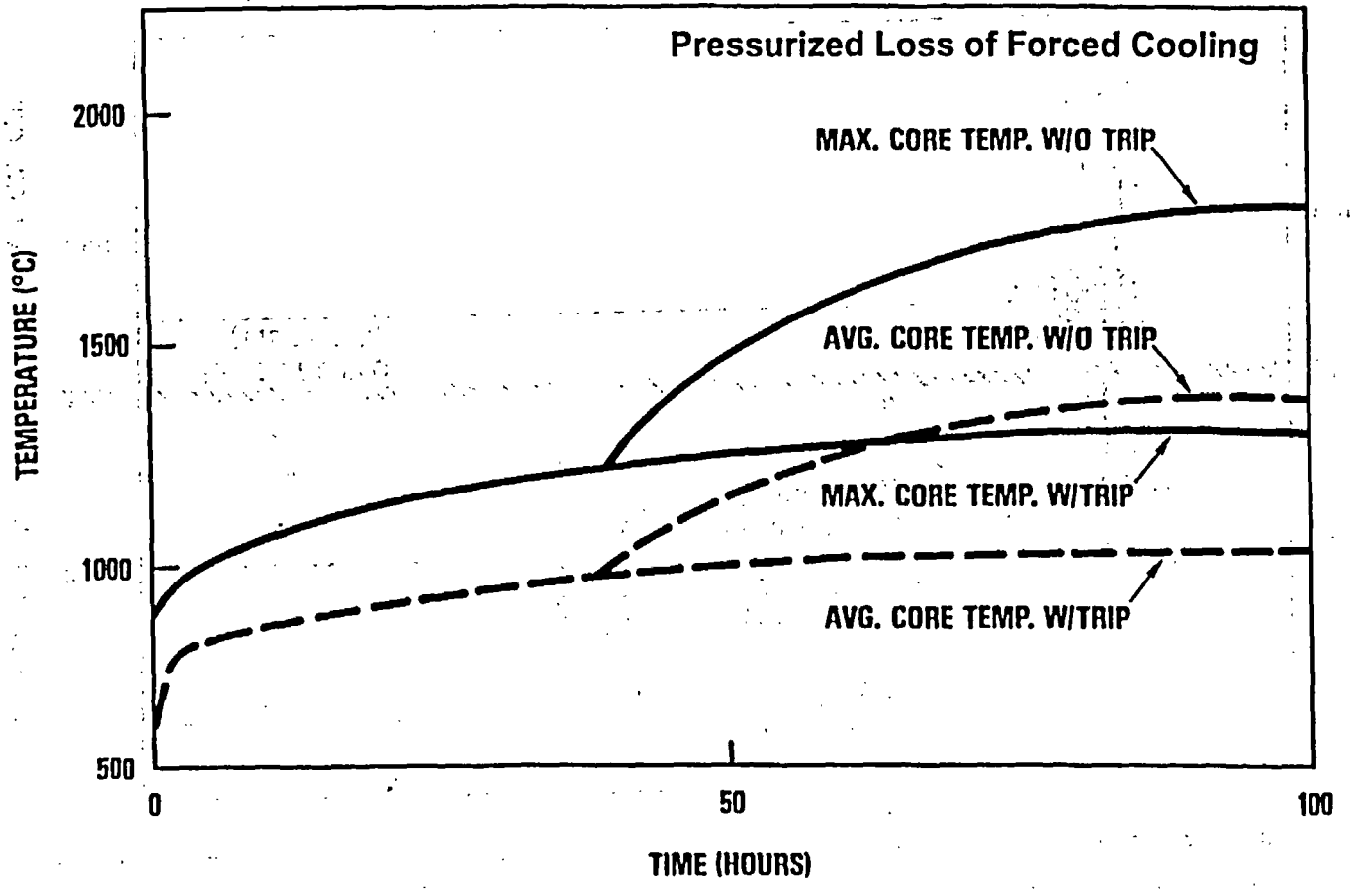
GENERAL ATOMICS

Heat Generation Stops During Loss of Cooling Without Rod Motion



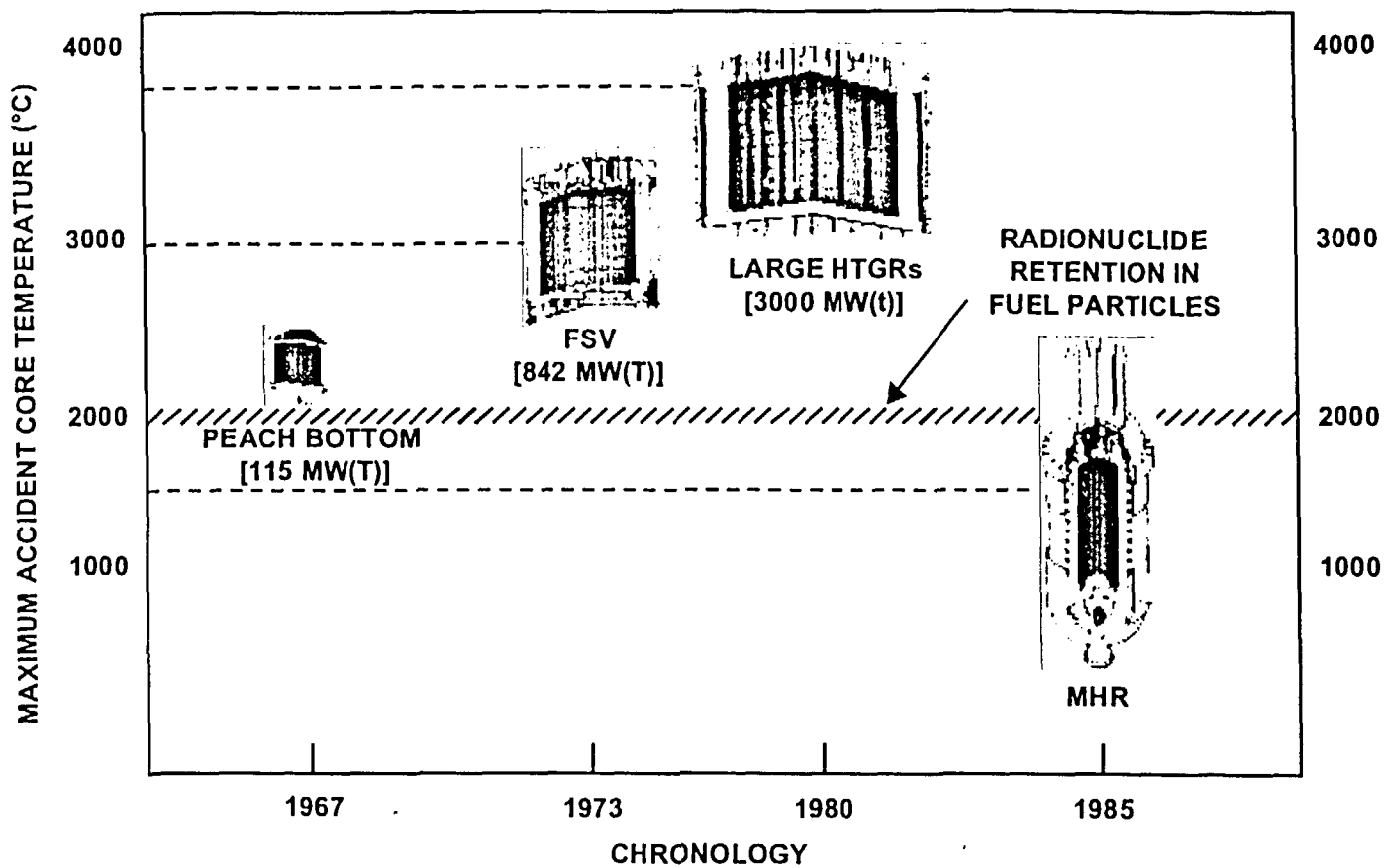
GENERAL ATOMICS

Core Temperatures Maintained at Safe Levels With and Without Reactor Trip



GENERAL ATOMICS

Passive Heat Removal Changes Reactor Design Philosophy

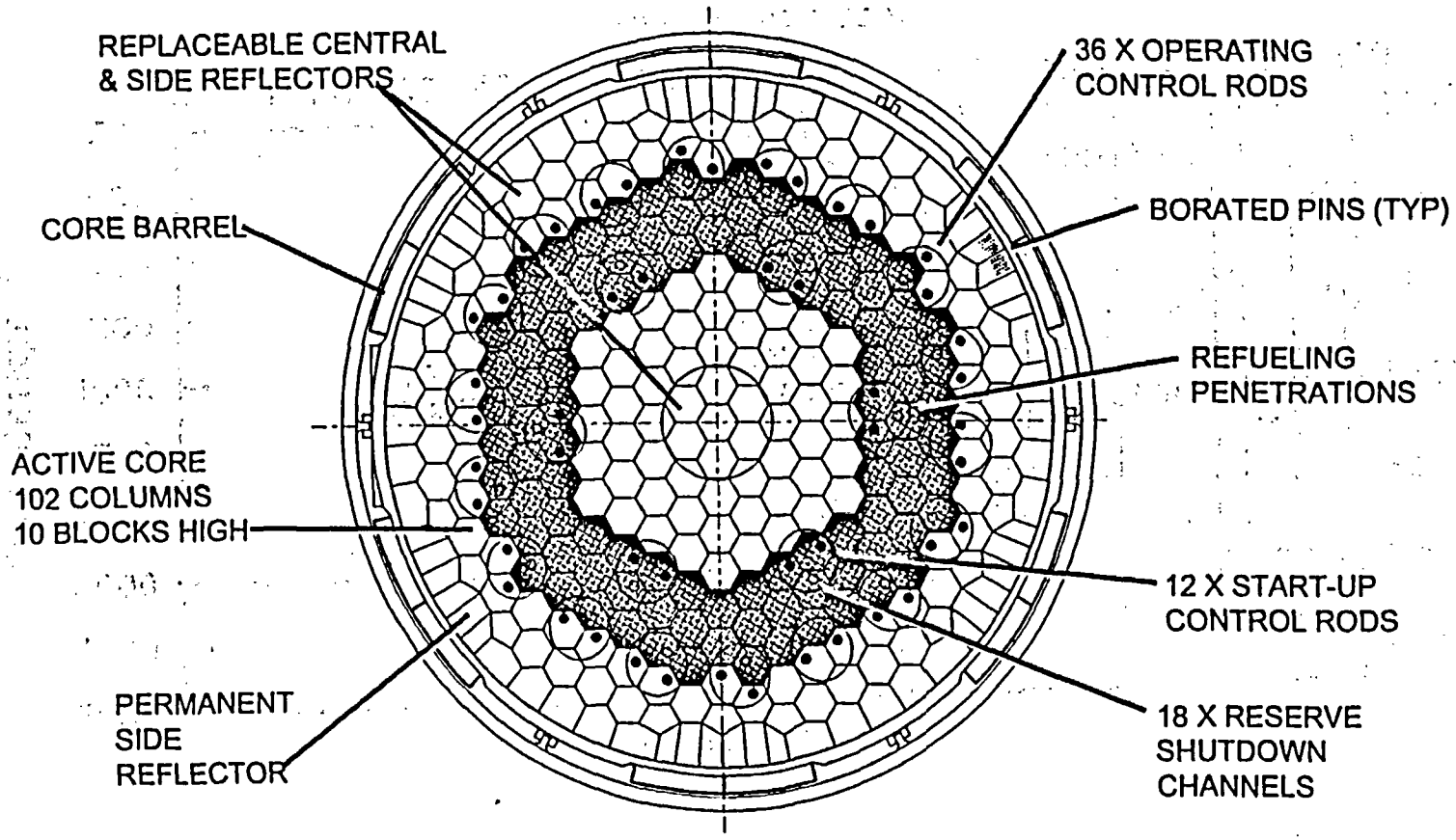


SIZED AND CONFIGURED TO WITHSTAND EVEN A SEVERE ACCIDENT

GENERAL ATOMICS

I-222(1)
1-12-96

ANNULAR CORE LIMITS FUEL TEMPERATURE DURING ACCIDENTS

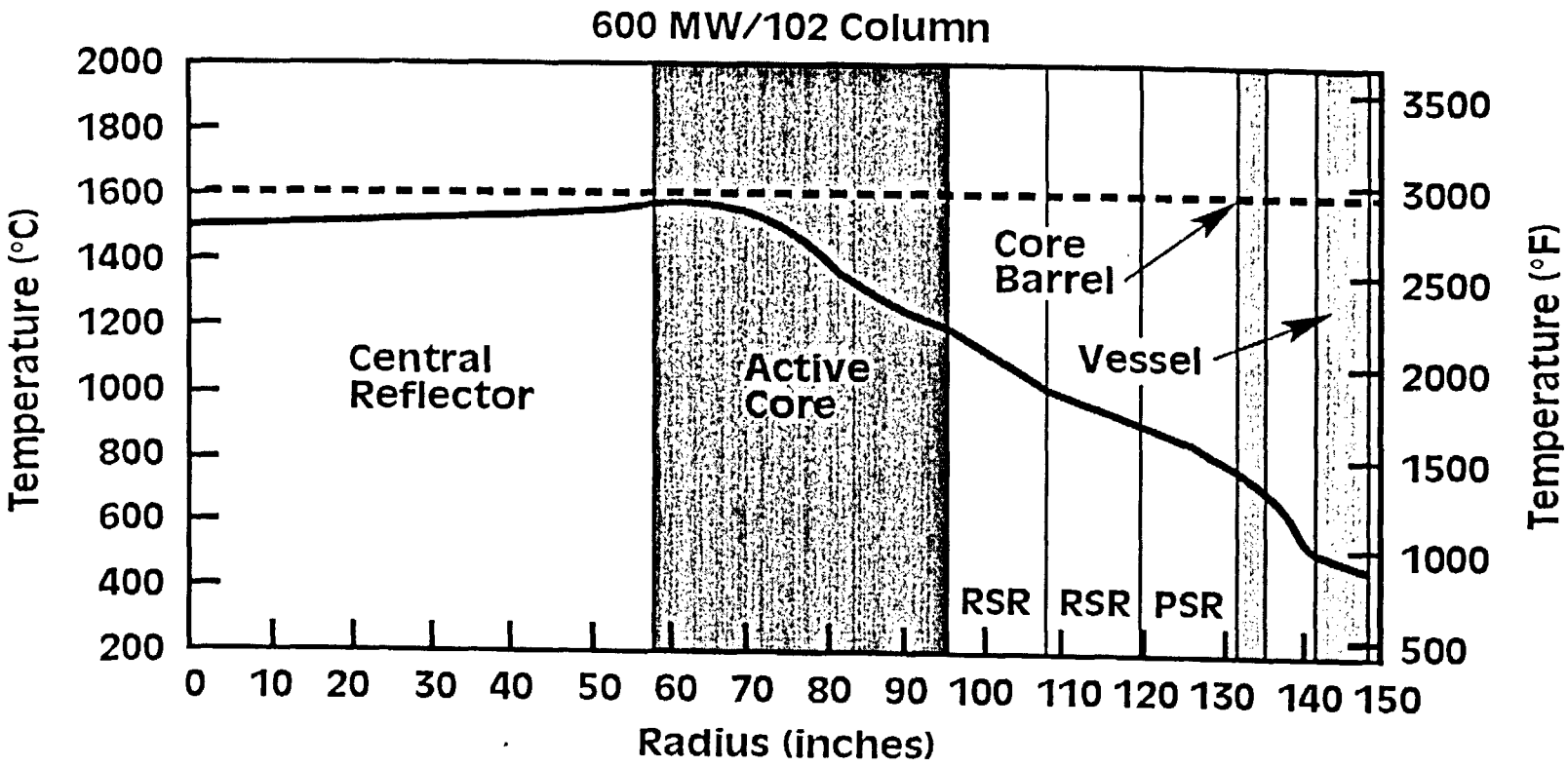


ANNULAR CORE USES EXISTING TECHNOLOGY

GENERAL ATOMICS

L-199(10)
6-9-95

Temperature Gradient Provides Driving Force for Residual Heat Removal

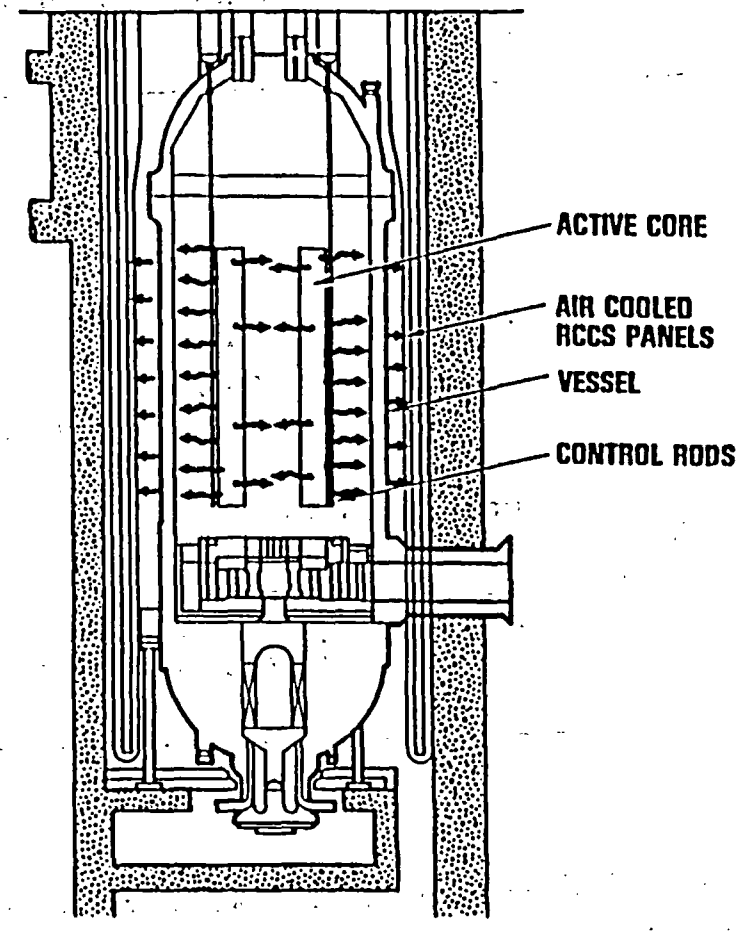


GENERAL ATOMICS

Heat Removed Passively Without Circulation or Coolant

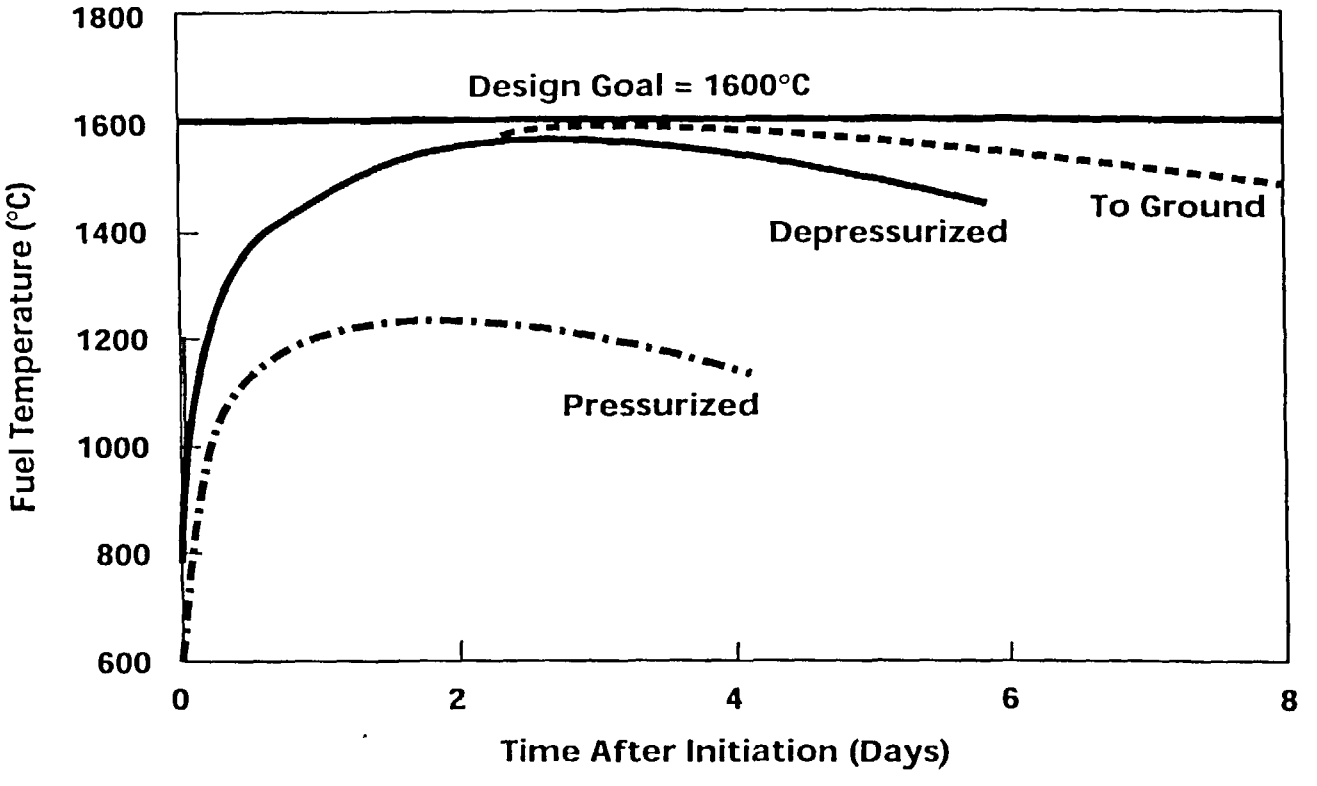
HEAT REMOVED BY:

- CORE CONDUCTION
- CORE INTERNAL RADIATION
- VESSEL RADIATION
- RCCS CONVECTION



GENERAL ATOMICS

FUEL TEMPERATURES REMAIN BELOW DESIGN LIMITS DURING LOSS OF COOLING EVENTS



passive design ensures fuel remains below 1600°C

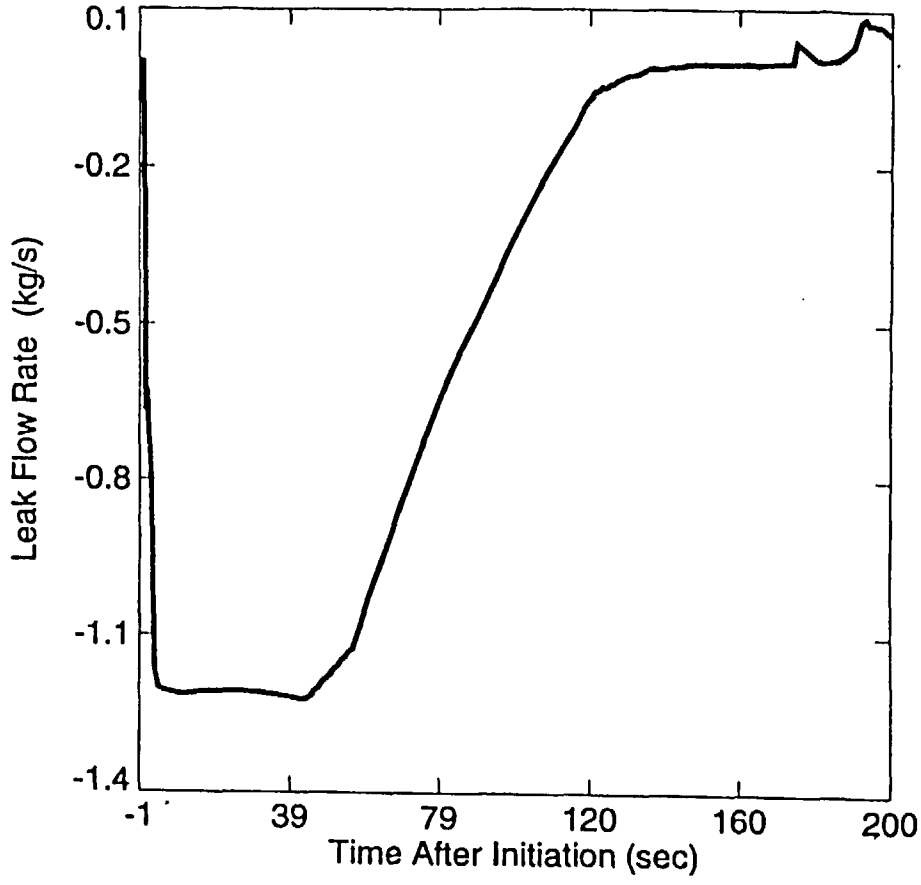
GENERAL ATOMICS

L-340(3)
11-16-94

Risk From Water Ingress Significantly Reduced in GT-MHR

- No steam generators therefore no high pressure steam source
- Precooler and intercooler water pressure below primary coolant operating pressure
- Low water pressure in heat exchangers greatly reduces potential for water ingress during normal operation
- Liquid water transport to core under depressurized conditions as unlikely as in steam cycle system

Leakage is Out of Primary Coolant System Following Tube Break



GENERAL ATOMICS

Inherent and Passive Features Control Air Attack

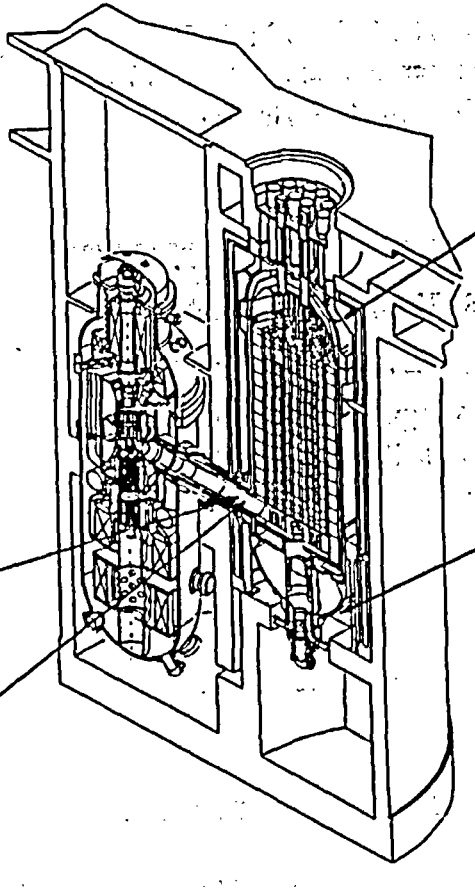
- Non-reacting coolant (helium)
- Embedded ceramic coated particles
- Air ingress limited (requires failure of Class 1 vessels)
- Below grade, closed reactor silo (isolation)
- Air flow rate limited by core flow area (L/D > 700)
- Slow oxidation rate (nuclear grade graphite)

Low Potential for Graphite Fires

- Test results successfully compared favorably to computer code (AIP) predictions
- Extremely low probability of burning graphite
  - requires temperatures above those during operation or accidents, <u>and</u>
  - requires large quantities of air
- MHTGR analyses show introduction of air results in limited, decay heat driven oxidation

GENERAL ATOMICS

Graphite Oxidation Limited by Available Air



OPENING AT TOP
- INGRESS OF ONE VESSEL VOLUME
- NEGLIGIBLE OXIDATION

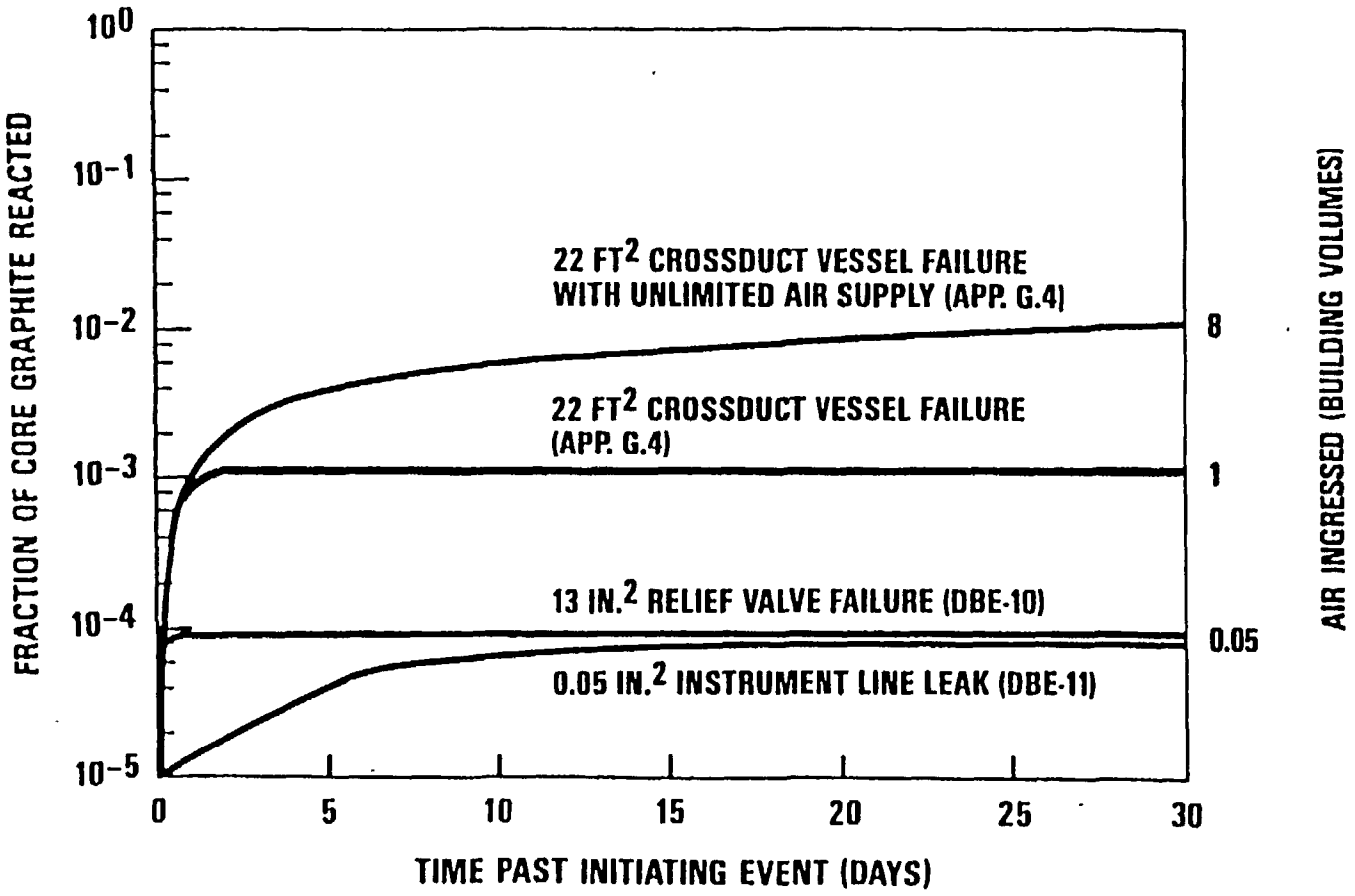
OPENING AT BOTTOM
- NO INGRESS
- NO OXIDATION

CROSS DUCT VESSEL FAILURE
- INGRESS OF ONE SILO VOLUME
- OXIDATION MINIMAL

CROSS DUCT VESSEL FAILURE WITH UNLIMITED INGRESS
- OXIDATION SMALL

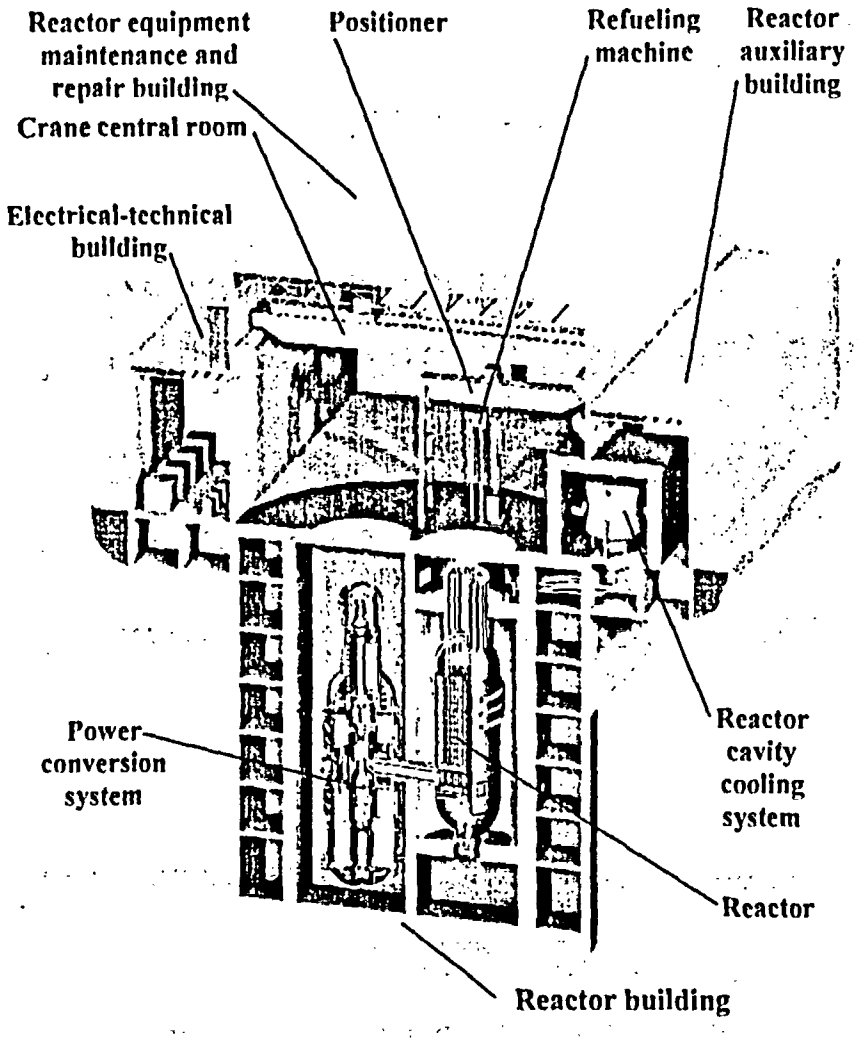
GENERAL ATOMICS

Mass Transfer, Core Temperature, & Graphite Purity Limit Oxidation Rate



GENERAL ATOMICS

Below-Grade Siting Augments Enhanced Safety



- Reduced seismic response
- Earth provides ultimate heat sink
- Robust structure
  - Additional holdup of accident releases
  - Reduces vulnerability of core and key safety features to surface events
  - Controls oxidant ingress

GENERAL ATOMICS

GT-MHR Optimization of Established Gas Reactor Features Provides

- Enhanced, easily understood safety
- Assured accomplishment of safety functions with simple, passive features
- Limited consequences, even for beyond design basis accidents

SAR intended to provide full demonstration of safety

GENERAL ATOMICS

Pre-Application Licensing Plan for the Gas Turbine - Modular Helium Reactor

Presented to NRC Staff
3 December 2001

Laurence L Parme
Manager, Reactor Safety & Licensing
General Atomics

GENERAL ATOMICS

Objectives of Pre-application Interactions

- Seek NRC licensability statement on
  - GT-MHR design licensability
  - Safety and licensing approach
- Establish foundation for future application
  - Combined License (COL) for a first module
  - Design Certification for the GT-MHR plant

NRC Advanced Reactor Policy guidance encourages earliest possible interaction

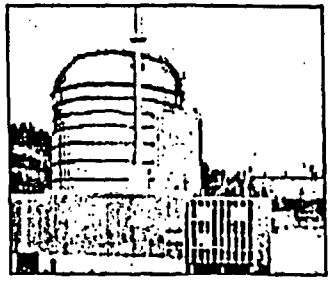
- Most effective regulation for advanced reactors
- Timely, independent assessment of the safety characteristics of advanced reactor designs

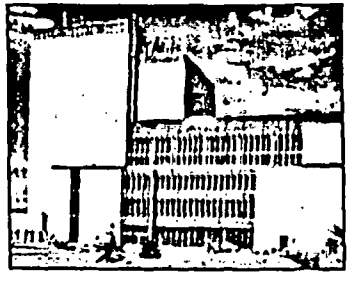
Licensing Plan Outlines
Pre-application Activities

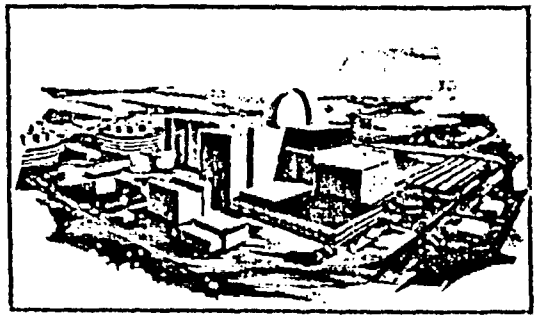
- Identify and schedule pre-application activities
- Define objectives and expectations
- Ensure planned activities facilitate future application
- Record NRC staff / GT-MHR agreement on planned activities

Significant History of HTGR Licensing Exists

- Peach Bottom 1 ('67 - '74)
  - Construction License
  - Operating License
  - Decommissioned
- Fort St Vrain ('79 - '88)
  - Construction License
  - Operating License
  - Decommissioned
- Large HTGR (mid '70s)
  - Summit 1 & 2 construction permit issued
  - Fulton 1 & 2 PSAR submitted



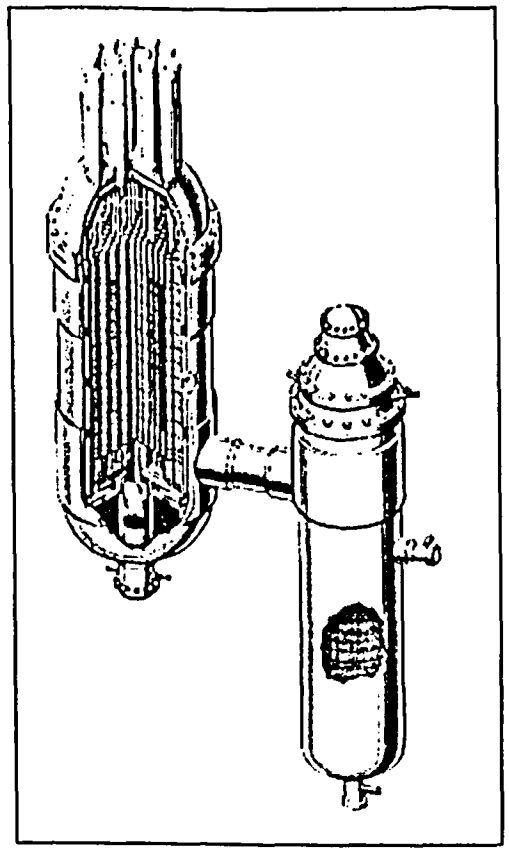




GENERAL ATOMICS

MHTGR - Starting Point for GT-MHR Interaction

- Steam cycle MHTGR interaction with NRC in mid-1980s
- Key items submitted for review
  - Top-level regulatory criteria
  - Risk informed licensing bases
  - Probabilistic Risk Assessment
  - Prelim Safety Information Document
- Extensive review by NRC staff and national labs
- MHTGR evolved to Brayton cycle GT-MHR in early 1990s
  - Similar safety characteristics
  - Similar licensing approach



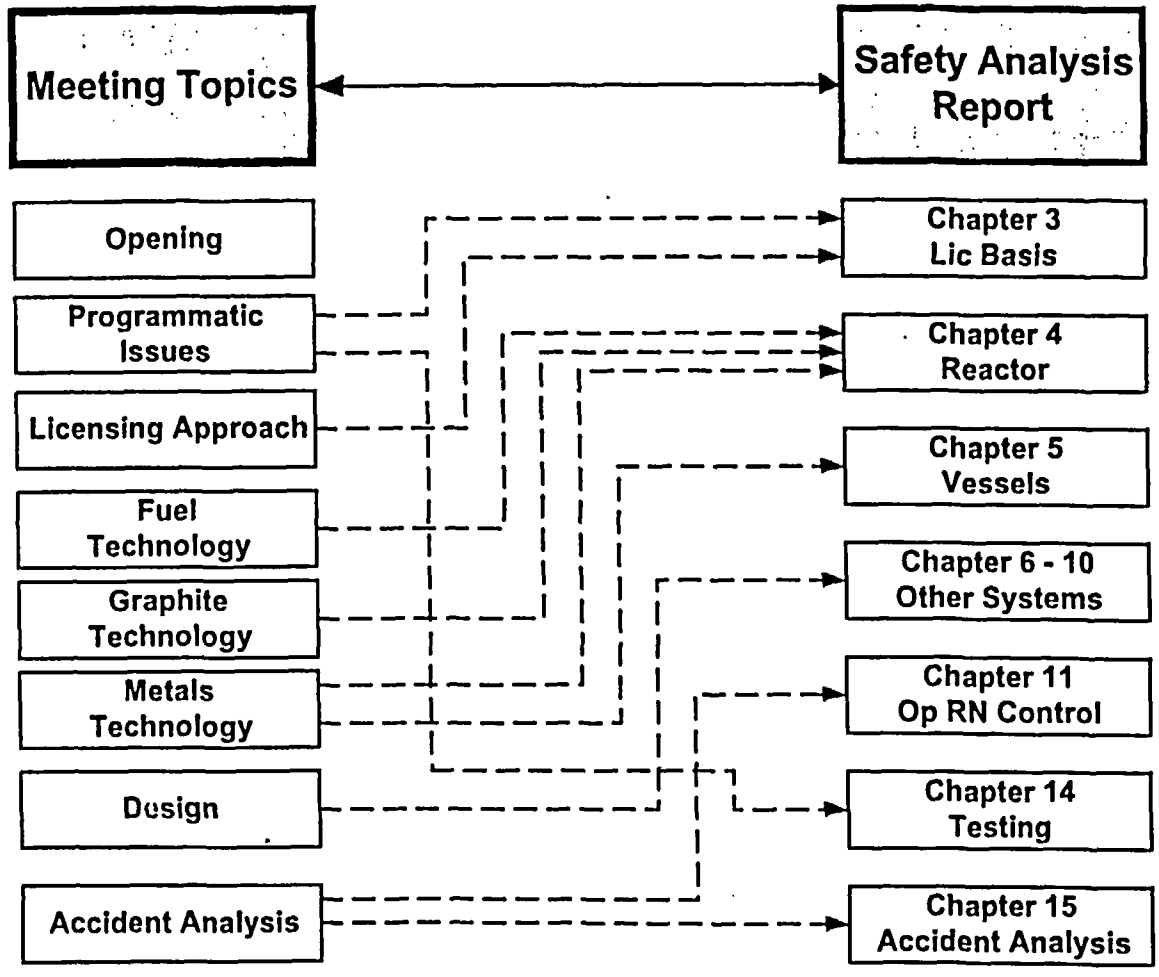
GENERAL ATOMICS

5 Areas Proposed for Discussion

- Programmatic and Process Topics
- Licensing Approach
- Technology Development
  - Fuel
  - Graphite
  - Metals
- Design Description
- Accident Analyses

GENERAL ATOMICS

Pre-application Topics Address draft SAR



GENERAL ATOMICS

Proposed Schedule of Activity Tied to Design

MILESTONE	DATE
Pre-Application Phase	
Opening meeting	December, 2001
Programmatic and process topics	January-March, 2002
Licensing approach	February-April, 2002
Technology development	April - August, 2002
Design Assessment	June - November, 2002
Submission of draft Safety Analysis Report (SAR)	March, 2003
NRC licensability statement	June, 2004
Application Phase	
Submission of SAR - Combined License (COL) application - Design certification application	July, 2004
Combined License Issued	June, 2007
Design Certification Issued	TBD

GENERAL ATOMICS

Interaction Process during Pre-application Phase

- Topical Meeting
  - GT-MHR presentation on topic or issue
  - NRC comments or questions at meeting
- GT-MHR follows up meeting with written documentation of presentation
  - Letter
  - Report
  - Draft SAR format
- Written comments or queries from NRC
- GT-MHR response

Licensability statement is final comment

GENERAL ATOMICS

GT-MHR PLANT DESIGN OVERVIEW

Presented to NRC Staff

December 3, 2001

Arkal Shenoy
Director, Modular Helium Reactor
General Atomics

GENERAL ATOMICS

Presentation Outline

- Design goals & requirements
- Design description
- International Program
- Commercial Program
- Design status and deployment schedule
- Conclusions

GENERAL ATOMICS

PLANT USER REQUIREMENTS

- Plant sizes 300-1200 MW(e) range
- Equivalent availability >80%
- Meet existing safety and licensing criteria with no release requiring public sheltering greater than $5X10^{-7}$ per year
- 10% power cost advantage over Fossil Fuel

ADDITIONAL REQUIREMENTS

- Utilize inherent characteristics for passive safety
- Do not require operator action (insensitive to operator error)
- Provide long time intervals for corrective action
- Actively support of users and suppliers during design and licensing

MODULAR HTGR DEVELOPMENT FOCUSED ON GEN IV GOALS (for past 15+ years)

- Modular HTGR first conceptualized in early '80s to provide simple, enhanced SAFETY
- GT-MHR conceptualized in early '90s to provide enhanced ECONOMICS
- Gas reactor TRISO coated particle fuel form ideal for spent fuel WASTE
- Fissile fuel inventory, isotopic composition, and fuel form provides PROLIFERATION resistance

GENERAL ATOMICS

MHR DESIGN APPROACH

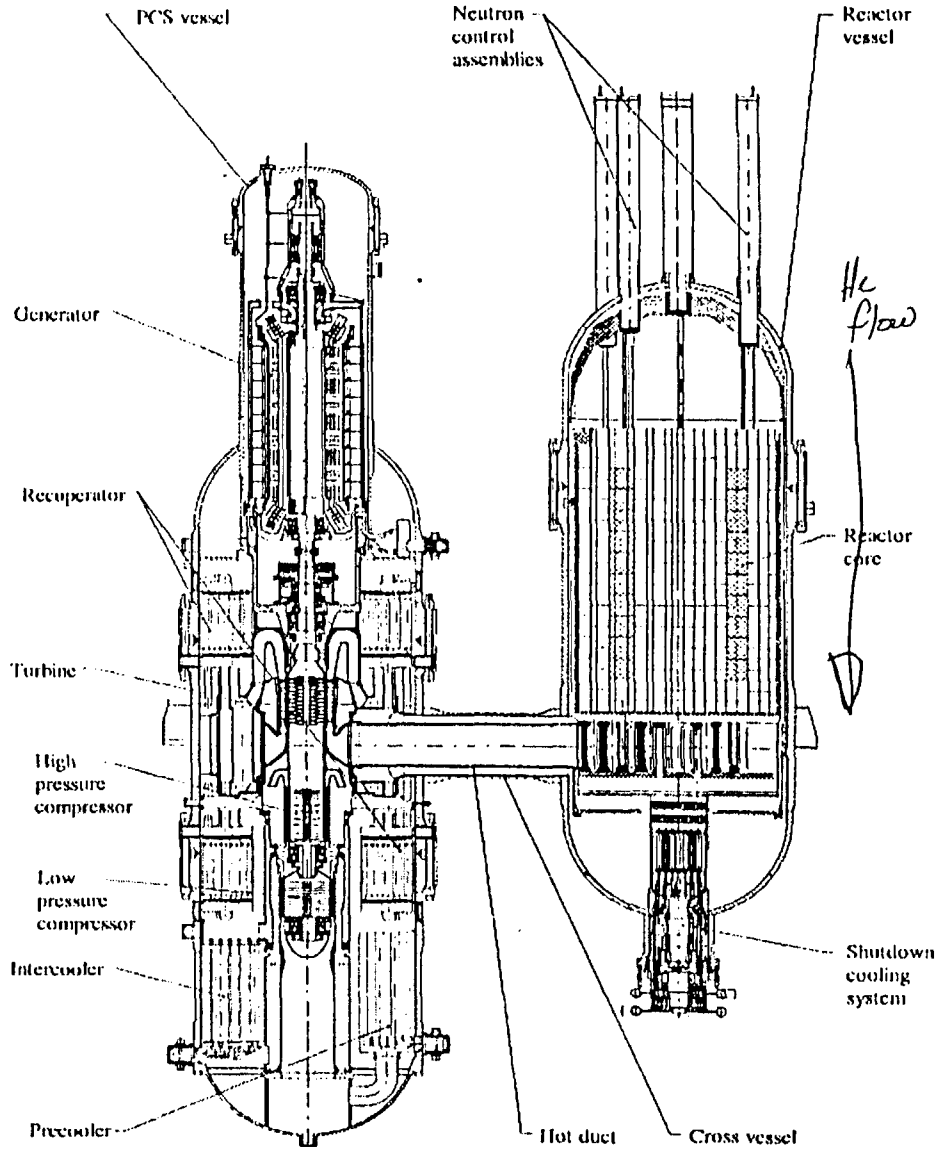
- Utilize inherent characteristics
  - Helium coolant - inert, single phase
  - Refractory coated fuel - high temp capability, low release
  - Graphite moderator - high temp stability, long response times
- Utilize existing technology, successfully demonstrate components and experience
- Develop simple modular design
  - Small unit rating per module
  - Below-grade installation
- Develop passively safe design
  - Annular core, large negative temperature coefficient
  - Passive decay heat removal system
  - Minimized powered reactor safety systems

SUMMARY DESCRIPTION OF GT-MHR DESIGN

- Plant Design
  - Electrical output 286 MW(e) per module, efficiency = 48%
  - Four identical reactor modules located below grade
  - Each module includes Reactor and Power Conversion System
- Reactor System Design
  - 600 MW(t), 102-column annular core
  - Hexagonal prismatic blocks similar to FSV
  - TRISO ceramic particle fuel
  - Redundant reactivity control system
- Power Conversion System Design
  - Generator, turbine, and two compressor sections on a single shaft
  - Magnetic bearings
  - Plate-fin recuperator
  - Cross-counterflow, water-cooled precooler and intercooler

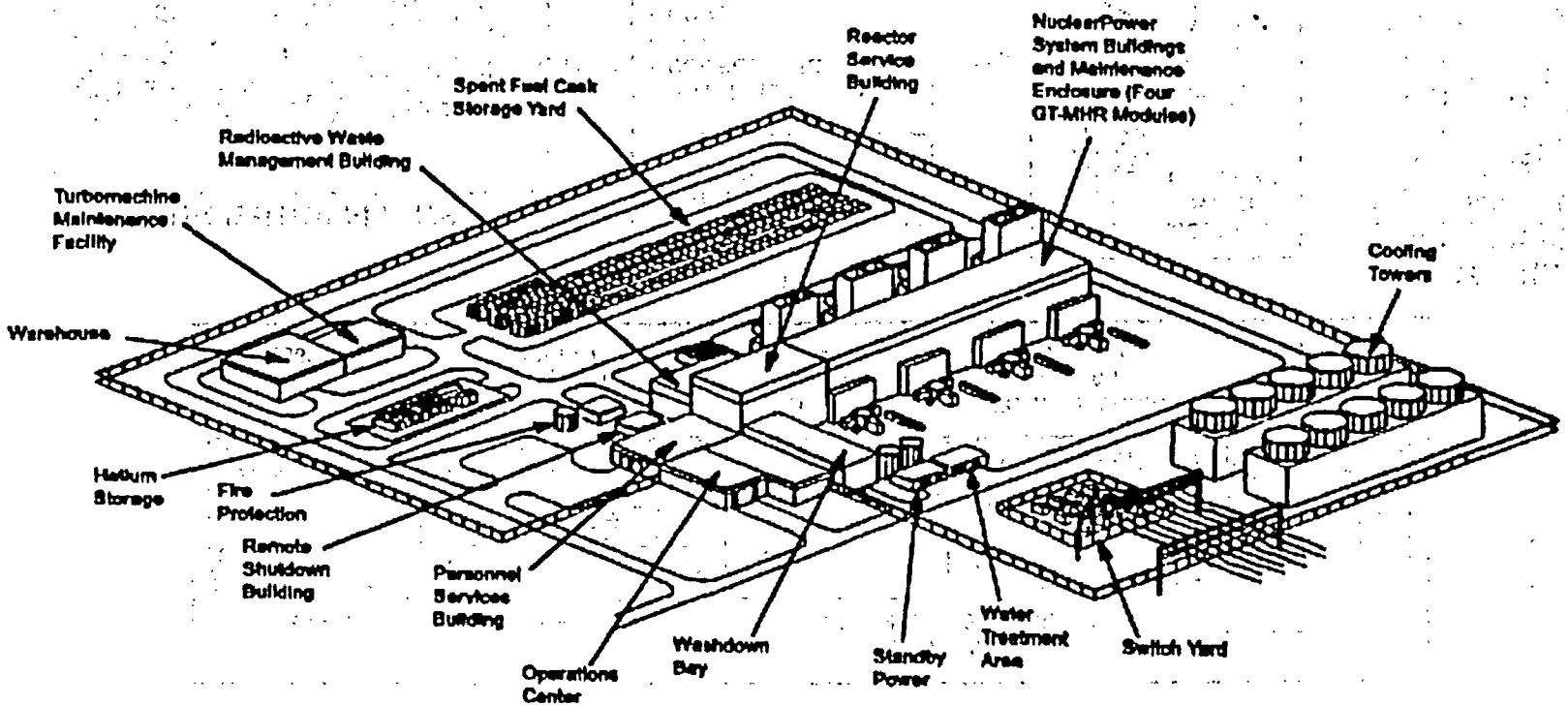
GT-MHR COMBINES MELTDOWN-PROOF ADVANCED REACTOR WITH HIGH EFFICIENY GAS TURBINE

POWER LEVEL 600 MWt



GENERAL ATOMICS

4 MODULES COMPRISE STANDARD PLANT



M-273(27)
8-27-01

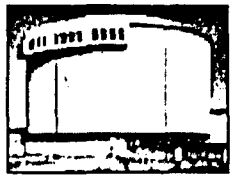
GENERAL ATOMICS

U.S. AND EUROPEAN TECHNOLOGY BASES FOR MODULAR HIGH TEMPERATURE REACTORS

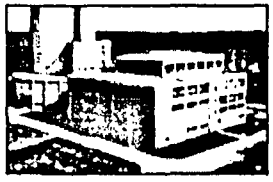
BROAD FOUNDATION OF HELIUM REACTOR TECHNOLOGY

EXPERIMENTAL REACTORS

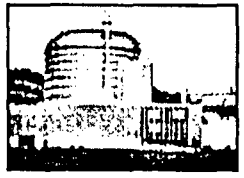
DEMONSTRATION OF BASIC HTGR TECHNOLOGY



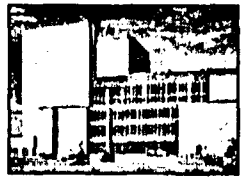
DRAGON
(U.K.)
1963 - 76



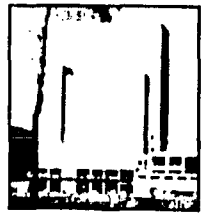
AVR
(FRG)
1967 - 1988



PEACH BOTTOM 1
(U.S.A.)
1967 - 1974

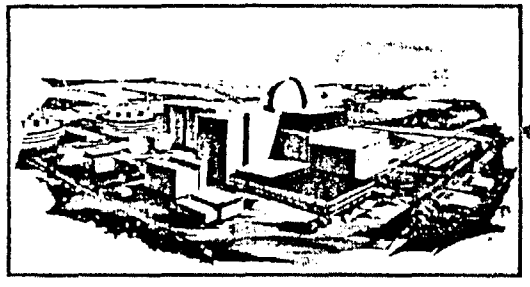


FORT ST. VRAIN
(U.S.A.)
1976 - 1989



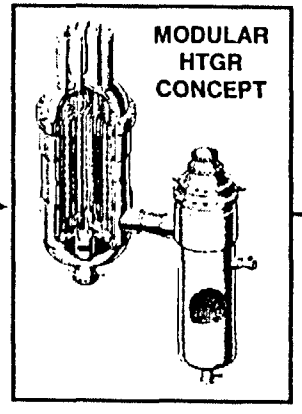
THTR
(FRG)
1986 - 1989

LARGE HTGR PLANTS

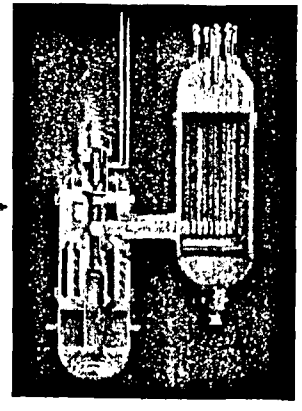


HTGR TECHNOLOGY PROGRAM

- MATERIALS
- COMPONENTS
- FUEL
- CORE
- PLANT TECHNOLOGY

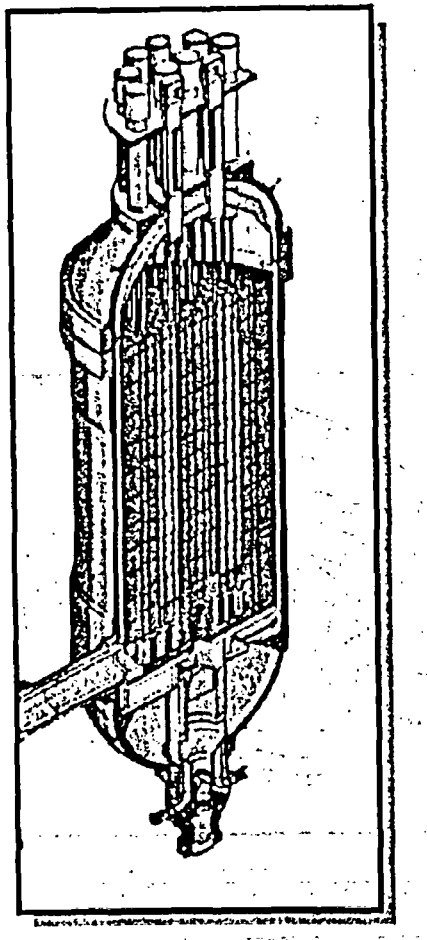


GT-MHR



GENERAL ATOMICS

MODULAR HELIUM REACTOR CHARACTERISTICS ATTRACTIVE FOR GEN IV GOALS



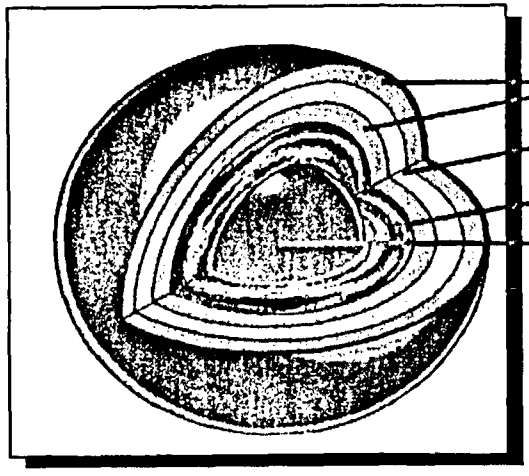
- Helium gas coolant (inert)
- Refractory fuel
  (high temperature capability)
- Graphite reactor core
  (high temperature stability)
- Low power density (order of magnitude lower than LWRs)
- Demonstrated technologies

. . . EFFICIENT, RELIABLE PERFORMANCE WITH INHERENT SAFETY

GENERAL ATOMICS

L-271(3)
6-6-95

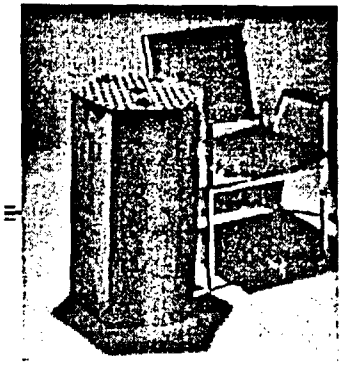
CERAMIC FUEL RETAINS ITS INTEGRITY UNDER SEVERE ACCIDENT CONDITIONS



TRISO Coated fuel particles (left) are formed into fuel rods (center) and inserted into graphite fuel elements (right).

PARTICLES

COMPACTS

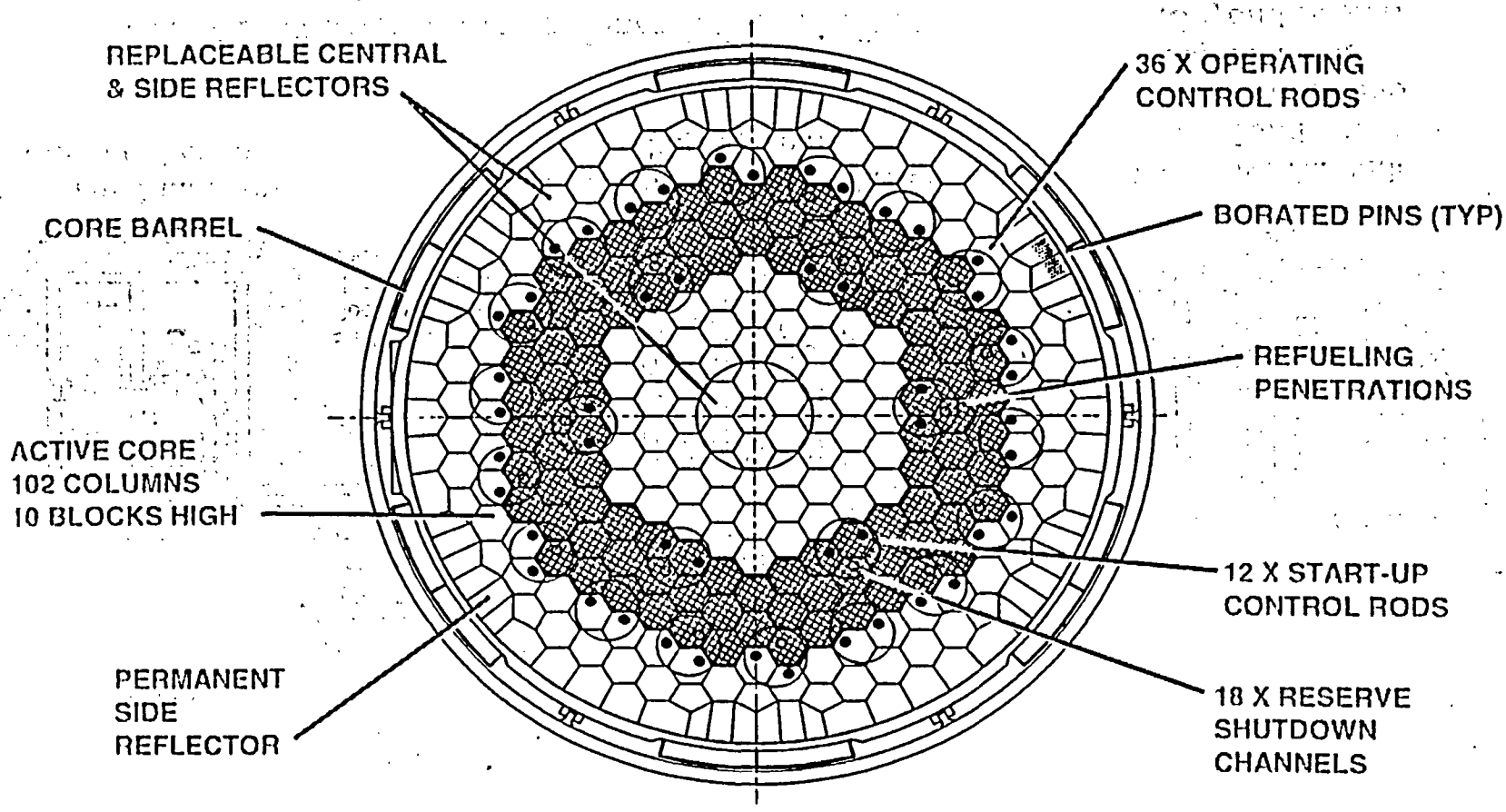


FUEL ELEMENTS

GENERAL ATOMICS

L-029(5)
4-14-94

ANNULAR REACTOR CORE LIMITS FUEL TEMPERATURE DURING ACCIDENTS

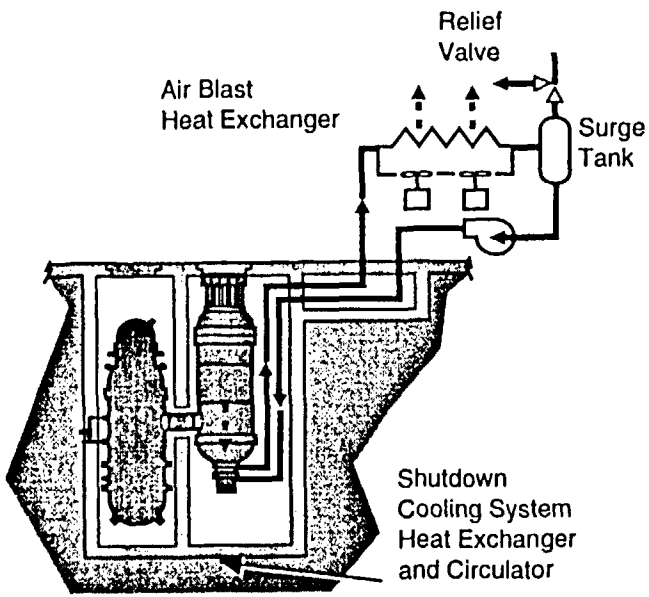


. . . ANNULAR CORE USES EXISTING TECHNOLOGY

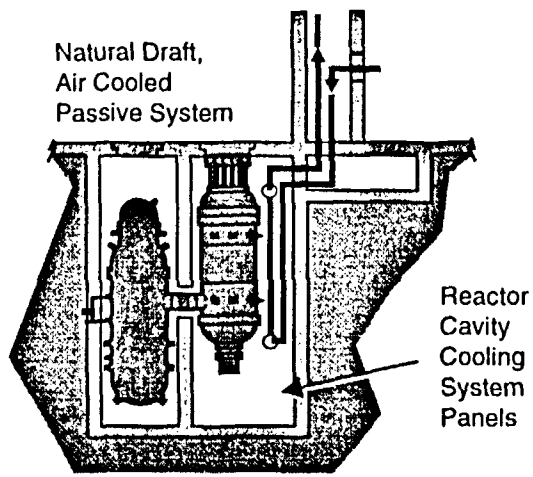
GENERAL ATOMICS

L-199(10)
6-9-95

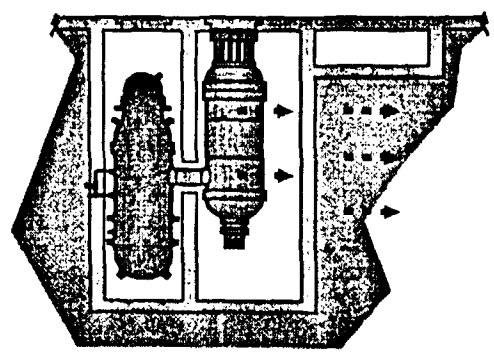
POSSIBLE HEAT REMOVAL PATHS WHEN NORMAL POWER CONVERSION SYSTEM IS UNAVAILABLE



A) Active Shutdown Cooling System



B) Passive Reactor Cavity Cooling System



C) Passive Radiation and Conduction of Afterheat to Silo Containment (Beyond Design Basis Event)

. . . DEFENSE-IN-DEPTH BUTTRESSED BY INHERENT CHARACTERISTICS

GENERAL ATOMICS

L-266(2)
7-28-94

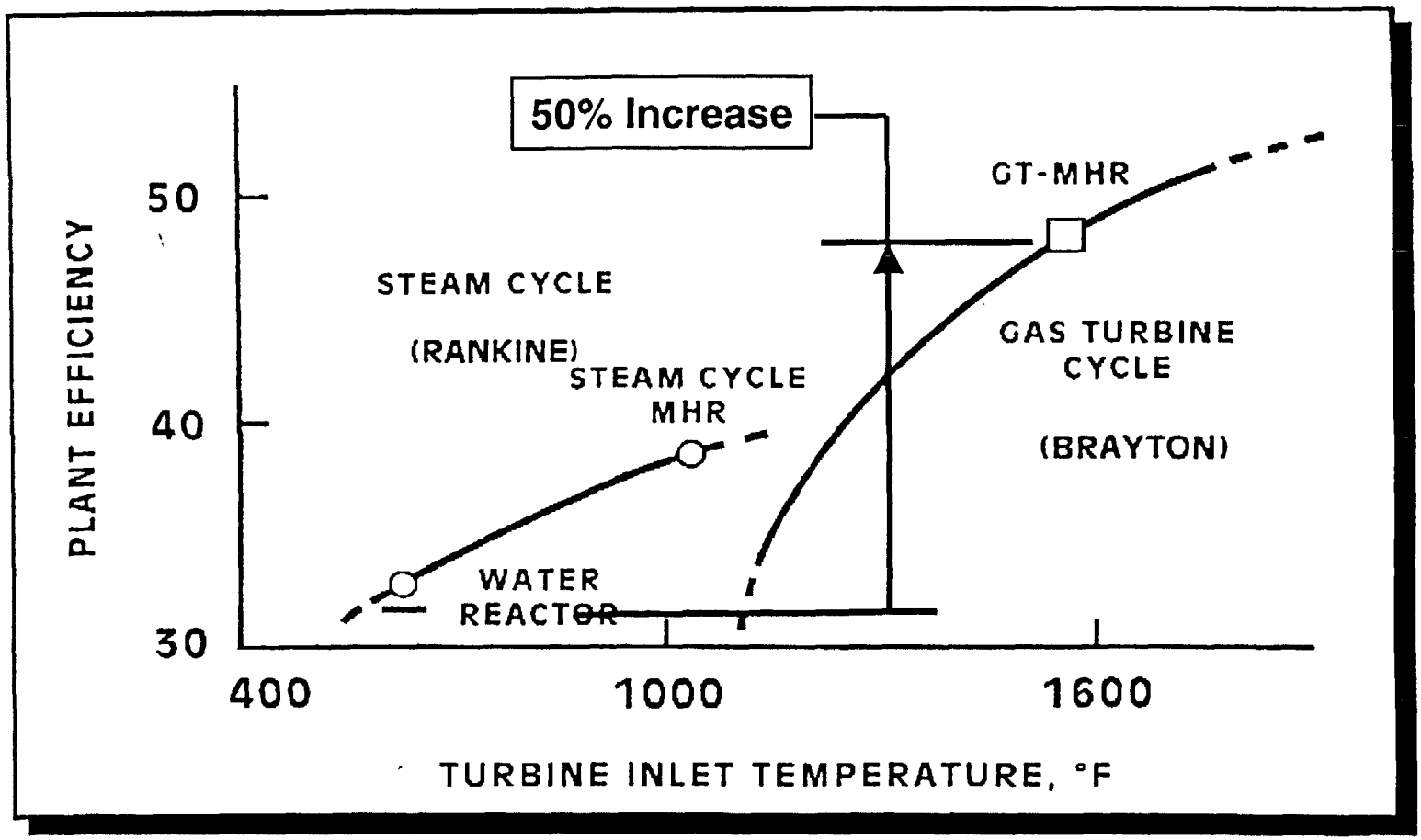
GT-MHR DEVELOPED FOR ENHANCED ECONOMICS

- Thermal Efficiency of HTGR Power Plants with Rankine (Steam) Cycle Limited to ~38%

- Direct Gas Turbine (Brayton) Cycle Long Time Vision and Incentive for HTGR Development

- Gas Turbine Brayton Cycle Improves Economics
  - *Significantly increases thermal efficiency*
  - *Significantly reduces plant equipment requirements*

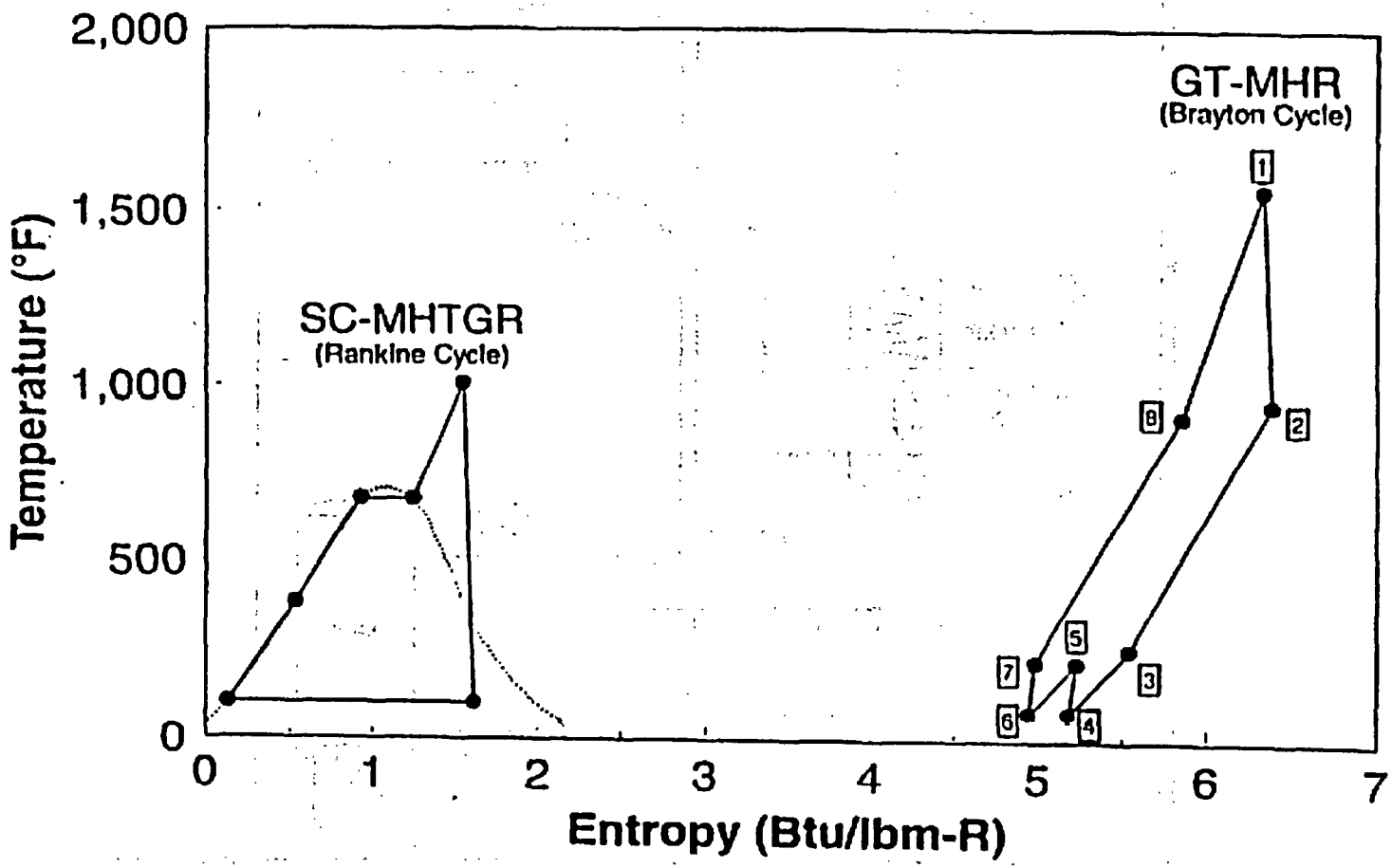
HIGH TEMPERATURE GAS REACTORS HAVE UNIQUE ABILITY TO USE BRAYTON CYCLE



GENERAL ATOMICS

L-029(4)
6-9-94

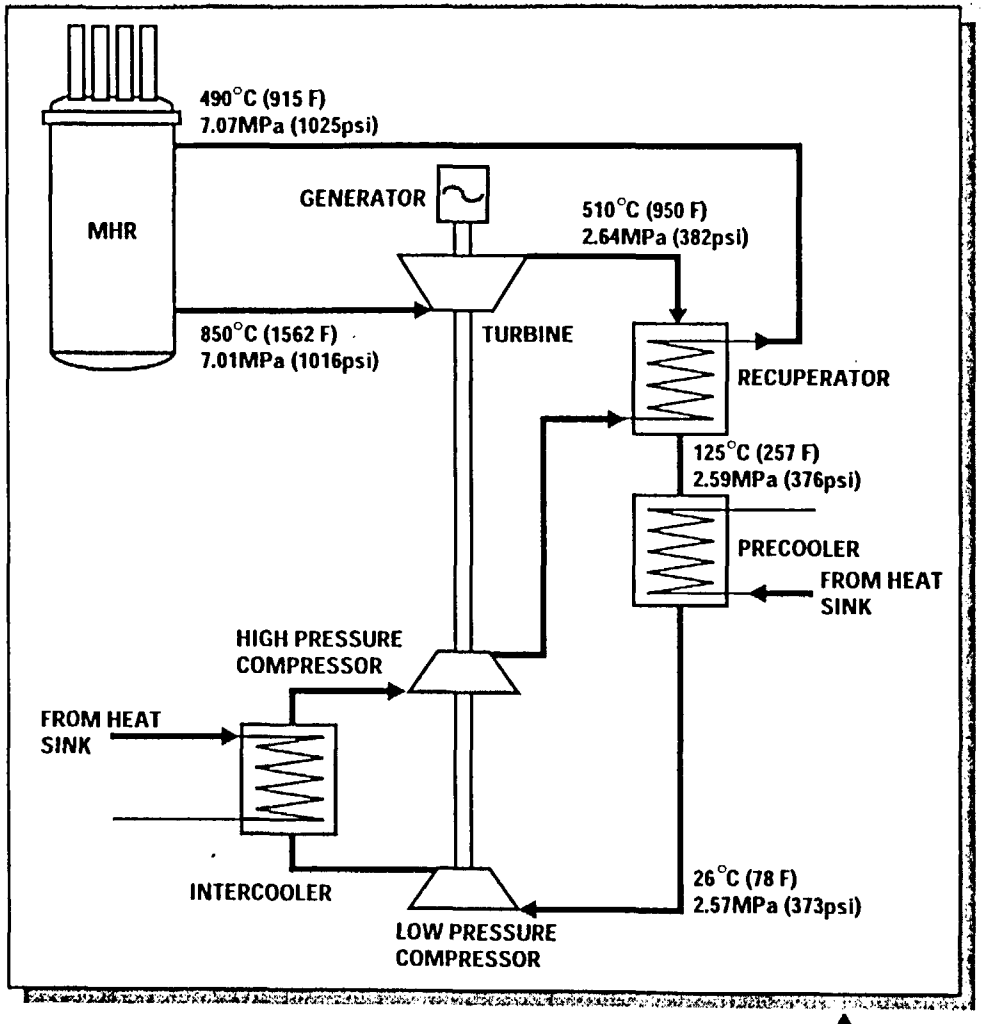
T-S DIAGRAM



M-272(38)
8-27-01

GENERAL ATOMICS

GT-MHR FLOW SCHEMATIC



GENERAL ATOMICS

L-271(12a)
8-14-94
A-36

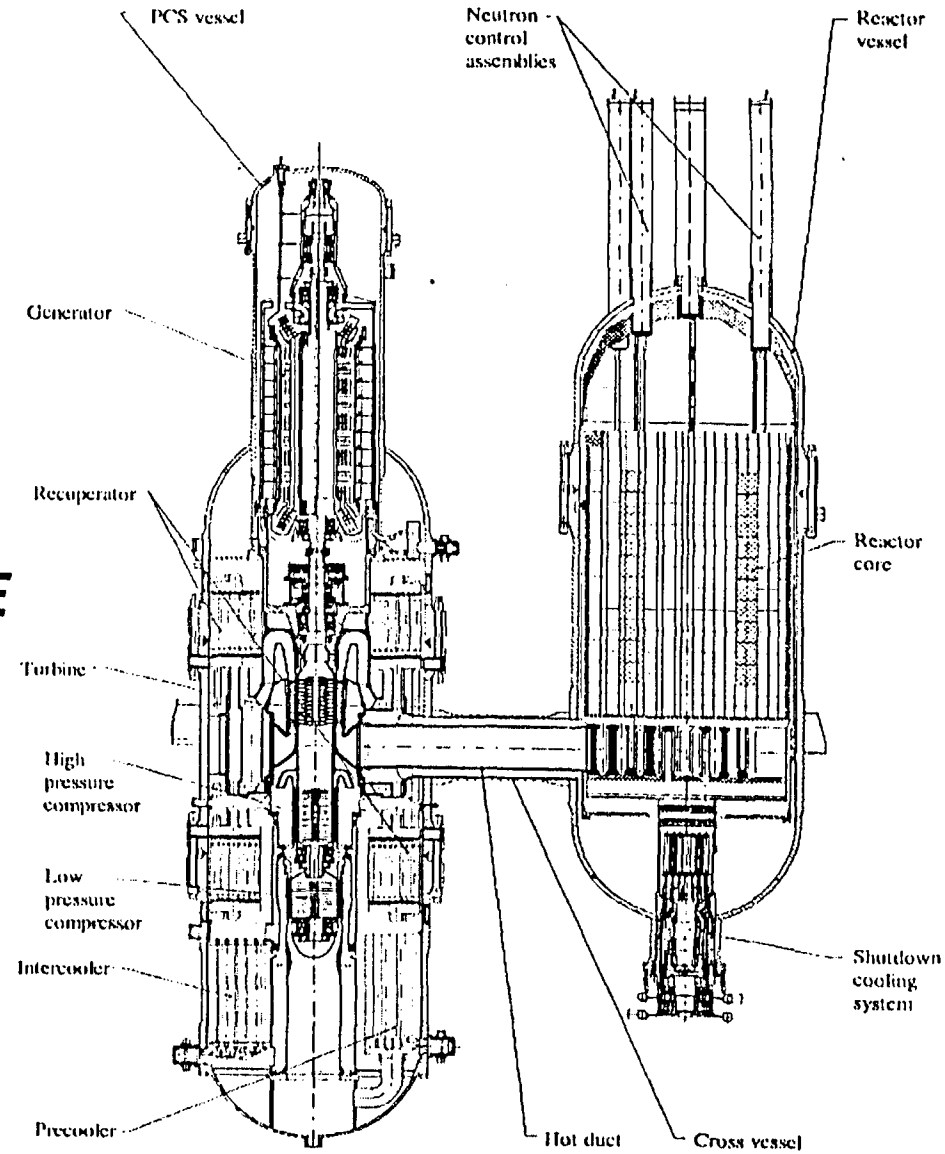
TECHNOLOGY ADVANCEMENTS HAVE ENABLED THE GT-MHR

- Small Passively Safe Modular Helium Reactor
  - *turbine size requirements reduced*
  - *insensitive to turbine failure accidents*
- Large Gas Turbine Engines
  - *significant increase in industrial applications*
  - *size now match modular reactor size*
- Magnetic Bearings
  - *eliminates oil ingress concerns*
  - *improves performance and reliability*
  - *rapidly increasing industrial experience; larger sizes*
- Compact Heat Exchangers
  - *dramatically improves efficiency*
  - *size improves design integration*
  - *extensive fossil operating experience*

GENERAL ATOMICS

GT-MHR COMBINES REACTOR AND GAS TURBINE PLANT IN COMPACT INTEGRATED PACKAGE

POWER LEVEL 600 MWt



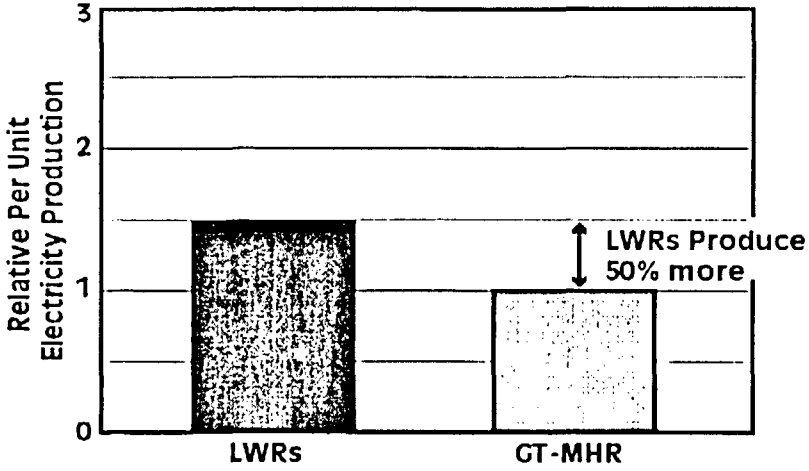
GENERAL ATOMICS

CONTROL BASED ON 3600 RPM SYNCHRONIZED GENERATOR

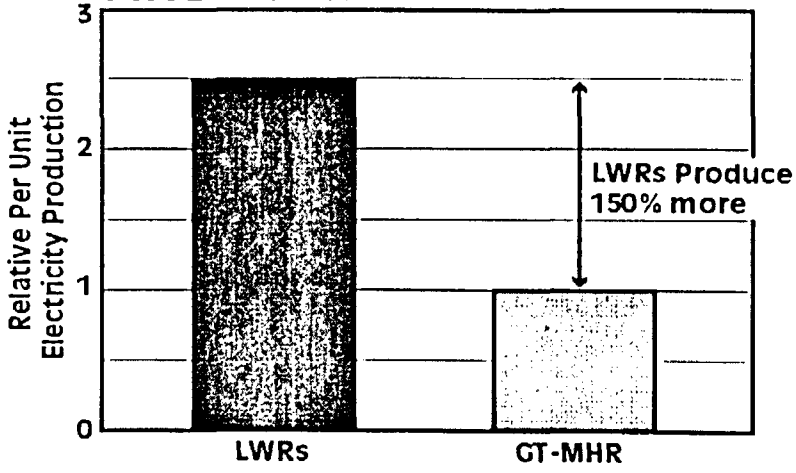
- Reactor controlled to maintain constant turbine inlet temperature during normal power operation
- Turbine bypass valve provides short term control
  - Rapid load following
  - Machinery protection
- Inventory (coolant pressure) control provides long term load control while maintaining high cycle efficiency
- Motorizing generator with frequency convertor provides startup and shutdown cooling capability

GT-MHR OFFERS MAJOR ENVIRONMENTAL BENEFITS

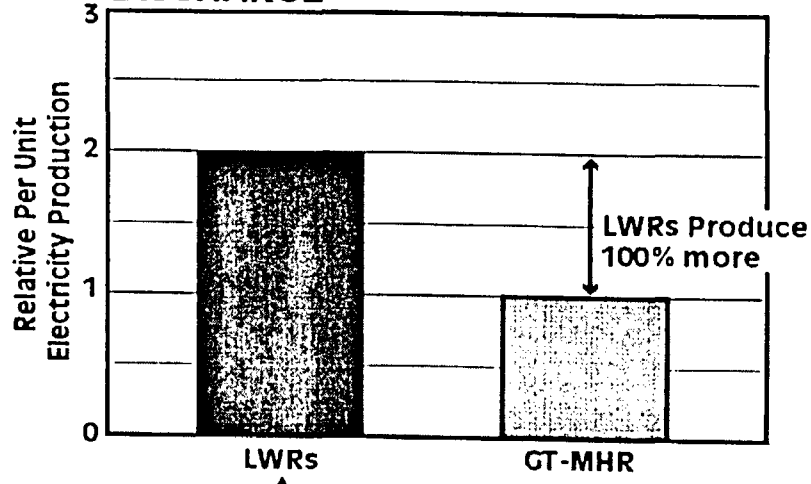
HIGH LEVEL WASTE



ACTINIDE PRODUCTION



THERMAL DISCHARGE



GENERAL ATOMICS

L-592(2)
11-14-95

GT-MHR IS PROLIFERATION RESISTANT AND SATISFIES SAFEGUARD REQUIREMENTS

- GT-MHR utilizes low enriched fuel
- Fuel particle refractory coatings make fissile material retrieval difficult
- Low fissile material volume fraction makes diversion of adequate heavy metal quantities difficult
- High spent fuel burnup degradation of Pu isotopic composition make it unattractive for weapons
- Neither a developed process nor capability anywhere in world for separating fissionable material from GT-MHR spent fuel

IN SUMMARY, GT-MHR MEETS ALL DESIGN REQUIREMENTS

- High level of inherent safety eliminating core melt without operator action
- Brayton cycle power conversion system for high thermal efficiency (~50% higher than LWRs)
- Low electricity generation cost (reduced equipment capital and O&M; high thermal efficiency)
- Significantly reduced environmental impact
- Superior radionuclide retention for long-term spent disposal
- High proliferation resistance

GT-MHR Being Designed for Prototype in Russia for Disposition of WPu

- April 1993: Minatom/GA MOU on joint GT-MHR development for commercial units
- June 1994: Russia proposes to build GT-MHR at Seversk to burn Russian WPu
- July 1994: GA and Minatom each pledge $1M for initial work
- Jan 1996: Framatome & Fuji Electric join GT-MHR program
- Dec 1997: Team completes Conceptual Design
- Sept 1998: GT-MHR becomes an option within the US/RF Pu Disposition Strategy
- Jan 2000: Work started on Preliminary Design

GENERAL ATOMICS

GT-MHR NOW BEING DEVELOPED IN INTERNATIONAL PROGRAM

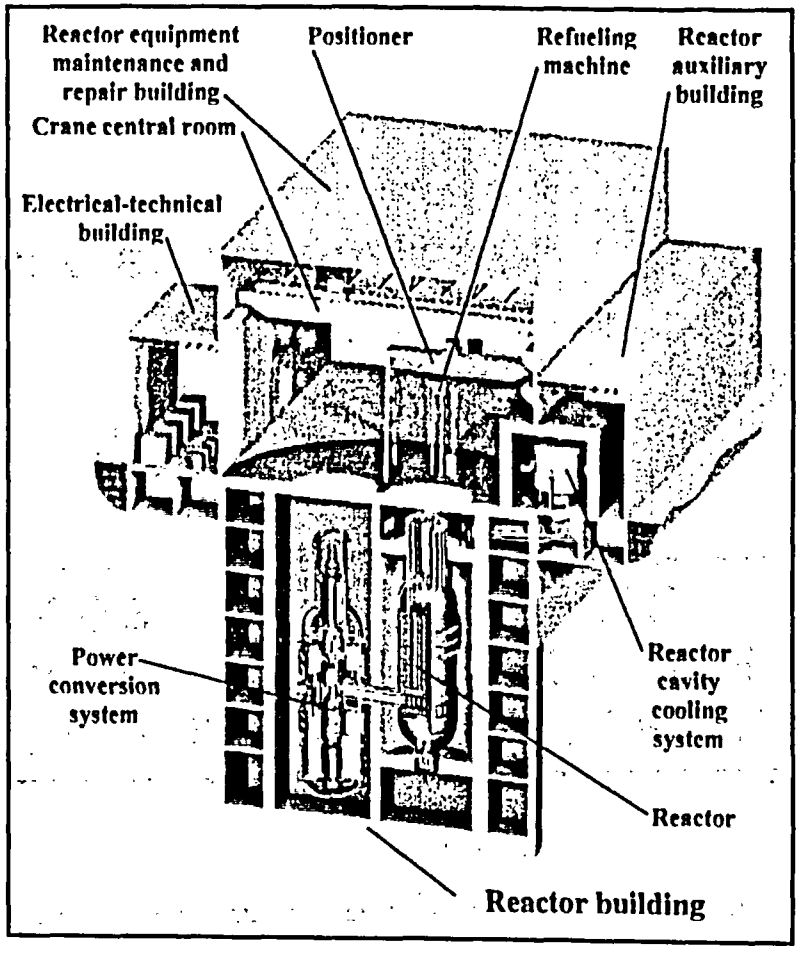
- In Russia under joint US/RF agreement for management of surplus weapons Plutonium
- Sponsored jointly by US (DOE) and RF (Minatom); supported by Japan and EU
- Conceptual design completed; preliminary design complete early 2002

GENERAL ATOMICS

INTERNATIONAL GT-MHR PROGRAM

- Design, construct and operate prototype GT-MHR module by 2009 at Tomsk, Russia
- Design, construct, and license a GT-MHR Pu fuel fabrication facility in Russia
- Operate first 4-module GT-MHR by 2015 with a 250 kg plutonium/ year/module disposition rate

....Fuel contains Pu only
.....No fertile component



GENERAL ATOMICS

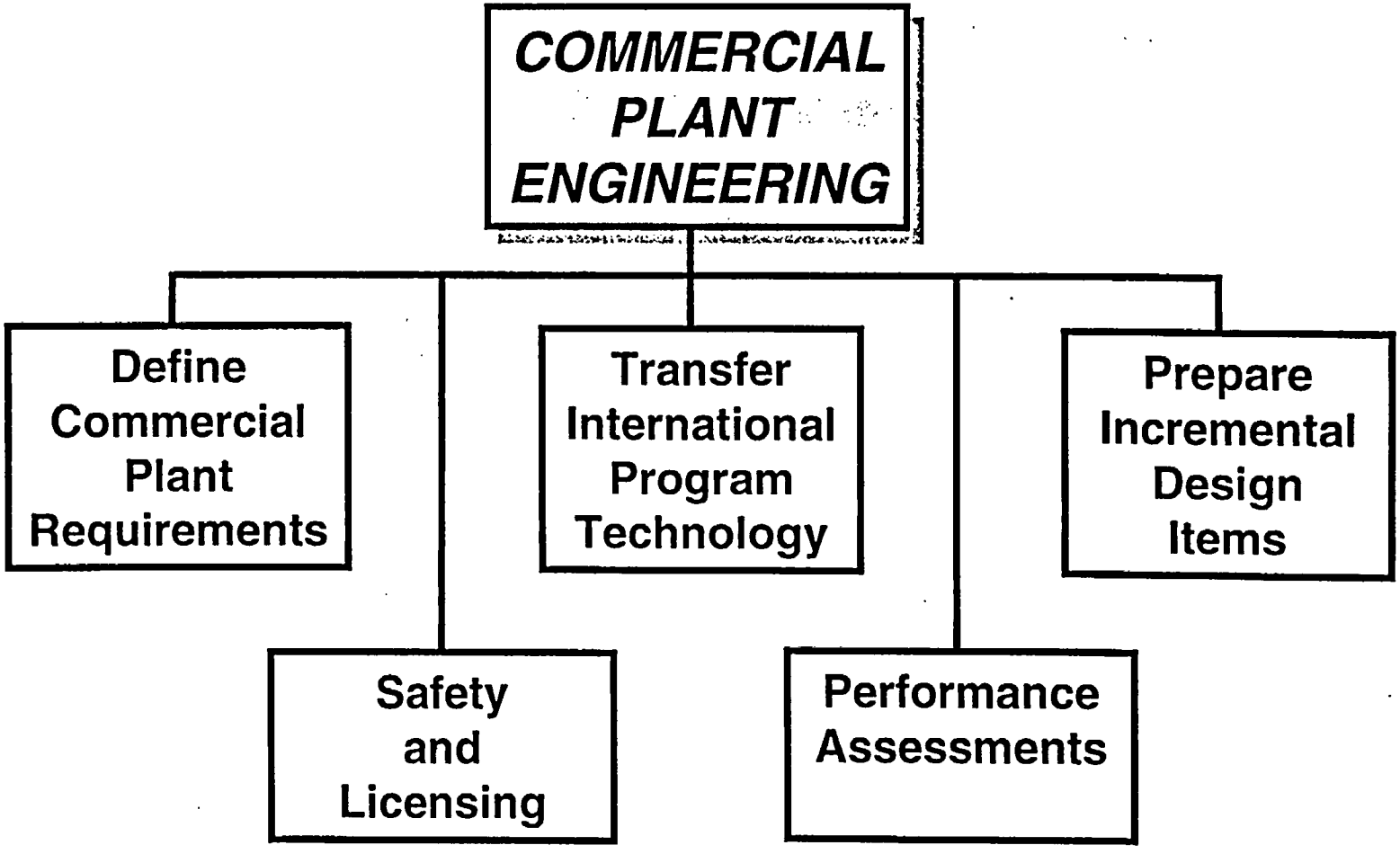
COMMERCIALIZATION PROGRAM

COMMERCIAL PROGRAM	=	INTERNATIONAL PROGRAM TECHNOLOGY	+	URANIUM FUEL RATHER THAN Pu FUEL

Plant construction can start in 5 years

GENERAL ATOMICS

LIMITED ENGINEERING WORK REQUIRED



GENERAL ATOMICS