NRC FORM 658
(9-1999)

U.S. NUCLEAR REGULATORY COMMISSION

TRANSMITTAL OF MEETING HANDOUT MATERIALS FOR IMMEDIATE PLACEMENT IN THE PUBLIC DOMAIN

This form is to be filled out (typed or hand-printed) by the person who announced the meeting (i.e., the person who issued the meeting notice). The completed form, and the attached copy of meeting handout materials, will be sent to the Document Control Desk on the same day of the meeting; under no circumstances will this be done later than the working day after the meeting.
Do not include proprietary materials.

DATE OF MEETING
05/29/2003

The attached document(s), which was/were handed out in this meeting, is/are to be placed in the public domain as soon as possible. The minutes of the meeting will be issued in the near future. Following are administrative details regarding this meeting:

Docket Number(s)	NA
Plant/Facility Name	Small Liquid-Metal Reactors
TAC Number(s) (if available)	
Reference Meeting Notice	ML031140541
Purpose of Meeting (copy from meeting notice)	Discuss small LMRs with LLNL and ANL

NAME OF PERSON WHO ISSUED MEETING NOTICE
Jerry N. Wilson

TITLE
Sr. Policy Analyst

OFFICE
NRR

DIVISION
NRLPO

BRANCH

Distribution of this form and attachments:
Docket File/Central File
PUBLIC

DF01

Small Liquid Metal Cooled Reactors

Presented to:

U. S. Nuclear Regulatory Commission Staff

May 29, 2003

Presented by:

Neil W. Brown
Lawrence Livermore National Laboratory
David C. Wade
Argonne National Laboratory
Akio Minato
Central Research Institute of Electric Power Industry (CRIEPI), Japan

Agenda

9:00 am	Introduction	DOE
9:15	Small LMR Projects at LLNL	LLNL
9:30	Background and Description of 4S Reactor	LLNL/CRIEPI
10:15	General Design Criteria and Safety Requirements for 4S	LLNL
11:00	Small Reactor Safety Evaluation	ANL
12:00	Lunch	
1:00 pm	Small Reactor Safety Evaluation	ANL
2:00	Proposed Approach to Certification-by-Test of Small LMRs	LLNL
2:30	Site Suitability Source Term and Severe Accident Analysis	LLNL
3:00	Discussion and Planning	All

LLNL has been a proponent of small nuclear power plant development since 1996

1952-2002

- Small plant LDRD studies with UCB 1996, 1997
  - Precursor to Small Secure, Transportable, Autonomous Reactor (SSTAR) NERI proposals
  - Identified potential for a proliferation resistant sealed core liquid metal cooled fast reactor
- SSTAR-Encapsulated Nuclear Heat Source(ENHS) with UCB, Argonne and Westinghouse NERI program
- SSTAR-Autonomous Controls with Argonne, TAMU, NERI Program
- Joint Preliminary Feasibility Study of Super Safe, Small and Simple (4S) reactor with CRIEPI*, ANL and UCB
- Initiative for joint U.S. Japan small liquid metal cooled fast reactor test program in U.S.

*Central Research Institute of Electric Power Industry

Top level SSTAR performance objectives

1952-2002

- Eliminate on-site refueling and fuel access
- Incorporate a systems engineering approach to design of nuclear energy supply and infrastructure, including all aspects of equipment life, fuel cycle, and waste management
- Small size to enable factory assembly and transportability
- Replaceable standardized modules (nuclear and BOP)
- Robust design providing large safety margins, high reliability, and minimum maintenance
- Simple operation supports autonomous control
- Waste minimization and waste form optimization

There is a recognized need for small reactors to meet local energy needs

1952-2002

- Projected power growth in developing countries with small power grids
- Remote and island locations (Alaska, Hawaii, Indonesia)
- Potential to improve proliferation resistance
- Fresh water production
- Green house gas reduction
  - Replace fossil power plants
  - Avoid fossil power plant additions
  - Hydrogen production

Small LMRs have best potential to achieve SSTAR objectives

1952-2002

- Advantages of LMRs
  - High conversion ratio
  - High burn-up fuel supports long life core
- Long life permits sealed system
- LMR low pressure systems support compact reactor designs with size and mass compatible with factory fabrication and transportation
- Large safety margins support autonomous control with only monitoring on-site
- High conversion ratios (breeding) supports sustainable nuclear future
- Small LMR can also contribute to closing the fuel cycle

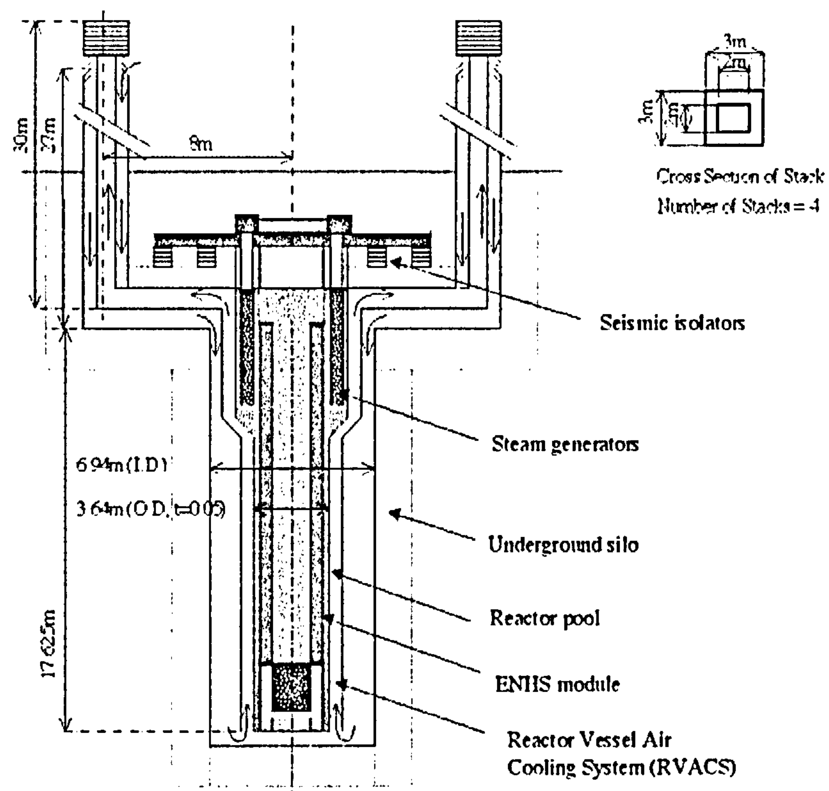
The international team supporting the DOE GEN IV program selected LFRs for further development and the U.S. has focused on small LFRs

UC Berkeley, LLNL, ANL and Westinghouse developed STAR-ENHS innovative concept

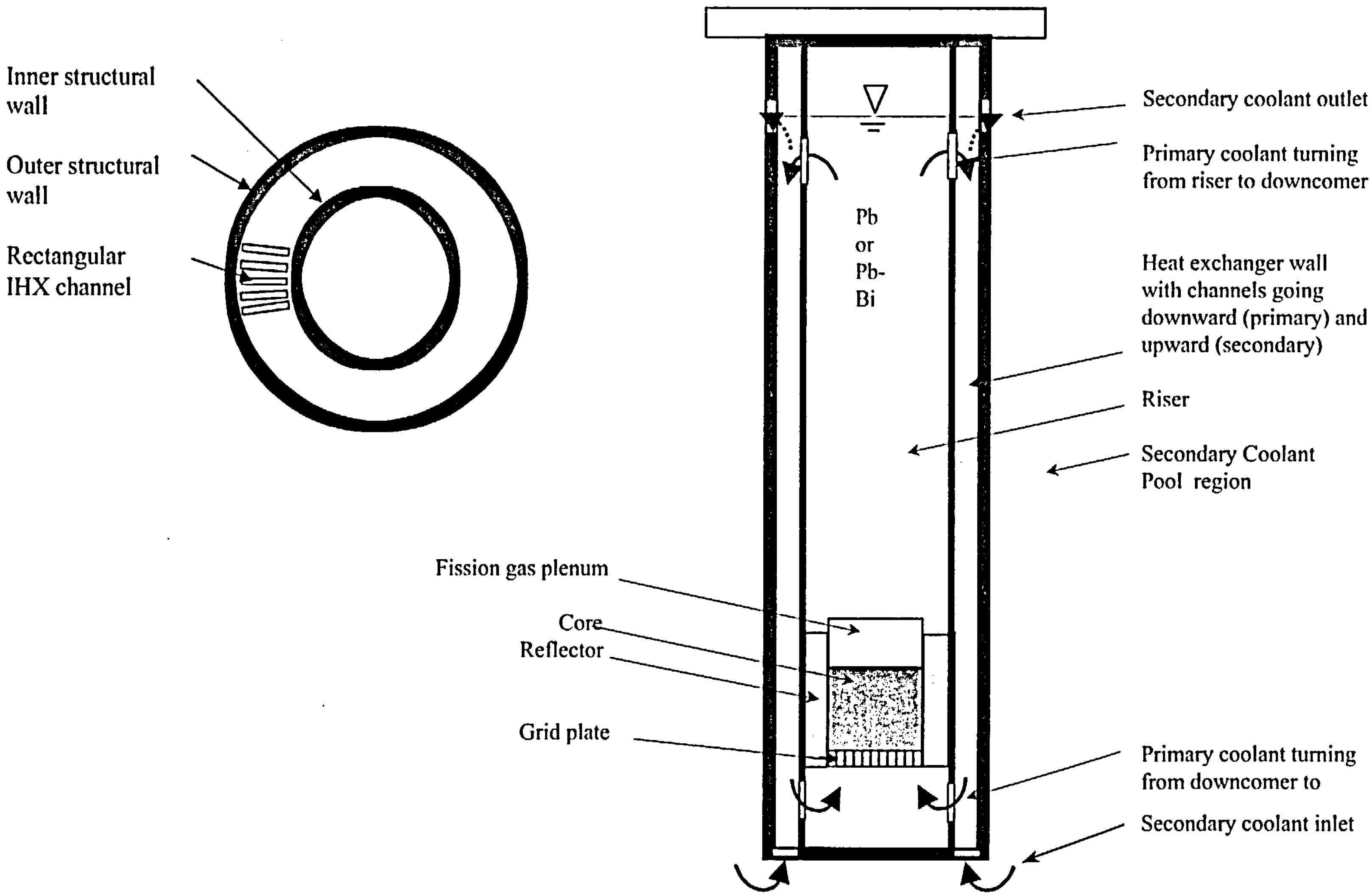
1952-2002

- 3-year NERI study with UCB, ANL, Westinghouse, KAIST, and CRIEPI completed in FY02
- Evolutionary concept developed from CRIEPI-Toshiba 4S reactor
- Natural circulation cooling
- Reactor core heat transferred from primary to secondary PbBi through capsule wall
- Fuel contained in capsule throughout fuel cycle
- Engineering feasibility demonstrated but economic feasibility is uncertain

Schematic vertical cut through the ENHS reactor

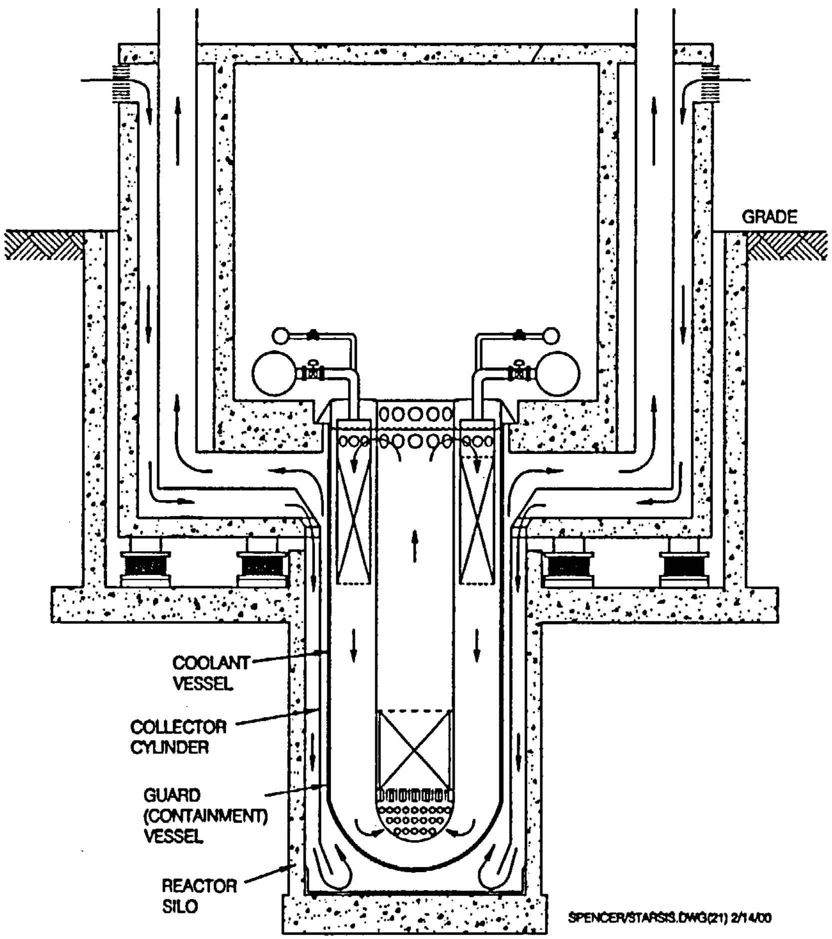


ENHS achieves SSTAR objectives and minimizes use of active components



ANL is developing a SSTAR-LM concept that uses heavy metal (Pb or Pb-Bi) coolant

1952-2002



STAR-LM Features

- More conventional design than ENHS
- Natural circulation cooling
- Cartridge core design with 15 year cartridge life
- Core replacement storage and shipping to be developed
- Coolant and materials development required
- Cost estimates need to be developed

Joint Preliminary Feasibility Study (JPFS)

1952-2002

- JPFS is LLNL, ANL, and CRIEPI program to identify a small liquid metal cooled fast reactor concept suitable for prototype testing in a joint U.S./Japan program
- UCB and industrial partner (TBD) will provide support
- CRIEPI/Toshiba 4S reactor is being evaluated in four areas
  - Market and economics
  - Proliferation resistance
  - Safety
  - R&D requirements
- Project will identify design modifications necessary to meet U.S. requirements, including proliferation resistance, and will also assess potential for joint prototype test project

DOE small Lead Fast Reactor (LFR) project under GEN IV has been expanded in FY03

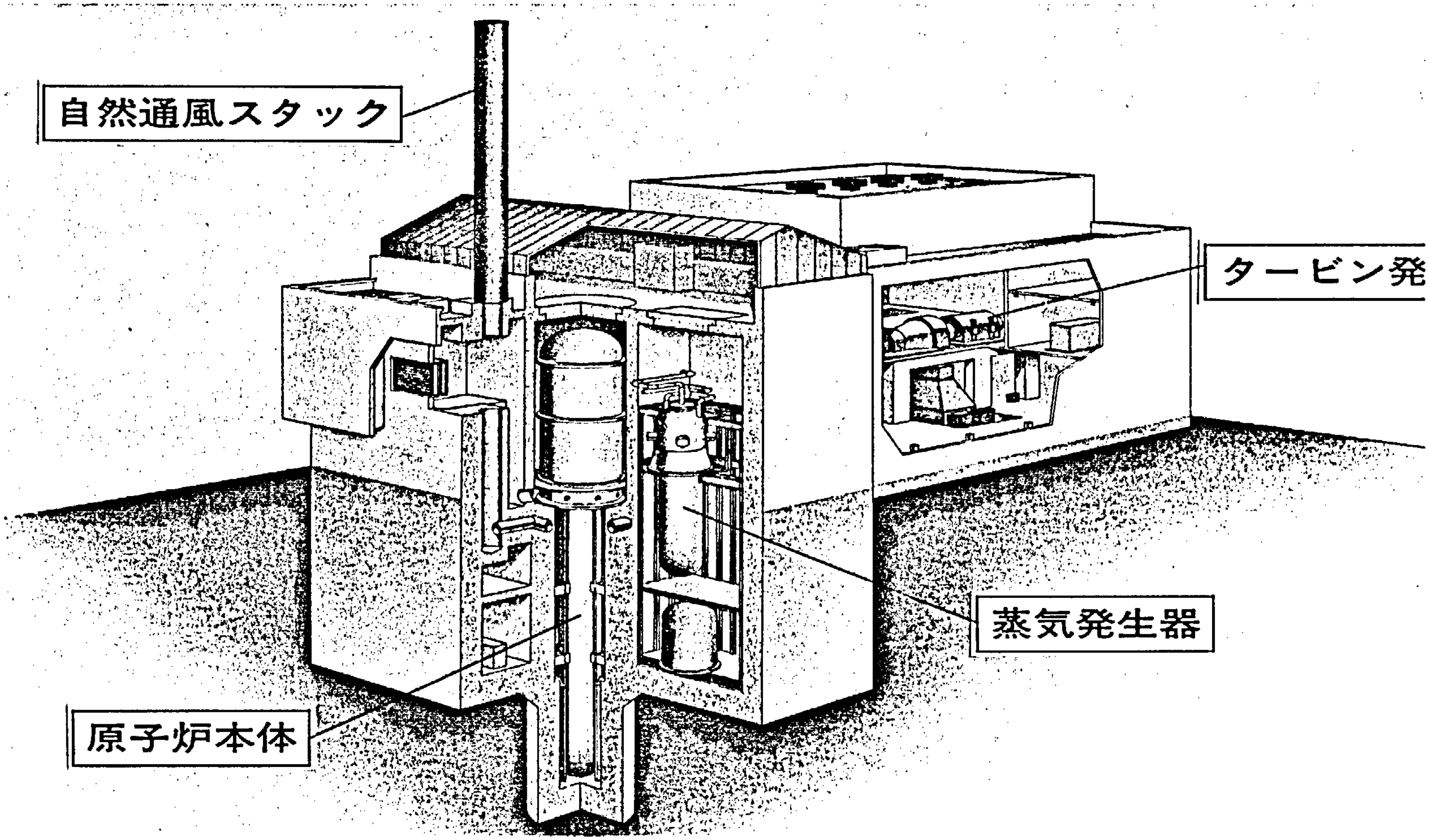
1952-2002

- Congressional support for small LMR development includes $2.0M in FY03 budget
- LLNL-led team has proposed an early jointly-funded U.S. Japan project to develop and test a small LMR in U.S.
  - Coolant selection (sodium or lead alloy) is to be resolved by FY05
- Team includes INEEL, LLNL, ANL, LANL, UCB, TAMU and industry (TBD)
- CRIEPI and Toshiba are working to establish government support for the program based on their experience developing 4S reactor

Objective is a long life sealed core reactor design certified by U.S. NRC using revised regulations that address unique characteristics of this small LMR

Super safe, small, and simple nuclear plant

1952-2002

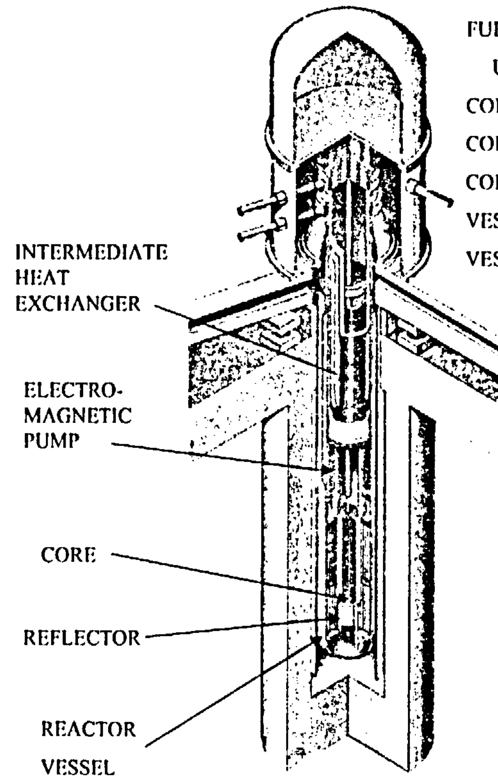


Japanese collaborator (CRIEPI) and Toshiba have developed the promising 4S reactor design

1952-2002

- Inherent safety features are robust
  - All reactivity feedback coefficients including coolant void reactivity are negative
  - Fully passive decay heat removal system
- Economic potential needs to be confirmed
- Achieving long life and sealed core objectives may depend on selection of coolant, sodium or heavy metal
- Origin of ENHS concept but does not emphasize security features

REACTOR ASSEMBLY



Major Specifications

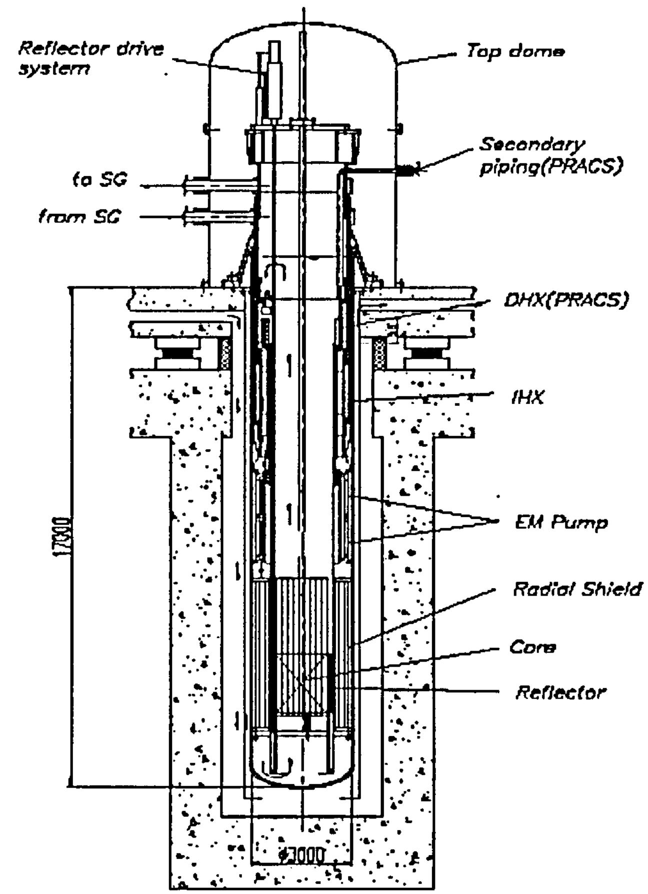
FUEL :
U-Zr METALLIC FUEL
CORE LIFETIME : 30Years
CORE HEIGHT : 2m
CORE DIAMETER : 1.1m
VESSEL HEIGHT : 15m
VESSEL DIAMETER: 2.7m

4S reactor layout Is compact

1952-2002

Specifications

Thermal Power, MW	125
Electrical power, MW	50
Primary Sodium Inlet Temp., C	355
Primary Sodium Outlet Temp., C	510
Secondary Sodium Inlet Temp.,C	475
Secondary Sodium Outlet Temp.,C	310
Primary Flow, m^3/min	44
Secondary Flow, m^3/min	41
Steam pressure, Mpa	10.8
Steam Temp.,C	453
Total mass, metric ton	250

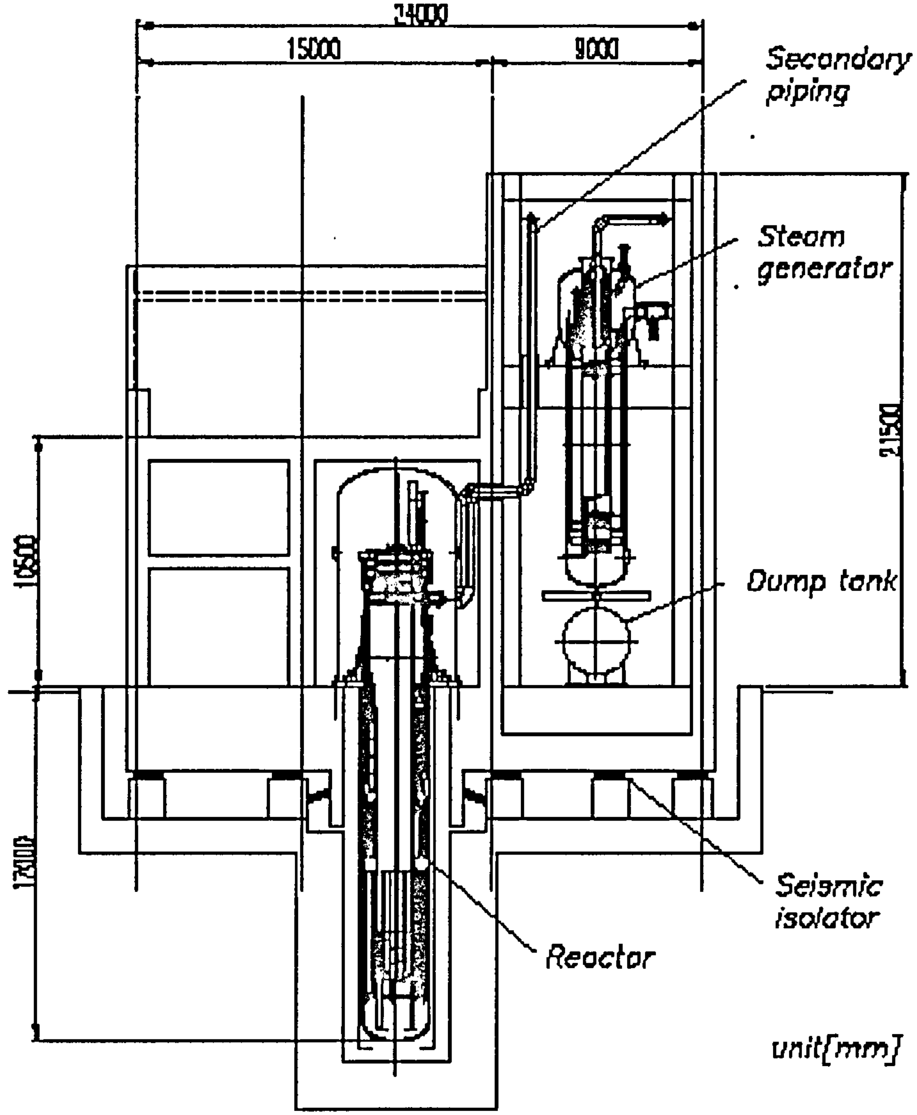


4S operations are simple and can be made autonomous

1952-2002

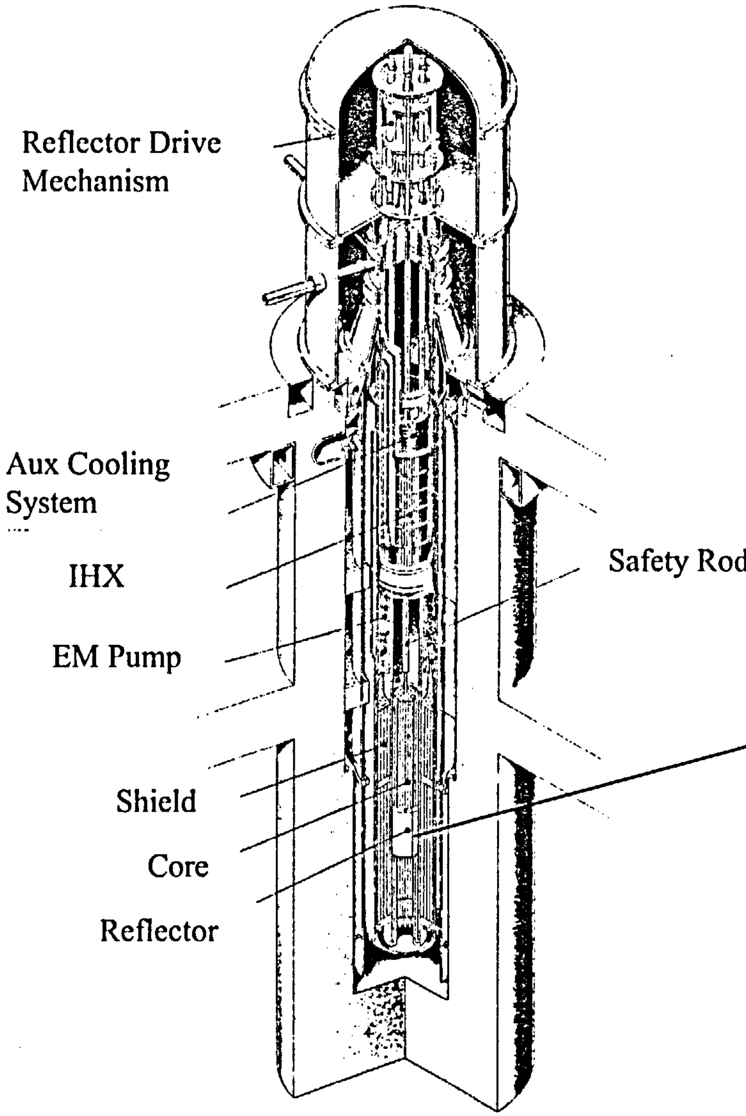
- To follow the load, the water flow is changed so that the steam generator power matches the load-following control, the resulting core inlet temperature causes the reactor power change to match the steam generator power
- There is no reactivity feedback control systems and no operator actions required for power changes of ±10% at the rated power; this a conservative limit that is the result of steam generator performance
- All other reactivity control is performed by the automatic movement of the reflector
- Burn-up reactivity compensation is attained by moving the reflector upward at a very slow constant speed such as 1 mm/day

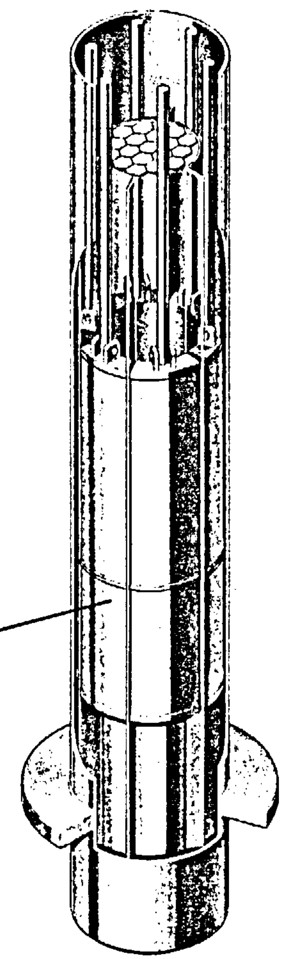
4S plant layout and dimensions



Reflector control is a unique feature of 4S

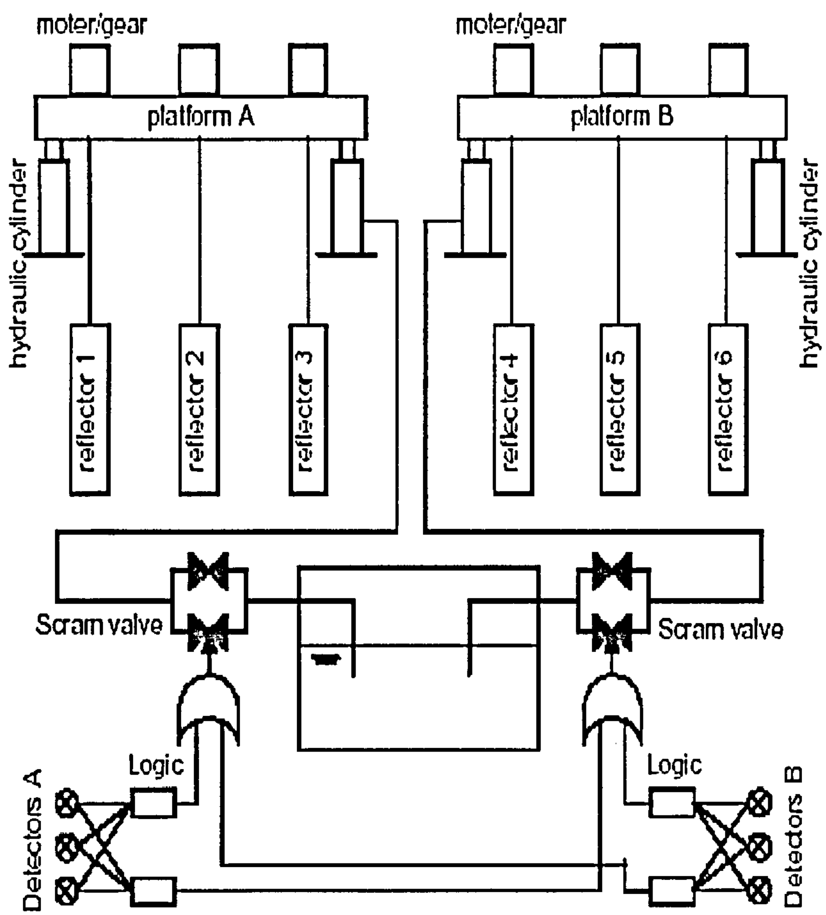
1952-2002





4S has highly reliable redundant shut down system

1952-2002



- Single reflector will shut reactor down
- Reflectors can be grouped to scram independently
- Electro-magnetic reflector drive system being developed as alternative to mechanical drive
- Central safety rod is diverse shut down system that responds to scram signal

Small reactor designs can provide electricity and fresh water (movie)

1952-2002

Small reactor safety evaluation (ANL)

1952-2002

Site suitability and site certification

1952-2002

- It is anticipated that 10CFR52 Part A can be used to obtain site certification for small LMRs
- The site suitability source term for small LMRs such as 4S is expected to be non-mechanistic and derived from postulated severe core accidents
  - The reactors will demonstrate a capability of terminating the most likely initiators (ATWS events) of severe core accidents without core damage
  - However, the reactors will also have an inherent capacity to accommodate non-mechanistic postulated core damage
- Small LMRs would likely have containments such as 4S with a leak rate 0.1%/day at a design pressure of more that 150kPa at a temperature of 150C°

Site suitable source term evaluation

1952-2002

- If the source term applied to PRISM

Noble gas	100%
Halogens	0.1%
Particulate	0.1%
Transuranics	0.01%

is applied to a 4S size reactor the dose consequences are:

	rem	%PAG
Whole body	0.05	5.0
Bone Marrow	0.05	5.0
Lung	0.13	10.0
Thyroid	0.22	5.0

A case will be made that the emergency response plans will not need to address areas beyond the site boundary

4S is being designed to GDCs similar to those used for MONJU and PRISM

1952-2002

- Pre-application SER for Power Reactor Innovative Small Module (PRISM) Liquid-Metal Reactor, NUREG-1368 was reviewed

GDCs for which the NRC staff agrees with pre-applicant

1, 2, 3, 5, 10, 11, 12, 13, 14, 16, 18, 20, 21, 22, 24, 29, 30, 32, 35, 39, 51, 52, 53, 54, 56, 60, 62 and 63

GDCs for which the NRC staff requests the pre-applicant to address changes to its position during the preliminary design phase on the GDC

4, 15, 17, 19, 23, 25, 26, 27, 28, 31, 33, 34, 36, 37, 38, 40, 41, 42, 43, 44, 45, 46, 50, 55, 57, 61, and 64

Results of review of the NRC proposed revisions to PRISM GDCs

1952-2002

- NRC proposed revisions to all except GDC 41 appear acceptable for a small sodium cooled LMR like 4S
  - GDC 41 provides requirements for containment atmosphere cleanup
  - Typically these systems will have such small compact containments that natural processes will take care of atmospheric cleanup
- The proposed addition of a criterion for protection against sodium reactions similar to CRBRP Criterion 4 appears acceptable
- GDCs applicable to lead (LBE) small LMRs are going to be developed under the DOE LFR program but are expected to be similar to those for sodium

SSTAR concept includes nuclear infrastructure changes

1952-2002

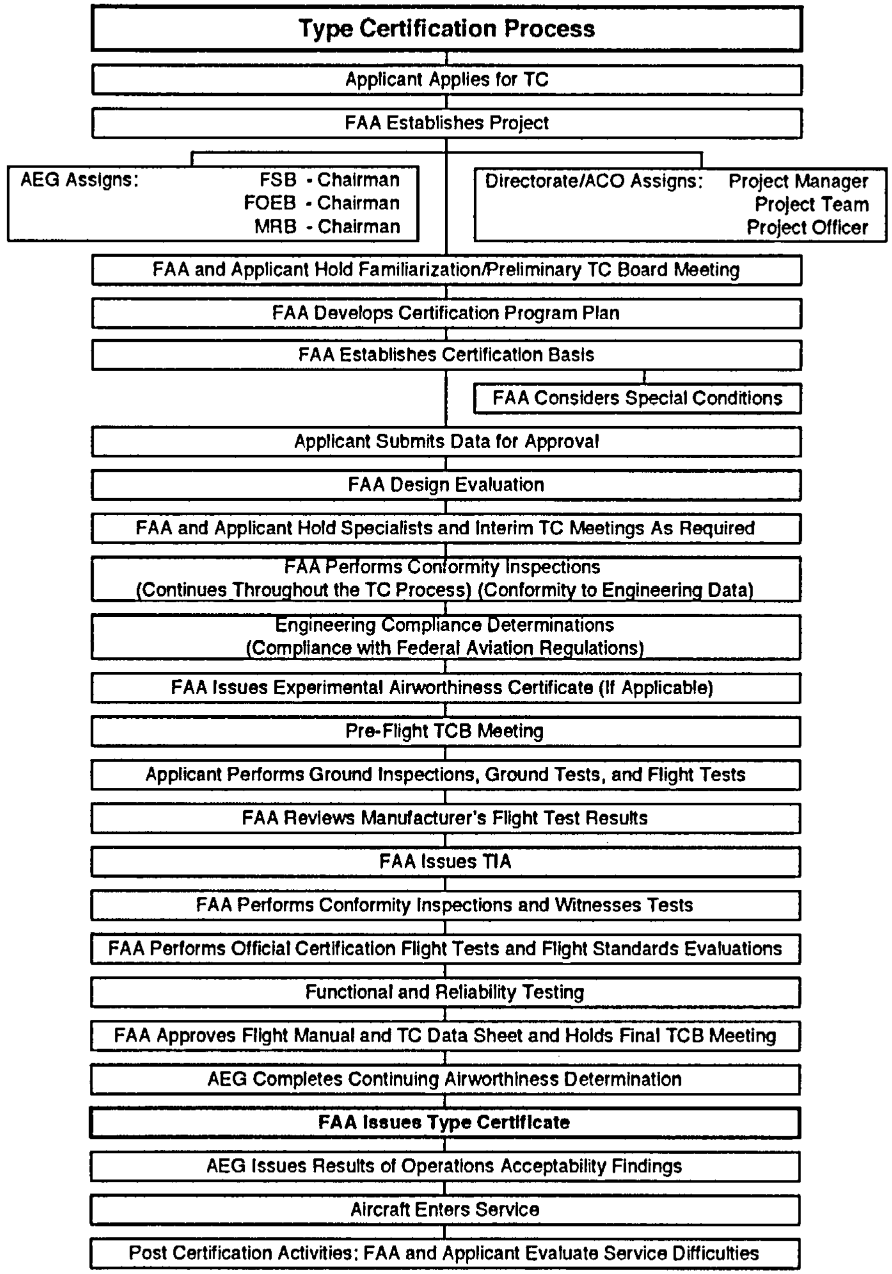
- Robust safety margins and simplicity of operation permits prototypical demonstration of full scope of safety challenges
- Economy of scale requires efficient factory production rate of about a factor of ten greater than large plants
- Industry financing and economics are more like commercial aircraft industry rather than nuclear
- Packaging and transportation of new and spent reactor module is a unique requirement
- Recycling and waste minimization is a major element in the new infrastructure

SSTAR concept includes proposed revision of nuclear regulations to address unique characteristics

Proposed approach to developing new regulations in parallel with design development

1952-2002

- Project will outline scope and path of regulatory revisions based on
  - 10CFR52, other applicable 10CFR parts such as those for spent fuel shipping and storage casks
  - FAA commercial aircraft regulations
  - Small LMR preliminary designs
- Proposed small LMR designs and regulatory revisions will be discussed and revised based on regulatory reviews, including ACRS as appropriate
- It is proposed that, like the FAA, the new regulations will include a certification program plan
- The certification program plan will include the nuclear power plant equivalent of a flight test program


Type Certification Process
Applicant Applies for TC
FAA Establishes Project
AEG Assigns: FSB - Chairman
FOEB - Chairman
MRB - Chairman
Directorate/ACO Assigns: Project Manager
Project Team
Project Officer
FAA and Applicant Hold Familiarization/Preliminary TC Board Meeting
FAA Develops Certification Program Plan
FAA Establishes Certification Basis
FAA Considers Special Conditions
Applicant Submits Data for Approval
FAA Design Evaluation
FAA and Applicant Hold Specialists and Interim TC Meetings As Required
FAA Performs Conformity Inspections
(Continues Throughout the TC Process) (Conformity to Engineering Data)
Engineering Compliance Determinations
(Compliance with Federal Aviation Regulations)
FAA Issues Experimental Airworthiness Certificate (If Applicable)
Pre-Flight TCB Meeting
Applicant Performs Ground Inspections, Ground Tests, and Flight Tests
FAA Reviews Manufacturer's Flight Test Results
FAA Issues TIA
FAA Performs Conformity Inspections and Witnesses Tests
FAA Performs Official Certification Flight Tests and Flight Standards Evaluations
Functional and Reliability Testing
FAA Approves Flight Manual and TC Data Sheet and Holds Final TCB Meeting
AEG Completes Continuing Airworthiness Determination
FAA Issues Type Certificate
AEG Issues Results of Operations Acceptability Findings
Aircraft Enters Service
Post Certification Activities: FAA and Applicant Evaluate Service Difficulties

Certification program plan concept

1952-2002

- Proposed key new requirement
- Initial activity would focus on developing scope of certification tasks
  - Equivalent of flight test program
  - Additional functional and reliability testing
- The scope of the "flight test" program would include anticipated transients with and without scram
- Functional testing would address maintenance and in service inspection
- Reliability testing would support risk informed decisions
- Factory certification for production of a series of type certified plants would also be required
- Site certification may be conducted similar to 10CFR52 Part A

Schedule of LFR and JPFS activities

1952-2002

- Schedule depends on U.S. and Japanese government level of interest and support
- LLNL team is seeking FY04 funding increase in LFR project to support early prototype
- GEN IV, LFR project plan includes option for early prototype with DOE CD-0 scheduled for FY-05
- CRIEPI team is working with LLNL to develop support in Japan on similar schedule
- Objective is to complete prototype testing by 2012

Passive Safety Design Approach for SSTAR's

David Wade

Argonne National Laboratory

A U.S. Department of Energy
Office of Science Laboratory
Operated by The University of Chicago

Outline of Presentation

- **Passive Safety Design Approach for SSTAR Reactors**
- **Metal Fuel – an Enabling Technology**
- **Elements of Passive Safety**
  - Passive Reactivity Shutdown
  - Tech Spec Monitoring of Integral Reactivity Feedbacks
  - Run Beyond Clad Breach
  - Avoidance of Energetics – The Benefits of Low Melting Fuel
  - Close-Coupled Containment & Passive Decay Heat Removal
- **Example Applications of the Passive Safety Approach to the 4S Reactor**

Passive Safety Design Approach for SSTAR Reactors

- **All SSTAR Reactors Rely on Passive Safety Features for Two Central Safety Functions:**
  - (1) Passive self regulation of power to match heat removal
    - *On basis of innate thermostructural reactivity feedbacks*
  - (2) Passive Decay Heat Removal
- **Payoffs:**
  - Close off Accident Initiation Pathways via Innate Response
    - *Safe termination of ATWS events*
  - Balance of Plant has no Safety Function
    - *Built and Operated to Industrial Standards*
  - Simplification
    - *Elimination of some Engineered Safety Systems*
- **The US NRC has Previously Examined Passive Safe Designs**
  - SERs for SAFR and PRISM ALMR's were issued in late 80's – mid 90's

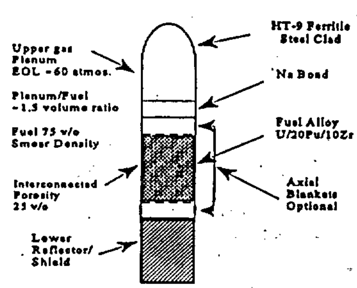
Design for Reliance on Passive Safety Responses

- **Decay Heat Range:**
  - Passive (buoyancy driven) heat removal channel to ultimate heat sink
- **Passive Protection of Decay Heat Removal Channel**
  - Atmospheric pressure primary system:
  - Large thermal mass coolant volume totally contained in a top entry double tank
  - Seismic isolation
- **Power Range**
  - Passive feedbacks to maintain power & heat removal in balance
  - Large temperature margins to boiling and clad damage
  - Large thermal inertia of sodium pool to slow down response
- **Passive Protection of Reactivity Feedback Thermo/Structural Response**
  - Seismic isolation
- **Severe Accident Range**
  - Self extinguish reactivity by means of early fuel dispersal
  - No vapor explosions because fuel disperses at low superheat
  - Porous, coolable debris morphology
    - *Invessel retention of disrupted core*

Metal Fuel – The Enabling Technology

- **Traditional Oxide Fueled LMFBR Safety Issues (FFTF, CRBR)**
  - Decay heat removal
  - Control rod runout
  - Positive sodium void worth
  - Hypothetical core disruption accidents
    - *Autocatalytic voiding of coolant*
    - *Potential vapor explosion*
    - *Potential recriticality upon debris compaction*
- **Physical Properties of Metal Alloy Facilitate Solutions to These Issues**
  - Solutions take advantage of metal fuel's high density, high thermal conductivity and low melting point
  - Same approaches apply for nitride fuel used in some SSTAR's

Metal Fuel Safety Performance Derives from Physical Properties



Diam. ~7 mm
Pitch/Diam. ~1.2
Clad Thickness ~0.5 mm
Linear Heat Rating ~500 w/cm (Peak)
Coolant Exit ~500°C
Peak Clad Midwall ~565°C
Peak Fuel ℄ ~800°C

	Metal Alloy		MOX
Therorectical Density (gm/cc)	15.8		10.6
Thermal Conductivity (w/cm °C	0.22		0.023
Eutectic Thermodynamic Threshold (°C)	725		-
Eutectic Penetration Threshold (°C)	1100		-
Melting Point (°C)	1160		2750
Boiling Point (°C)	3800		3400
Na Boiling Point (°C)		880	
Margin to Na Boiling (°C)		380	
HT-9 Rapid Creep Threshold (°C)		650	
HT-9 Melting Temperature (°C)		1400	

Passive Reactivity Shutdown

- **What Information Flows Inward across Reactor Vessel Boundary?**
- **Reactor Core Influenced through Only 3 Paths to External Events (recall – ambient pressure)**
  - Changes in Secondary Coolant Flow Rate
  - Changes in Secondary Coolant Inlet Temperature and
  - Externally-Supplied Reactivities
    - + *Control Rod Motion*
    - + *Seismically Induced Core Geometry Changes*
- **Their range is bounded by innate phenomena e.g., zero flow to cavitation**
- **Presentation Approach:**
  - Examine the Inherent Response of a Reactor Core to the Three Generic Types of External Perturbation
  - Express Resulting Asymptotic Core Temperature Changes in Terms of Ratios of Measurable Integral Reactivity Parameters
  - Find Range of Values of Integral Reactivity Parameters which will Guarantee Acceptable Core Temperatures for Unprotected (i.e., autonomous) Accident Scenarios Initiated through the Three Generic Communication Paths
- **Then:**
  - Discuss Design Choices which Yield the Favorable Integral Reactivity Feedbacks

Measurable Integral Reactivity Parameters

- **Given We are Interested in Reactivities Associated with:**
  - Power Level Changes
  - Flow Rate Changes
  - Inlet Temperature Changes
- **Consider Three Measurable Integral Reactivity Parameters**

(A+B) = "Power Reactivity Decrement" (units = ¢); (size ~20 to 300 ¢)
= Reactivity Loss in Going to Full Power, Full Flow from Zero Power Isothermal at Normal T_{INLET}

B = "Power/Flow Reactivity Decrement" (units = ¢); (size ~20 to 60 ¢)
= Component of (A+B) Due to Core ΔT
= Reactivity Loss in Going from Zero Power Isothermal at Normal T_{INLET} to Full Core ΔT but at Very Low Power (such that coolant and fuel are at same temperature)

C = "Inlet Temperature Coefficient" (units = ¢/°C); (size ~1/2 ¢/°)

Reactivity Change per Unit Change in Inlet Temperature

Inherent Core Response to External Disturbances

- **A Quasistatic Reactivity Balance Gives the Response of Core to External Perturbations:**

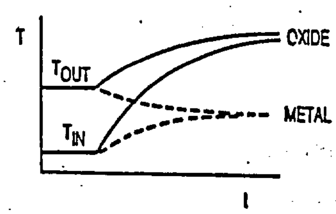
$$0 = +\Delta\rho = (P\text{-}1)A + (P/F\text{-}1)B + \delta T_{IN}C + \Delta\rho_{EXTERNAL}$$

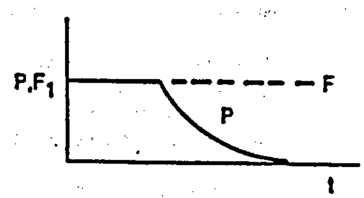
where

P	=	**Power Normalized to 100% full power**
P/F	=	**Power/Flow Ratio Normalized 100% Full Power and Flow**
δT_{IN}	=	**Incremental Change in Core Inlet Temperature (°C)**
$\Delta\rho_{EXT}$	=	**Externally Imposed Reactivity (¢)**
$-(A+B)$	=	**Power Decrement (¢)**
$-B$	=	**Power/Flow Decrement (¢)**
$-C$	=	**T_{INLET} Coefficient (¢/°C)**

- **Use of Formula: Power Adjusts Up or Down to Compensate through the Power Coefficient any Reactivity Change Caused by External Event**

LOHS Without Scram Temperature Rise Drives Power to Zero





- **Scenario**
  - BOP Heat Rejection Terminates
  - Flow Stays Constant
  - TINLET Increases
  - Power Reduces to Hold Reactivity at Zero
  - Power/Flow Reduces and T_{OUT} Collapses onto T_{IN}

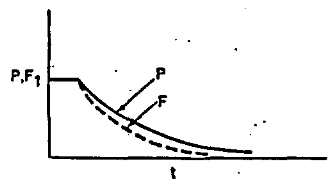
- **Reactivity Balance**

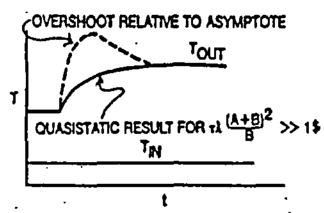
$$0 = (0-1)A + (0-1)B + \delta T_{IN}C + 0$$

$$\delta T_{IN} = \frac{(A+B)}{C} \qquad \delta T_{OUT} = \frac{(A+B)}{C} - \Delta T_c$$

- **Design for Minimum Temperature Rise**
  - Small Power Coefficient
  - Large T_{INLET} Coefficient

LOF Without Scram
Power/Flow Increase Drives Power to Zero





Long Term Scenario

- **Primary Pump Coasts Down, F → Nat Circ.**
- **T_{INLET} Remains Constant**
- **Power/Flow Increases Causing A Negative Reactivity**
- **Power Increases to Keep Reactivity at Zero**

Long Term Reactivity Balance

$O = -\Delta\rho = (O-1)A + (P/F-1)B + O + O$

| P/F-1 = A/B | δT_{OUT} = A/B ΔT_c |

Ratios of Integral Reactivity Parameters Control Passive Shutdown

- **Cases Which Encompass Events Possible Through the Three Generic Communication Paths**
  - Primary Pump Induced Events (Changes in Flow)
    - *LOF*
    - *Pump Overspeed*
  - Control Rod Induced Events (Changes in External Reactivity)
    - *TOP*
  - BOP Induced Events (Changes in Inlet Temperature)
    - *LOHS*
    - *Chilled Inlet Temperature*
- **Core Outlet Temperature Is Always Determined by Three Dimensionless ratios of Measurable Integral Parameters**
  - A/B
  - $C\Delta Tc/B$
  - $\Delta\rho_{TOP}/B$ where $\Delta\rho_{TOP}$ = TOP Initiator = $\frac{\text{Burnup Control Swing}}{\text{No. of Primary Rods}} \cdot \left(\begin{array}{c}\text{1stRodOut}\\ \text{Interaction}\\ \text{Factor}\end{array}\right)$
  - τ λ+ A/B)2|B| (In $ Units) (Controls Transient Overshoot in LOF)
    - λ — Delayed Neutron Time Constant
    - τ — Pump Coastdown Time Constant

- Using the Most Unfavorable Bound of the Sufficient (but not necessary) Ranges

$0 \le A/B \le 1$	A = reactivity vested in temperature rise of fuel above coolant
$0 \le -\Delta\rho TOP/B \le 1$	B = reactivity vested in temperature rise of coolant above inlet
$1 \le C\,\Delta Tc/B \le 2$	C = inlet coolant temperature coefficient of reactivity

It is seen that the asymptotic outlet temperature changes are bounded to an acceptable value ($\le 1\,\Delta Tc$) for all unprotected events

Event	$(\delta T_{OUT})Max$	
LOF	$1\,\Delta Tc$	Asymptotic (Peak Overshoot requires dynamic analysis)
TOP	$1\,\Delta Tc$	
BOP Induced Events;		
LOHS	$1\,\Delta Tc$	
Chilled Inlet	$\frac{3}{4}\,\Delta Tc$	

Design for Reactivity Parameters To Yield Inherent Safety

Desired Trend		Rationale
• A, B, C	All Negative	• A is proportional to prompt power coefficient
• A/B	Small i.e.,	• Essential for LOF: keep reactivity vested in fuel small
• $-\Delta\rho TOP/B$	Small i.e., ≤ 1	• Essential for TOP: keep reactivity vested in control rods small
• $C\Delta T_{c/B}$	Between 1 and 2	• Balance of conflicting requirements for decoupling reactor from BOP (i.e., for both LOHS and chilled inlet)
• Adjusted so that $\tau\lambda\,(1 + A/B)^2\lvert B\rvert >> 1\$$		• Minimize outlet temperature overshoot relative to asymptotic value in the LOF

Key Enabler is Metal Fuel

- **High Thermal Conductivity**
  - Keeps $\overline{T}_{fuel}$ near $\overline{T}_{coolant}$ → A/B is small
- **High Density**
  - Allows to design for internal breeding → $\Delta\rho_{TOP}$ is small
- **Note that SSTAR Reactors have an added Advantage**
  - Linear heat rate on pins is derated (to achieve long refueling interval)
  - This keeps $\overline{T}_{fuel}$ near $\overline{T}_{coolant}$ → A/B is small
- **(Note that Nitride fuel has the same favorable properties)**

Tech Spec Monitoring of the Integral Reactivity Feedback Parameters as A Basis for Licensing Inherently Safe Reactors

Proposed Approach

- In Traditional Licensing Approach, Tech Specs Require Periodic Testing of the Engineering Safety Features which Protect the Public
- In the New Inherent Shutdown Regime where Inherent Processes Protect the Public:

  Tech Specs require Periodic Testing of the Inherent Feedback Reactivities

Synopsis of the Idea

1. **We know that the external world can influence the reactor's reactivity through only three communication paths:**

   Coolant Flow Rate
   Coolant Inlet Temperature
   Reactivity from Rod Motion
   Inertial Force Rearrangements of the Core

2. **We know that the reactivity coefficients for each of these communication paths can be measured on the reactor by simple means amenable to a utility environment:**

   (A+B) Power Reactivity Decrement
   B Power/Flow Coefficient of Reactivity
   C Inlet Temperature Coefficient of Reactivity

   Along with

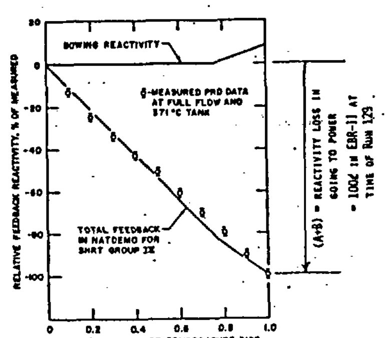
   τ Primary Pump Coastdown Time Constant
   $\Delta\rho_{TOP}$ (BOEC excess reactivity/(# of primary rods)

Synopsis of the Idea (Contd.)

3. **We know that the core temperatures resulting from passive reactivity control of all accidental scenarios possible by means of the external event communication paths of item (1) can be expressed as simple ratios of the measurable reactivity parameters of item (2):**
   - So can figure out from these formulas what the allowed ranges of the measurable parameters must be in order to guarantee acceptable core temperatures in all possible inherent shutdown scenarios
   - i.e., we know the ranges of A, B, C, τ, $\Delta\rho_{TOP}$ required to protect the public
4. **Write Tech Specs which require periodic measurement of the measurable reactor parameters**
5. **Require power reduction or shutdown and notification of NRC is measurable parameters lie outside the specified range**

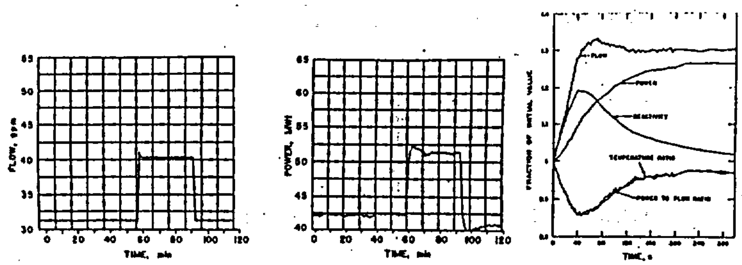
Measure (A+B) = Power Reactivity Decrement (PRD) EBR-II PRD (Run 129)

Measurement: Take Reactor from Zero Power Isothermal at T_{INLET} to full power and flow. Worth of calibrated control



Open Loop "Self Regulation" Interpretation of EBR-II Tests

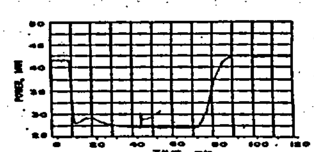
- With rods held fixed: power innately adjusts to match heat sink presented by coolant inlet temperature and flow rate

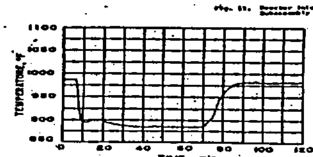


- Two Measured Powers and Flows: 2 unknowns A&B

Measure (C) = Inlet Temperature Coeff
EBR-II Response to Inlet Temperature Perturbation

Measurement: Speed Up Feedwater Pump; See Where Power Ends UP





Measure (C)

- Measurement: Speed Feedwater Pump Up
- Use Quasi Static Balance

$$O = (P'-1)A + (P'/F-1)B + \delta T_{IN}C$$

$$C = \frac{(P'-1)A + (P'/F-1)B}{-\delta T_{IN}}$$

One equation; one unknown since:

B and A known from previous 2 tests
P' and δT_{IN} measured

- A, B, and C can be (and have been on EBR-II) measured on an operating plant without elaborate procedures or equipment
- Alternate methods could be done also

  e.g., Same as before except maintain constant power with calibrated rod

  (direct determination of B and C and no change in temperature rise in fuel pin)

- **More sophisticated, non-intrusive ways of introducing perturbations and reducing the data could, if needed, be put in place to strip out the components of A, B, and C having different time constants**

Prompt	Associated with Fuel Temperature	• Doppler
Fast	Associated with Core ΔT	• Na Density • Radial Expansion
Slow	Associated with Core Support Temperatures	• Grid Plate Thermal Expansion • Core Restraint Ring Thermal Expansion • Vessel Wall Elongation

- **A development program was worked out in mid 90's to develop non-intrusive measurement techniques for A, B, C, τ, and Δp_{TOP} and/or continuous on-line monitoring for changes in these and other quantities**

EBR-II Passive Safety Demonstration tests (1986)

Loss of Flow Without Scram

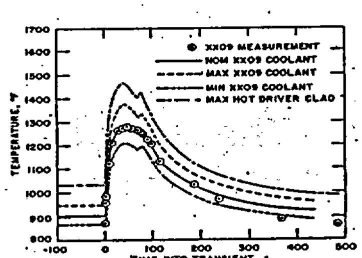


Fig. 3. Loss of flow without scram from 100% power with 100 s pump coastdown time. Test 45. Pretest predictions and measurements of in-core temperatures

Loss of Heat Sink Without Scram

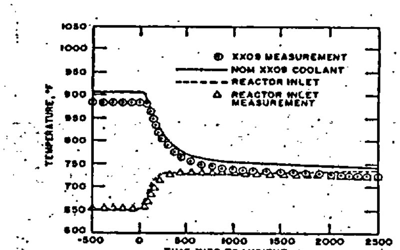


Fig. 4. Loss of heat sink without scram from 100% power. Test B302. Pretest predictions and measurements of reactor temperatures

Run Beyond Clad Breach

- **Fuel Pin manufacturing Flaws Cannot be Totally Eliminated**
- **For A Long-Refueling Interval Core**
  - Fuel and Coolant must be Chemically Compatible
    - *No High-Volume chemical reaction products to choke off flow*
    - *No significant dissolution of fuel in coolant*
- **Metal Fuel and Sodium Coolant are Chemically Compatible**
  - Use Na to thermally bond metal fuel to inside of fuel cladding
  - Many tests at EBR-II of purposely flawed pin clad
    - *No fuel/coolant interaction in run beyond clad breach*

Avoidance of Energetics – The Benefits of Low Melting Point of Metal Fuel

Reactivity Addition Accidents

Give a U/Pu Fuel Cycle:

- Can Design for

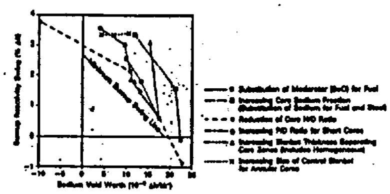
  Either

  Zero Reactivity Loss with Burnup (good neutron economy)

  or

  Zero Sodium Void Worth (poor neutron economy)

  But Not Both at Once



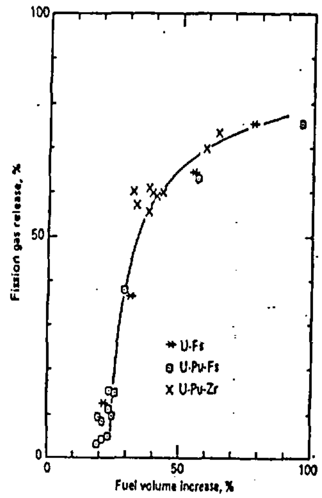
Trade-off ov void worth and burnup swing for 900-MW (thermal) cores

- A Potential for Reactivity Addition Is Unavoidable
- Passive Safety Designs Close off the pathways for ATWS events to lead to reactivity insertion
- If the Available Reactivity Exceeds that of Passive Feedback
  - Then, the ultimate shutdown is still available – by fuel dispersal

SSTAR Reactors Use Different Approaches

- Some SSTAR Designs Achieve Zero Reactivity Loss over Burn Interval
  - Good Neutron Economy
    - *Minimize Neutron Leakage*
    - *Maximize Internal Breeding*
  - Minimal Reactivity Vested in Rods – but
  - Positive Coolant Void Worth
- 4S Design Does the Reverse
  - Cigar Shaped Core
    - *Large Neutron Leakage*
  - Reduced Coolant Void Worth – but
  - Large Reactivity Loss with Burnup
  - (Potential for Rod Runout is Avoided by Use of Programmed Reflector Insertion with increased Burnup)
- But No Matter What, (as learned with SAFR & PRISM SER reviews by NRC) One Must Address a Hypothetical Low Probability Reactivity Insertion Initiator for SSTAR reactors

Effect of Fuel Swelling on Fission Gas Release in Metal Fuels

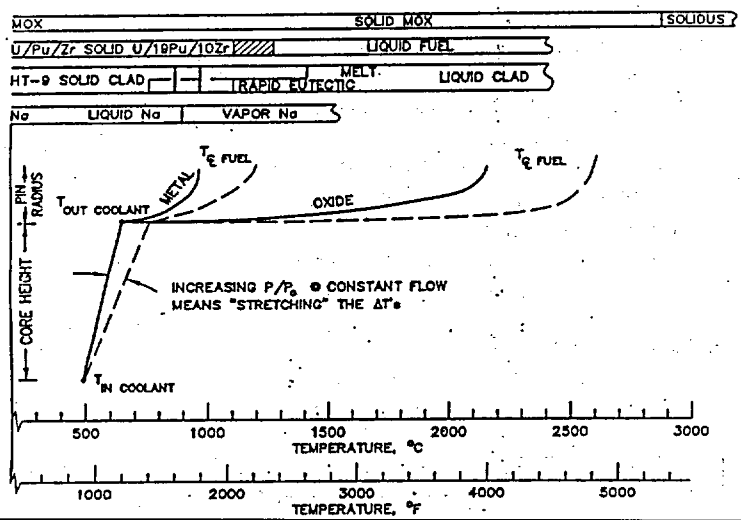


Metal Fuel – Innate Fuse-like Quenching Response to Reactivity Insertion Accidents

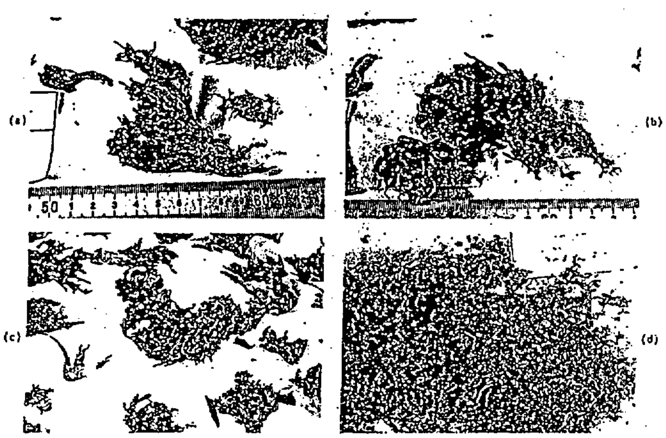
For Metal Fueled Cores, Initiating Phase is Self Quenched; No Super Prompt Critical;

No Energetics

- **Innate Quenching Shutdown Relies on Early, Low-energy Fuel Dispersal**
- **The Metallic Alloy Fuel Melts at a Low Temperature**
  - Small energy increment will make fuel mobile and permit fuel dispersal (for oxide, large energy deposition is required to melt fuel and make it mobile)
- **For Metal Alloy Fuel, Fission Gas in the Interconnected Porosity is Entrapped Upon Fuel Melting and Provides a Dispersive Driving Force**
  - Activated at small deposited energy (for oxide, fuel vapor is the dispersal driving force → requires high deposited energy to activate
- **For Metallic Alloy Fuel, the Low Temperature Fuel/Clad Eutectic Permits Early Fuel Dispersal at Low Superheat vis-à-vis Sodium (for high melting oxide fuel, dispersal occurs late**
  - After further reactivity addition due to clad drainage
  - With fuel at high superheat relative to sodium
- **Metal fuel Phenomena Displayed in TREAT Tests M2-M7**



Fragments from FFC-4 – Coolable Invessel Debris Bed Formed by Dispersed Metal Fuel



Summary: Metal Fuel Safety Performance

For Metal Alloy fuel the Innate Physical Properties are the Cause of Favorable Safety Response:

- **High thermal conductivity keeps fuel temperature near coolant temperature:**
  - Small stored energy
  - Small stored positive reactivity (in Doppler)

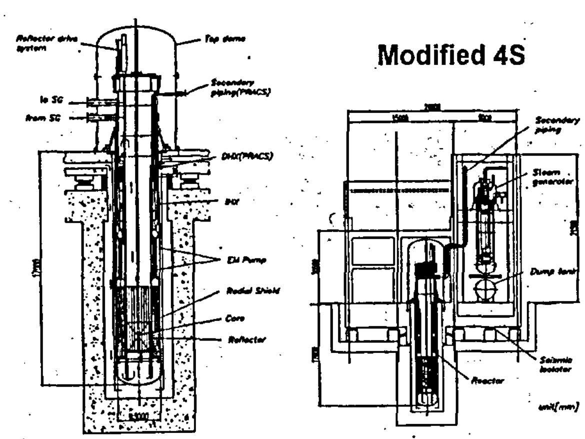
  } → **Rideout ATWS with out damage**
- **Low melting point of metal alloy:**
  - Ensures early fuel mobility
- **100 atmosphere fission gas in 30 v/o Interconnected Porosity:**
  - Provides the driving force for early fuel dispersal
- **Low eutectic penetration temperature (matched to fuel melting and coolant boiling temperature)**
  - Ensures fuel/coolant contact at low superheat → no vapor explosion
  - Ensures early fuel dispersal out of core

Fuse-like behavior leads to avoidance of prompt criticality & No energetics even with positive void worth core designs

Close – Coupled Containment and Passive Decay Heat Removal

- **SSTAR has no credible mechanism for pressurizing containment**
  - Ambient coolant pressure
  - Detached Na/H_2O steam Generator
  - No source of H_2
  - No Energetics in Hypothetical Pin Disruption Events
- **A "close coupled" containment can be used**
  - A guard vessel – plus
  - A close coupled containment dome or a confinement building
- **This facilitates passive decay heat removal to ambient air via an RVACS**

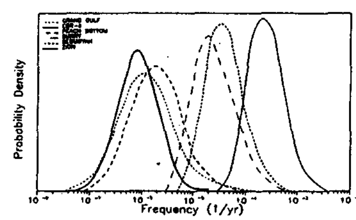
Reactor Vessel Auxiliary Cooling System (RVACS)



Level 1 PRA With Passive Safety for EBR-II

- **Passive Safety Approach is Effective in Limiting Risk**
- **EBR-II Employed the Passive Safety Discussed Above**

Comparison of EBR-II Damage Frequency
with Core Damage at Commerical LWRs
(LWR data from NUREG-1150)



- **"Damage" for EBR-II defined as overheating (vis-à-vis Tech Specs) of Aggressive Test Pins**
- **"Damage" for LWR's defined as core disruption**

Example Applications of the Passive Safety Approach to the 4S Reactor

Safety Evaluation Events and Criteria

Evaluated Events	Safety Criteria
Passive DHRS (RVACS) - PLOHS loss of AC power →N/C	Structure T<650°C
	No boiling Coolant T<960 °C
Passive Shutdown - ULOF loss of flow and heatsink without scram	No melting Fuel T<1180 °C
- UTOP reactivity insertion without scram	Target fuel element Nominal hottest pin HCF=1.53, 593°C

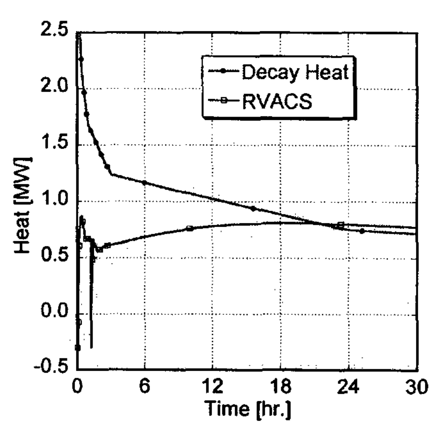
PLOHS Results (1)

Analytical condition

Reactor shutdown at 0 sec.

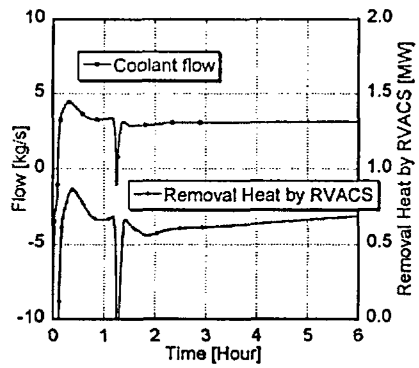
Flow coastdown
flow halving time: 10 sec.

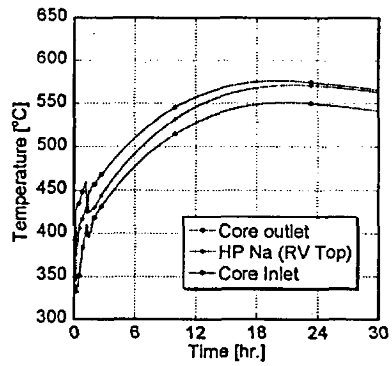
Heat sink
feed water suddenly stops
steam blow in SG
PRACS isolated



effective surface: 130 m^2
heat flux at 0.8 MW: 6.2 kW/m^2

PLOHS Results (2)





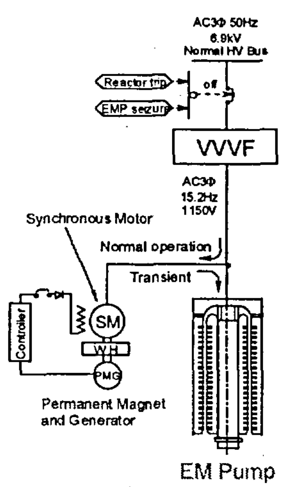
RVACS performance

Temperature changing

designed 1.0 MW at 650 °C

core flow rate: 3.4% rated flow
RVACS flow: 15% of core flow

EM Pump Control/Characteristic

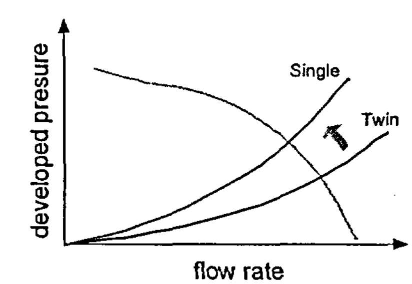


Control circuit

4S design: two EMPs in series

One EMP seizure

Flow rate: More than 50%



Q-H characteristics

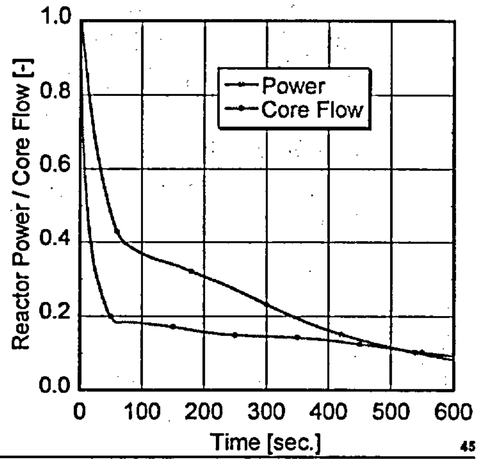
ULOF Results (1)

Analytical condition

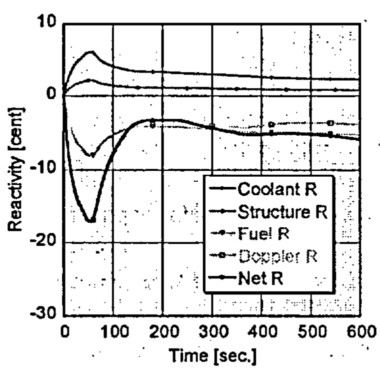
Flow coastdown
flow halving time: 10 sec.

Heat sink
feed water suddenly stops
steam blow in SG
PRACS isolated

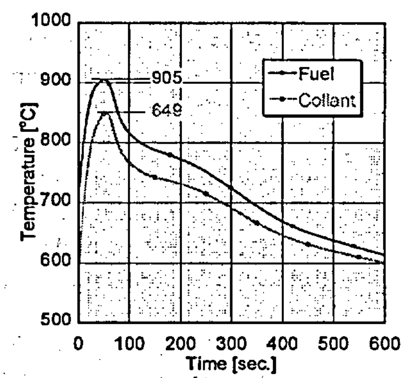
Reactivity effects
no radial core expansion



ULOF Results (2)



Reactivity components



Temperature changing

$\tau_{1/2}$=5 sec.: 975/921

Concluding Remarks

- The several transient sequences are analyzed to evaluate the passive safety capability of the improved 4S by the suitable analytical code CERES
- RVACS demonstrates its ability through the simulation of PLOHS
- The flow halving time of 5 seconds can be acceptable in ULOF
- An acceptable external reactivity input varies with the transient conditions

Summary

- **SSTAR's are designed for passive safety**
  - Ambient pressure system with long thermal time constant
  - Large Thermal Margins
  - Passive termination of ATWS events with zero damage
  - Passive decay heat removal
  - Monitor passive feedback parameters to assure safe response
  - Safe run beyond clad breach
- **Pathways to core damage are closed by innate passive response**
- **None-the-less**
  - Fuse-like fuel dispersal would preclude energetics in HCDA
  - Coolable debris bed and no recriticality would apply in HCDA
- **SSTAR's could be licensed by Test**
  - Actually subject the prototype to ATWS
  - Was already done at EBR-II in 1986 tests)