PennState
College of Engineering

NucE 497: Reactor Fuel Performance

Lecture 36: LOCA

April 12rd, 2017
Michael R Tonks
Mechanical and Nuclear Engineering

Today we will discuss a loss of coolant accident

- Module 1: Fuel basics
- Module 2: Heat transport
- Module 3: Mechanical behavior
- Module 4: Materials issues in the fuel
- Module 5: Materials issues in the cladding
- Module 6: Accidents, used fuel, and fuel cycle
    - Reactivity insertion accident
    - **Loss of coolant accident**
    - **Accident tolerant fuel**
    - Fuel cycle
    - Used fuel disposition

First, lets review from last lecture

- Reactivity Initiated Accident requires
  a) Small and rapid insertion of reactivity
  b) Large and slow insertion of reactivity
  c) Large and rapid insertion of reactivity
  d) Small and slow insertion of reactivity

- Which one is not a consequence of RIA?
  a) Fuel dispersal due to PCMI
  b) Cladding ballooning and burst
  c) Hydride formation due to the accelerated corrosion in high T_{clad}
  d) All of the above

Reactor accidents can have major consequences

Date	Location	Description	Fatalaties	Cost ($M)
Jan 3, 1961	Idaho Falls, ID, US	Explosion at National Reactor Testing Station's SL-1 Stationary Low-Power Reactor Number One	3	22
March 28, 1979	Middletown, PA, US	Loss of coolant and partial core meltdown	0	2,400
April 26, 1986	Chernobyl, Ukrainian SSR	Overheating, steam explosion, fire, and meltdown, dispersing radioactive material across Europe	56 direct; 4,000 to 985,000 cancer	6,700
March 12, 2011	Fukushima, Japan	A tsunami flooded and damaged the 5 active reactor plants. Loss of backup electrical power led to overheating, meltdowns, and evacuations.	2 (from the tsunami)	Still counting

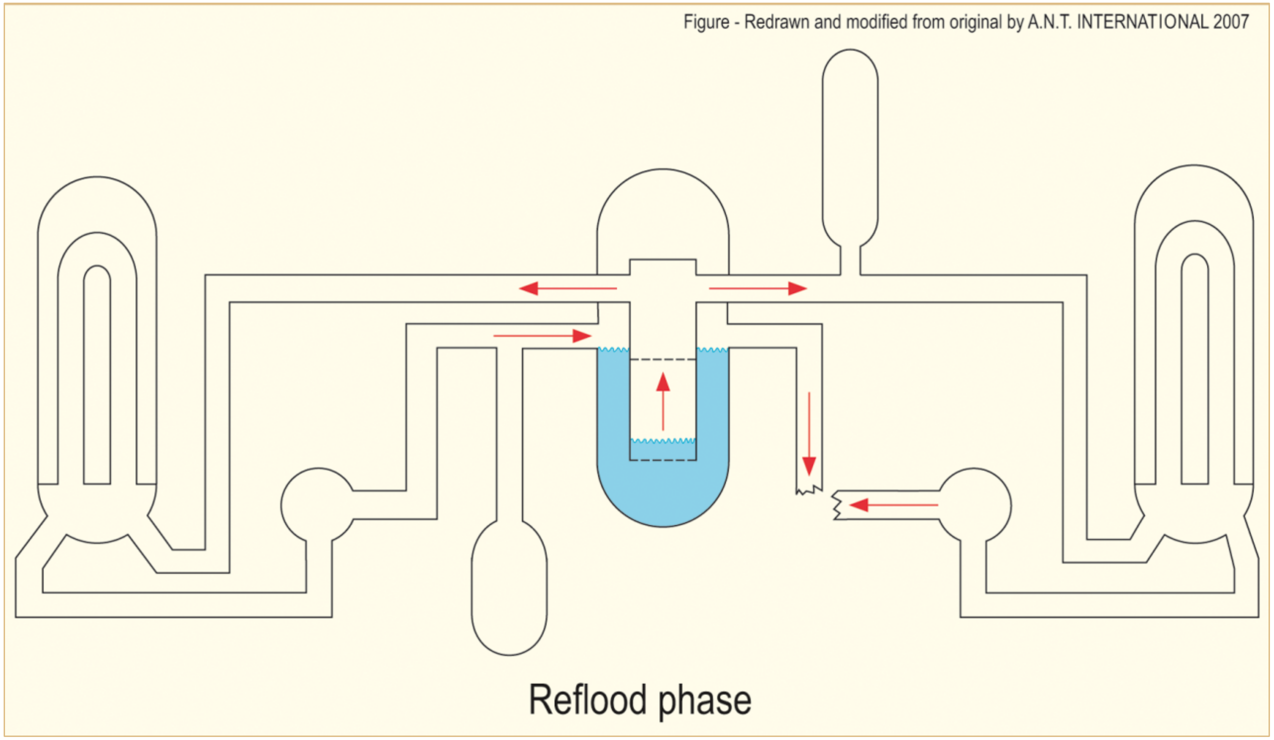
Reactors are designed to prevent release of radioactive material if something goes wrong

- Reactor safety during normal operation is well proven

- However, they need to stay safe even if something goes wrong
- Design base accidents
  - Reactivity Initiated Accident (RIA)
  - **Loss of coolant accident (LOCA)**

In a LOCA, the coolant flow is reduced or lost altogether

- When this occurs, pressure drops, causing the emergency shutdown system SCRAMS the reactor, stopping the fission chain reaction.
- Also, the reactor water is expelled into the containment
- The emergency core cooling system (ECCS) begins to remove heat



Assuming the ECCS does not activate, what happens to the fuel rods?

- With the fission chain reaction stopped, is any additional heat produced in the fuel?
- As the heat goes up, what will happen to the remaining coolant?
- What will happen to the outer cladding pressure?
- With no external pressure, what will happen to the cladding?
- What will happen to the fuel centerline temperature?

The changes in pressure and temperature result in large changes in the cladding

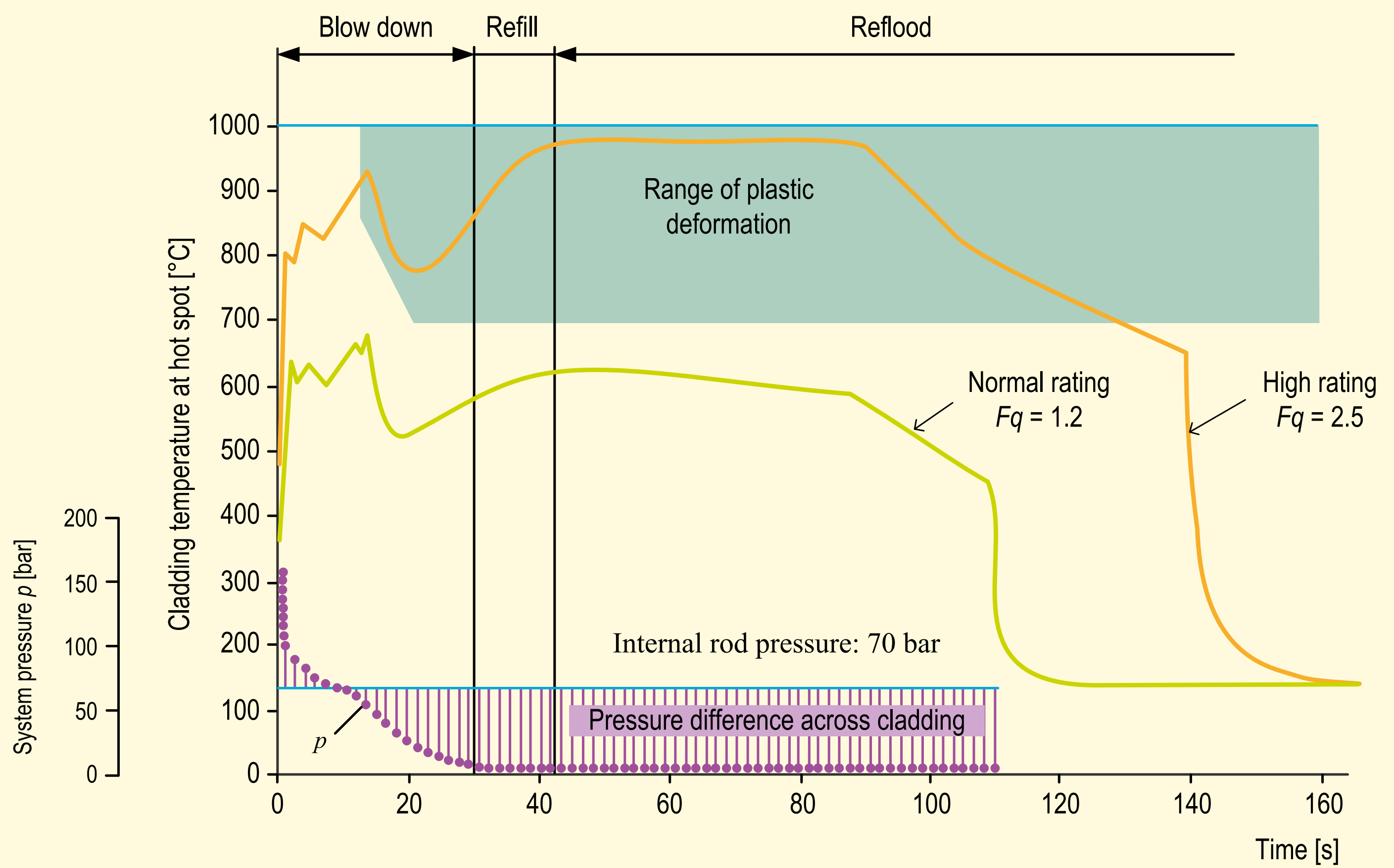
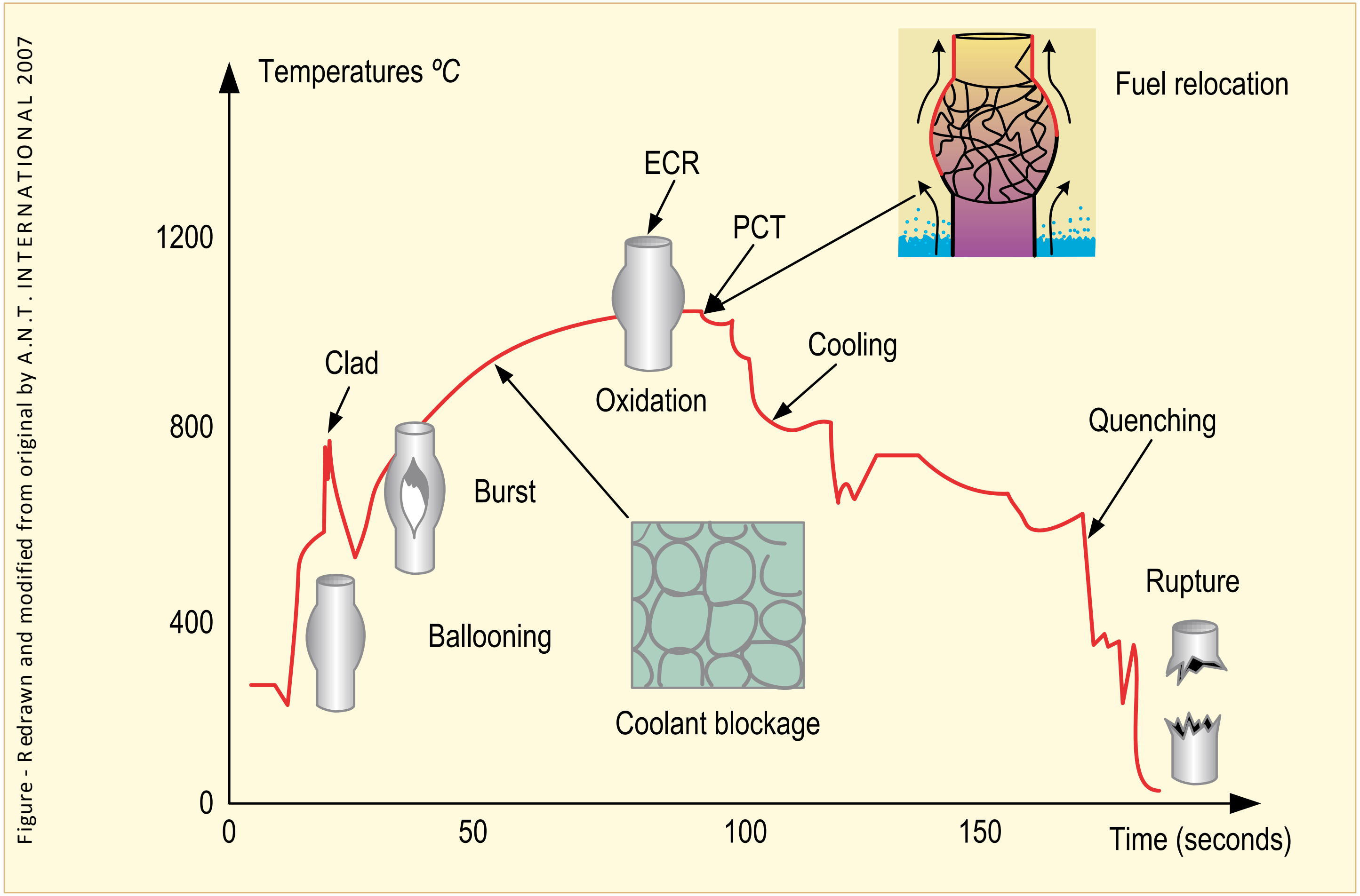


Figure - Redrawn and modified from original by A.N.T. INTERNATIONAL 2007

There are standards on what can happen to the fuel rod during a LOCA

- Maximum clad temperature < 1204°C
- Clad oxidation < 17% of clad thickness
- Hydrogen gas produced < 1%
- Fuel must have coolable geometry (no fuel dispersal and no coolant blockage)
- Core temperature maintained at low value for extended time

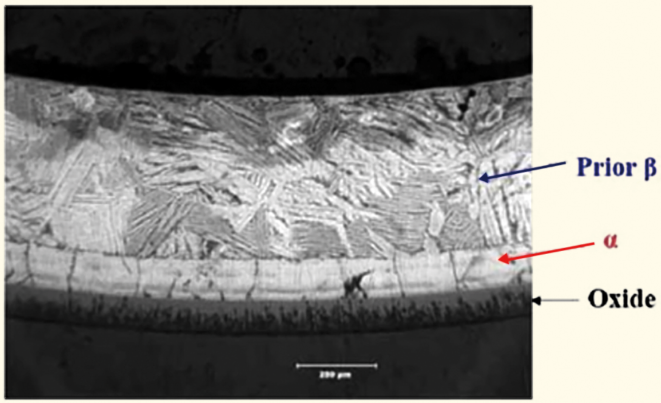
LOCA can easily result in cladding rupture

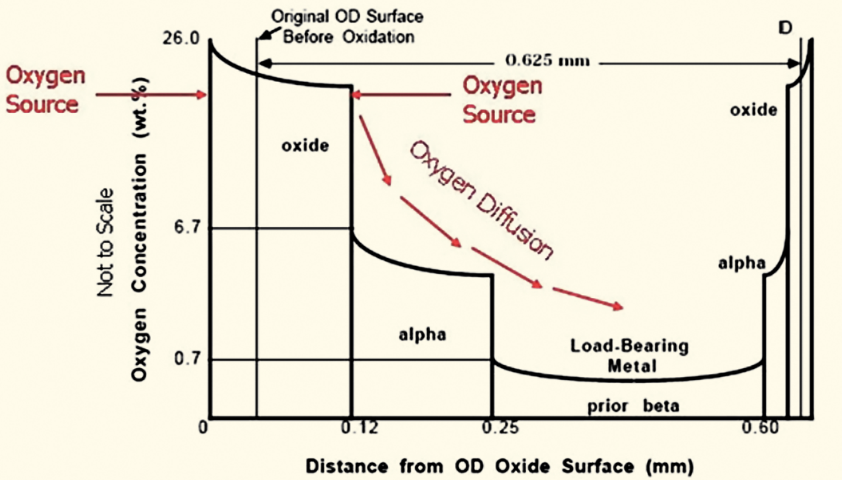


LOCA causes large changes in both the fuel and cladding

- Cladding changes
  - Alpha to beta transition as cladding temperature goes above 863C
  - Break away oxidation
  - Rapid hydrogen pickup
  - Ballooning
  - Burst
- Fuel changes
  - Thermal stress
  - Transient induced fission gas release
  - Relocation

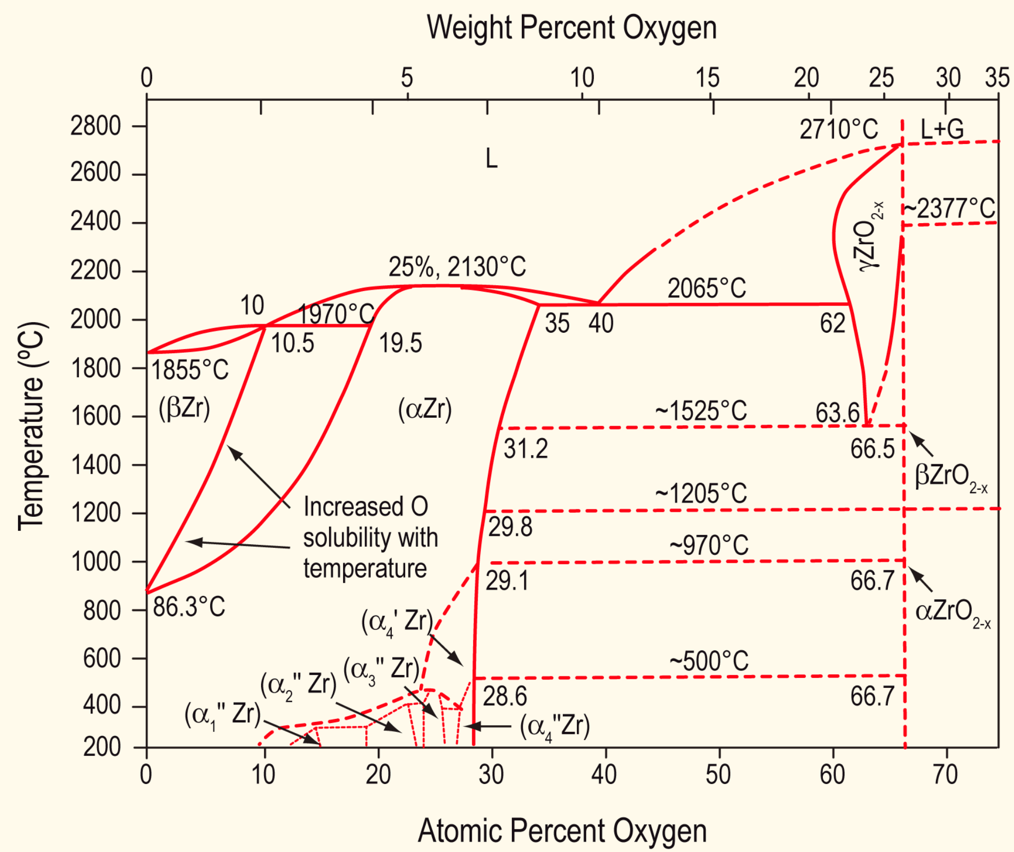
High temperature causes α to β phase transformation and oxidation



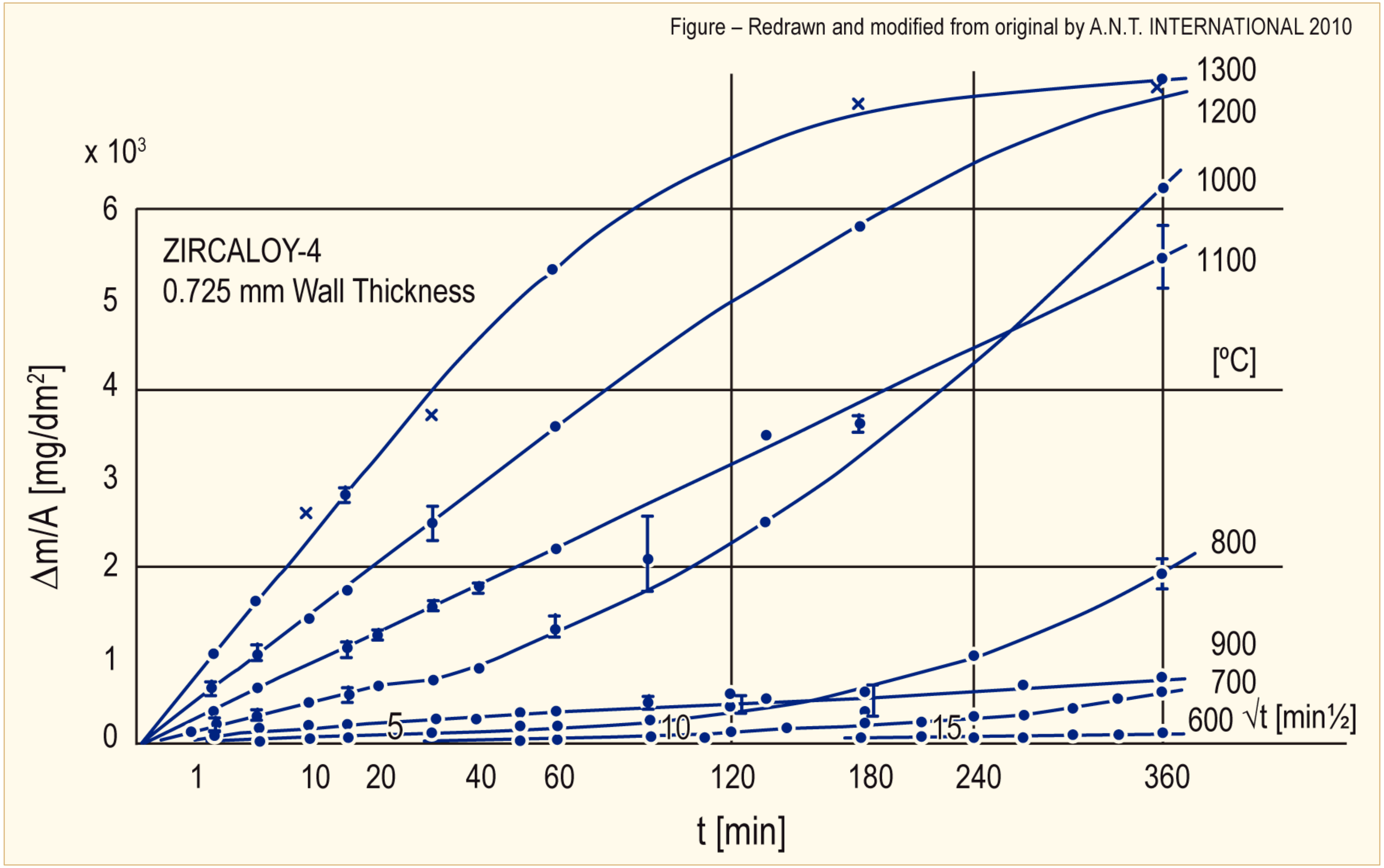


Structure of Oxidized Cladding (Meyer, 2002)

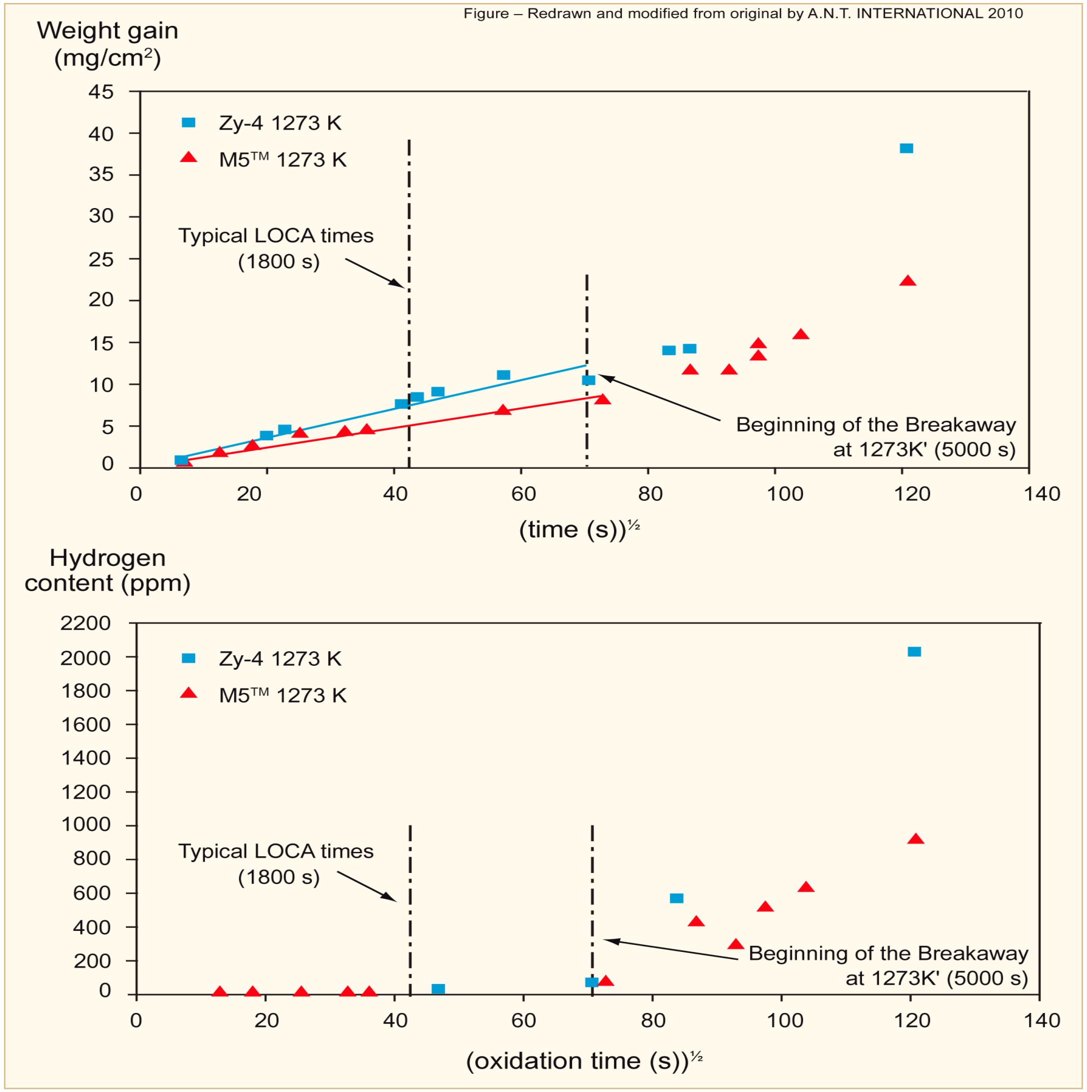
Figure – Redrawn and modified from original by A.N.T. INTERNATIONAL 2010



Oxidation significantly increases at high, accident temperatures



Breakaway oxidation also results in increased hydrogen pickup in the cladding



Decrease in coolant pressure and increase in internal pressure causes the cladding to balloon out

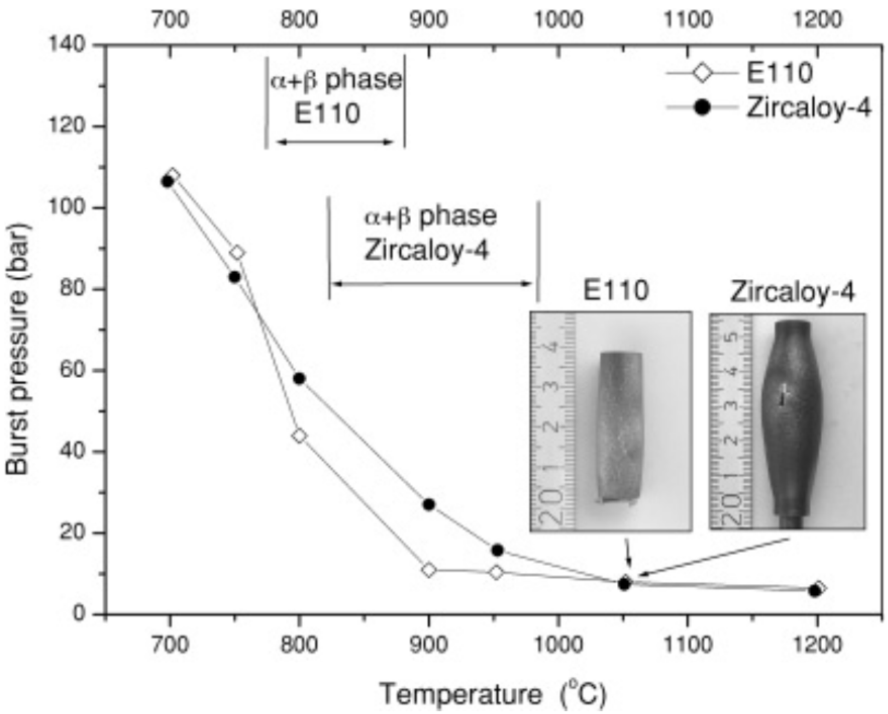


Fig. 9. Burst pressure versus burst temperature of E110 and Zircaloy-4 claddings tested under similar conditions.

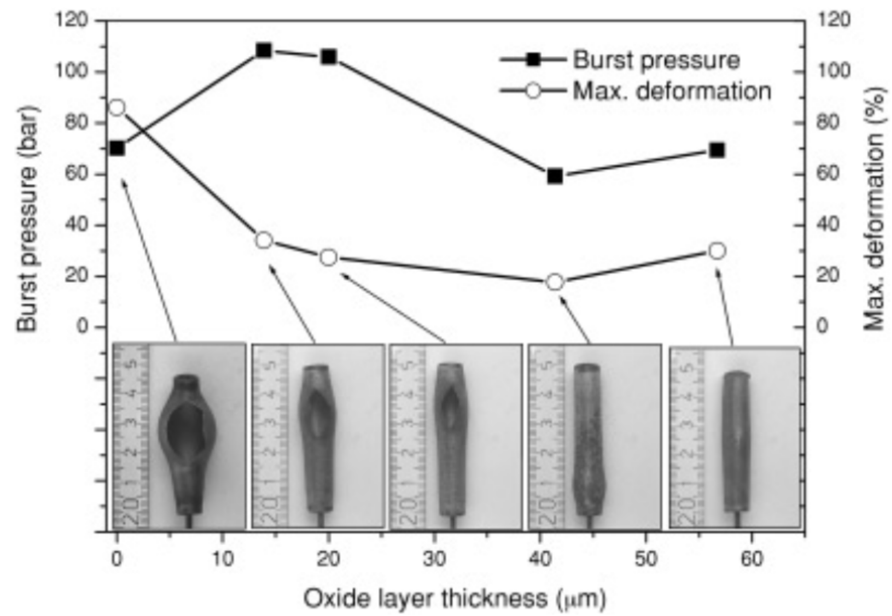
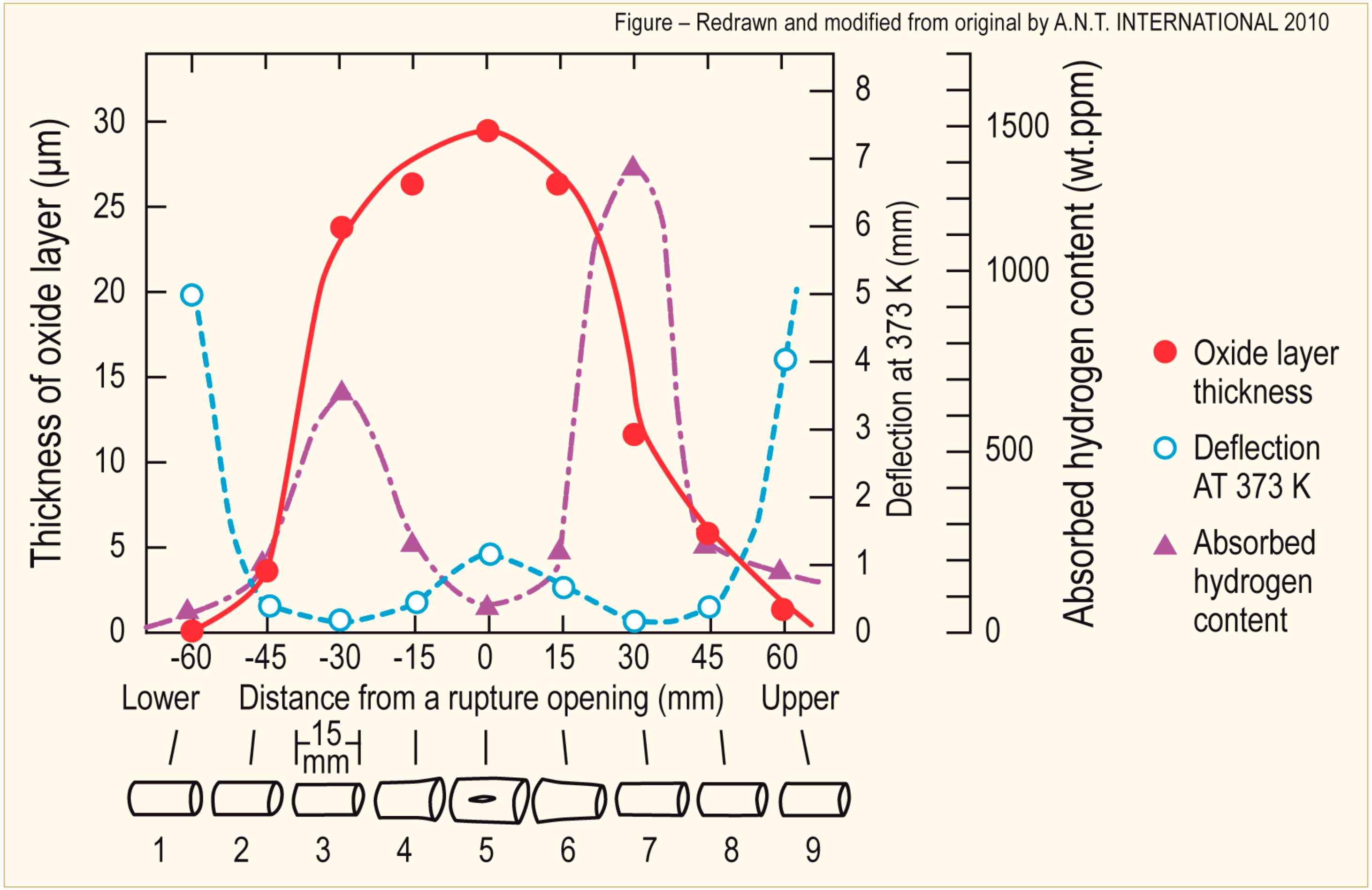


Fig. 10. Burst pressure and maximum deformation versus oxide-layer thickness of E110 claddings.

Hozer et al, 2005

Cladding burst is significantly impacted by oxidation and hydride embrittlement



During the LOCA, rapid temperature changes result in fuel pellet stresses that could cause cladding failure

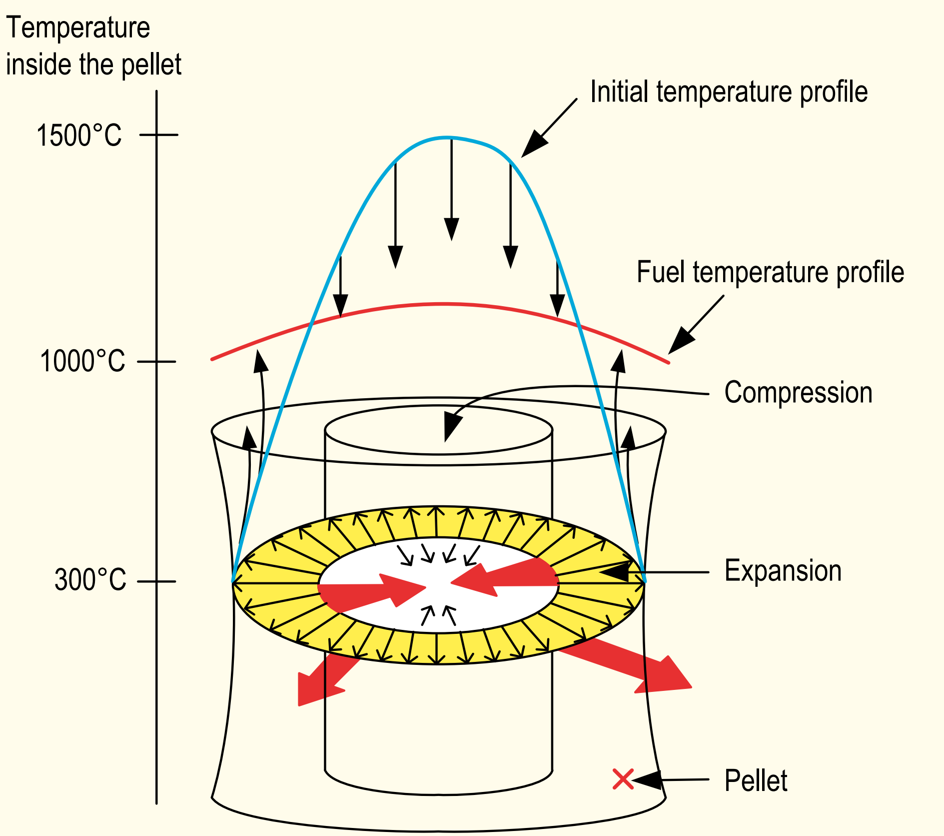
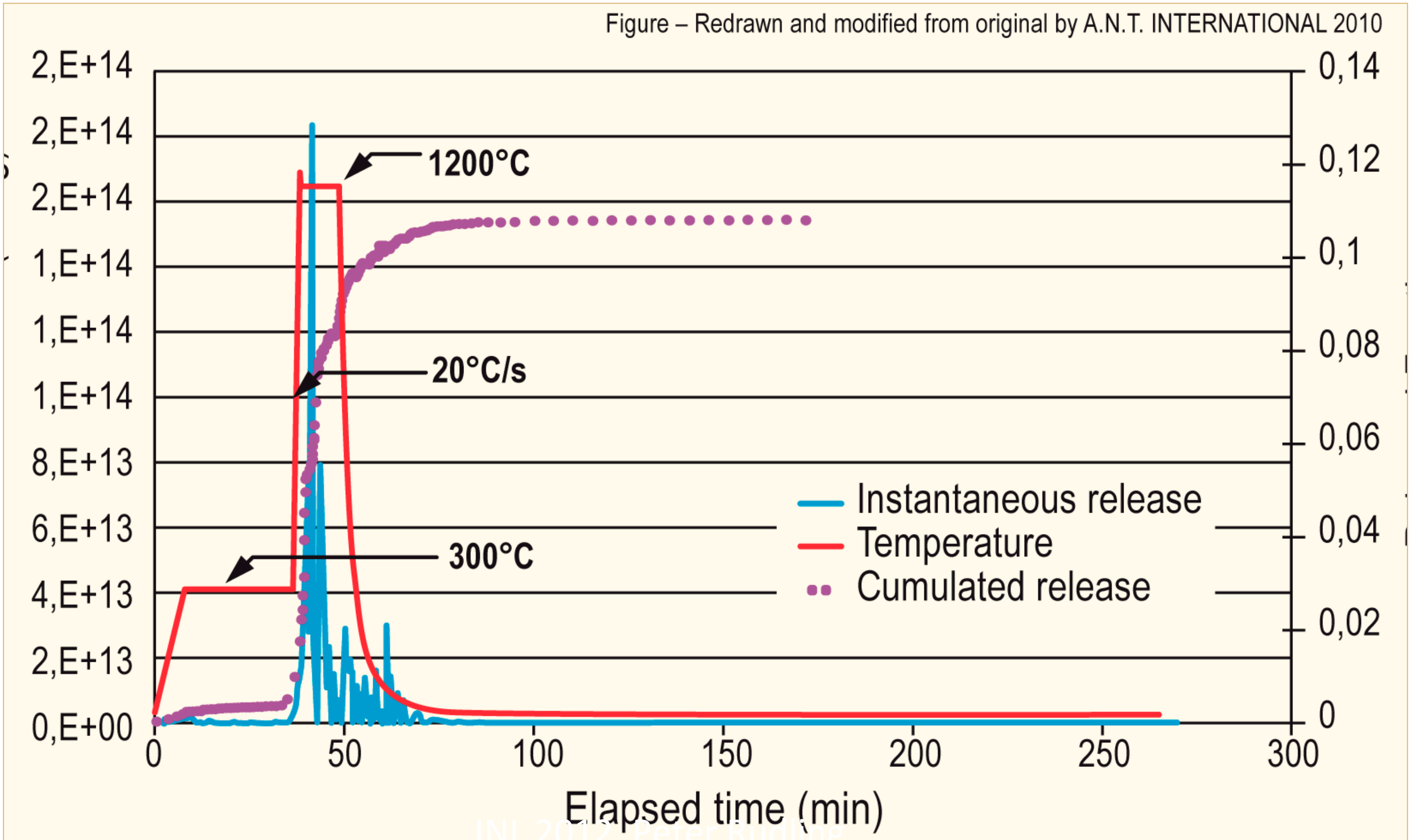


Figure - Redrawn and modified from original by A.N.T. INTERNATIONAL 2010

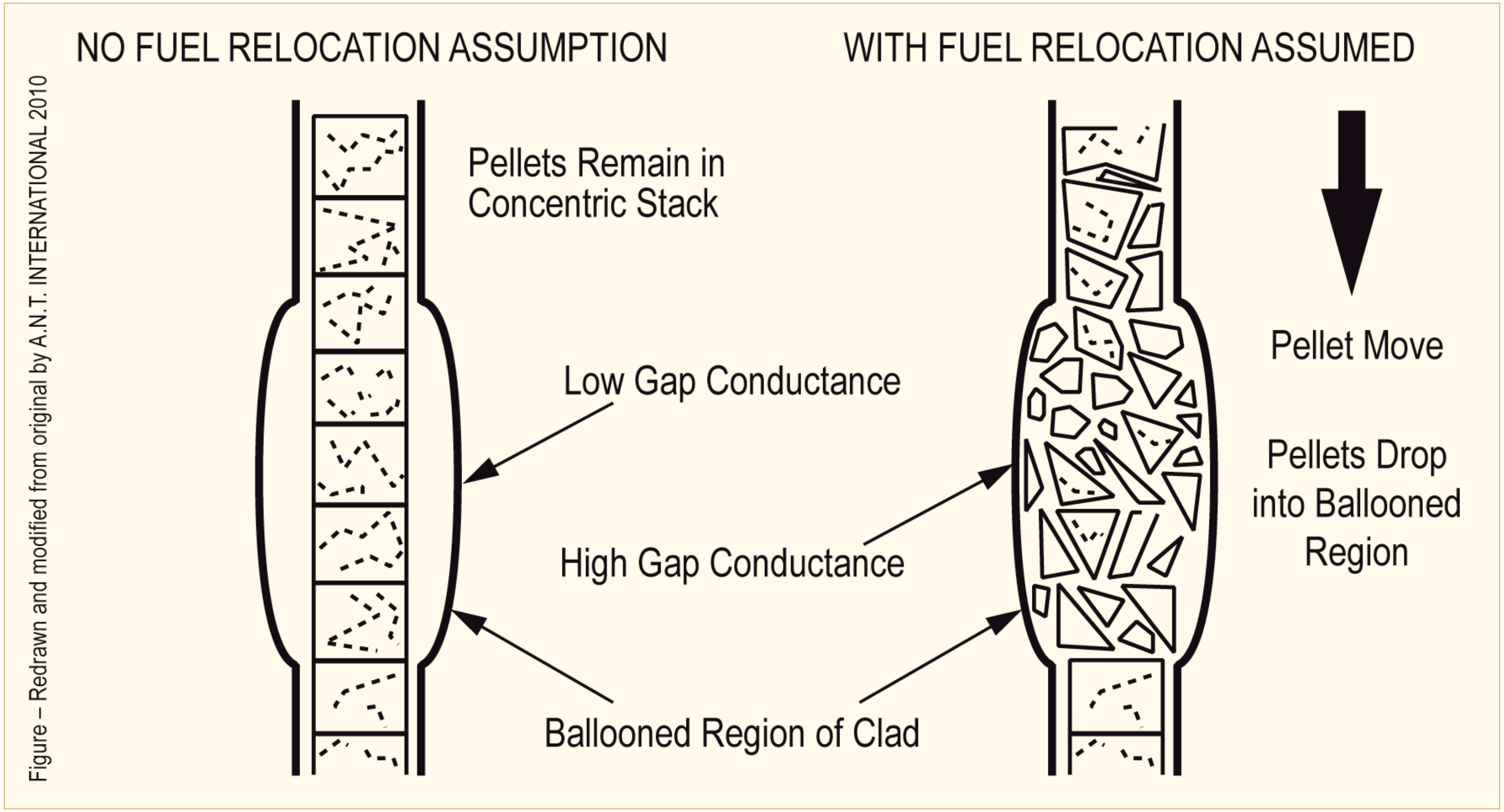
[Maillat et al, 2003]

Temperature jumps result in rapid releases of fission gas into the gap and plenum



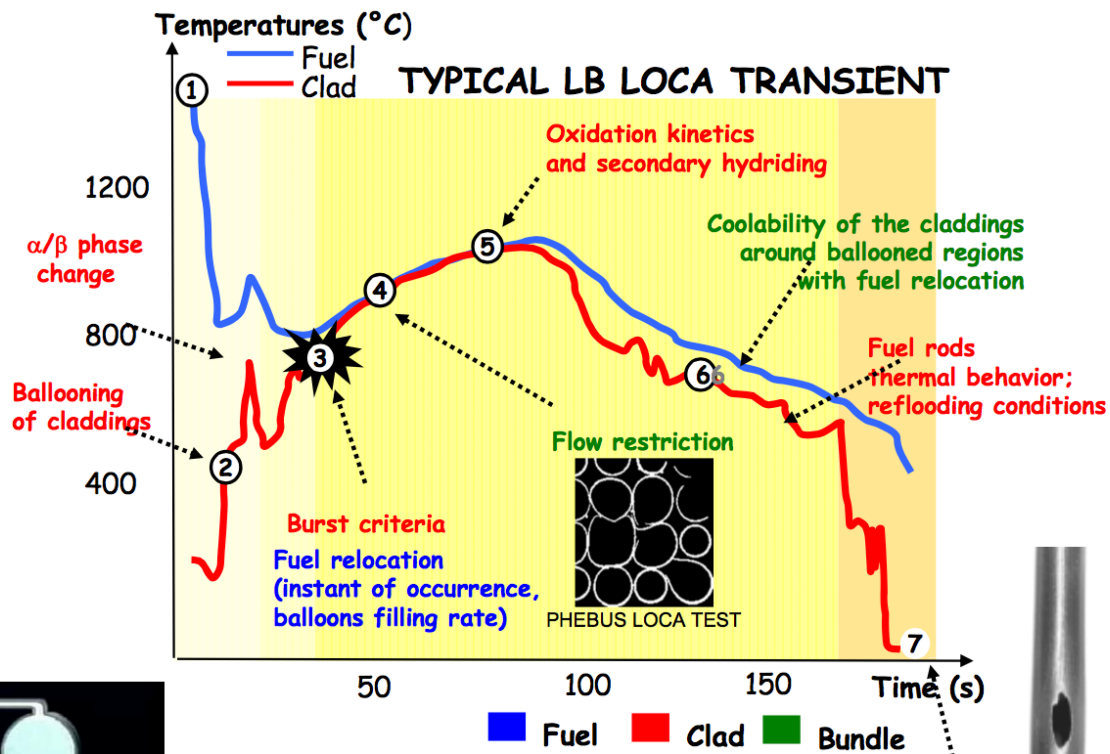
[Marcet et al, 2009]

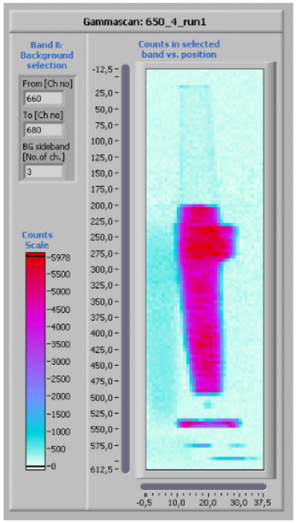
The fuel pellets are in pieces inside the cladding, and could fill the ballooned area

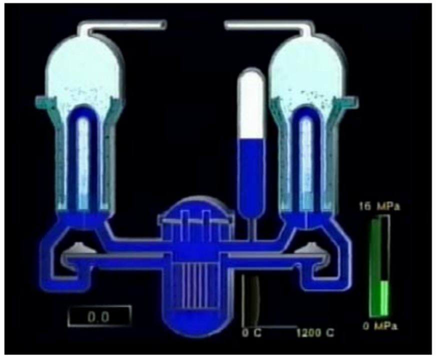


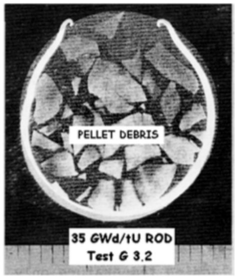
[Moreno et al, 2005]

High burnup fuel behaves worse than fresh fuel during a LOCA



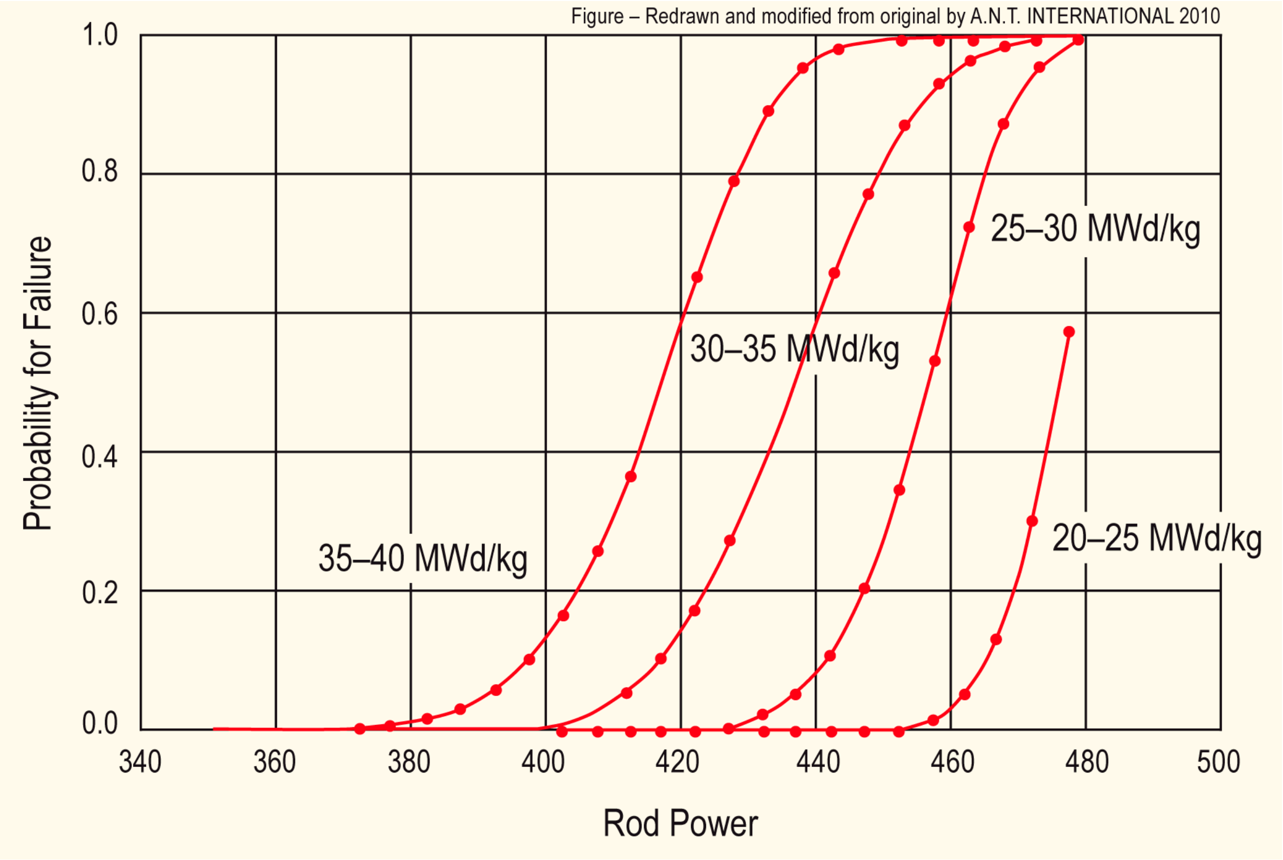






F.Barre, IRSN

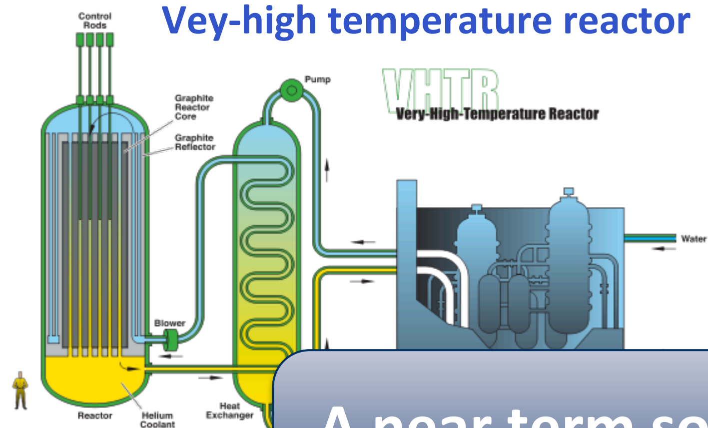
The probability of failure increases for higher burnup fuel



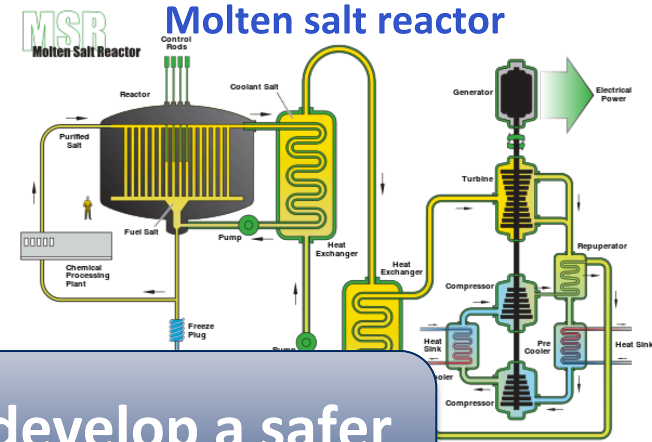
[EUR 19256EN, 1999]

Next generation reactors will be more accident tolerant, but won't be in use for many years

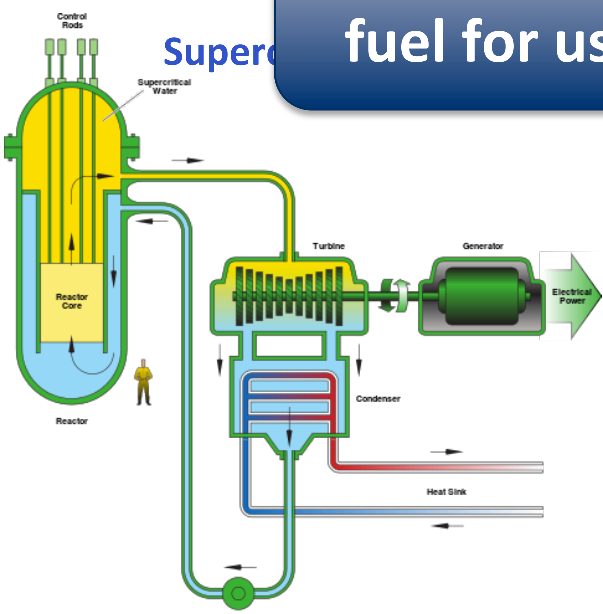
Vey-high temperature reactor



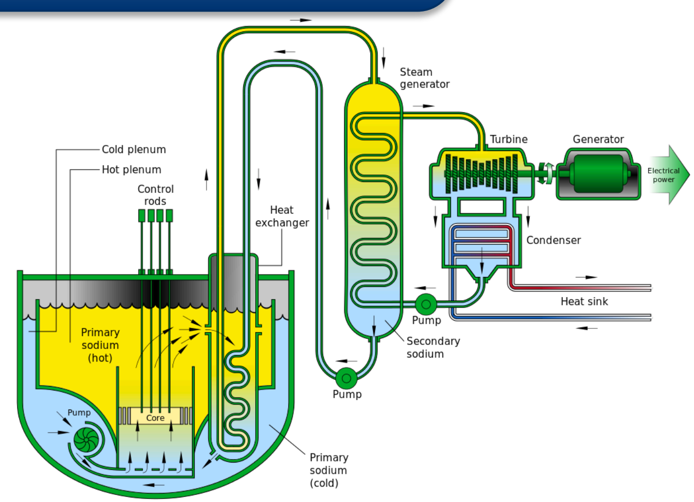
Molten salt reactor



Super



actor



A near term solution is to develop a safer fuel for use in our current fleet of LWRs

Fuels with enhanced tolerance can *tolerate loss of active cooling* for a *considerably longer period*, …

…while maintaining or improving performance during normal operation

Improved Reaction Kinetics with Steam
- Decreased heat of oxidation
- Lower oxidation rate
- Reduced hydrogen production (or other combustible gases)
- Reduced hydrogen embrittlement

Improved Cladding Properties
- Resilience to clad fracture
- Robust geometric stability
- Thermal shock resistance
- Higher cladding melt temperatures
- Minimizing fuel-cladding interaction

Enhanced tolerance to loss of active core cooling

Improved Fuel Properties
- Lower fuel operating temperatures
- Minimized cladding internal oxidation
- Minimized fuel relocation/dispersion
- Higher fuel melt temperature

Enhanced Fission Product Retention
- Retention of gaseous fission products
- Retention of solid/liquid fission products

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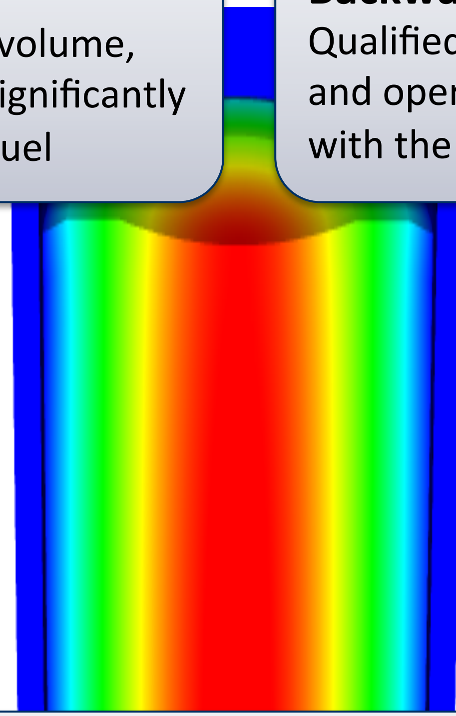
ATF material concepts must meet general criteria to be an acceptable LWR fuel

Economics
When produced in large volume, concepts must not cost significantly more than current LWR fuel

Backward compatible
Qualified in existing reactor, and operable in a reactor along with the current fuel



Fuel cycle
Concepts must be amenable to a complete fuel cycle (cradle to grave)

Operations
Performance during general operation must be equal to or better than current concept

Safety
Spectrum of design basis accidents and beyond design basis accidents

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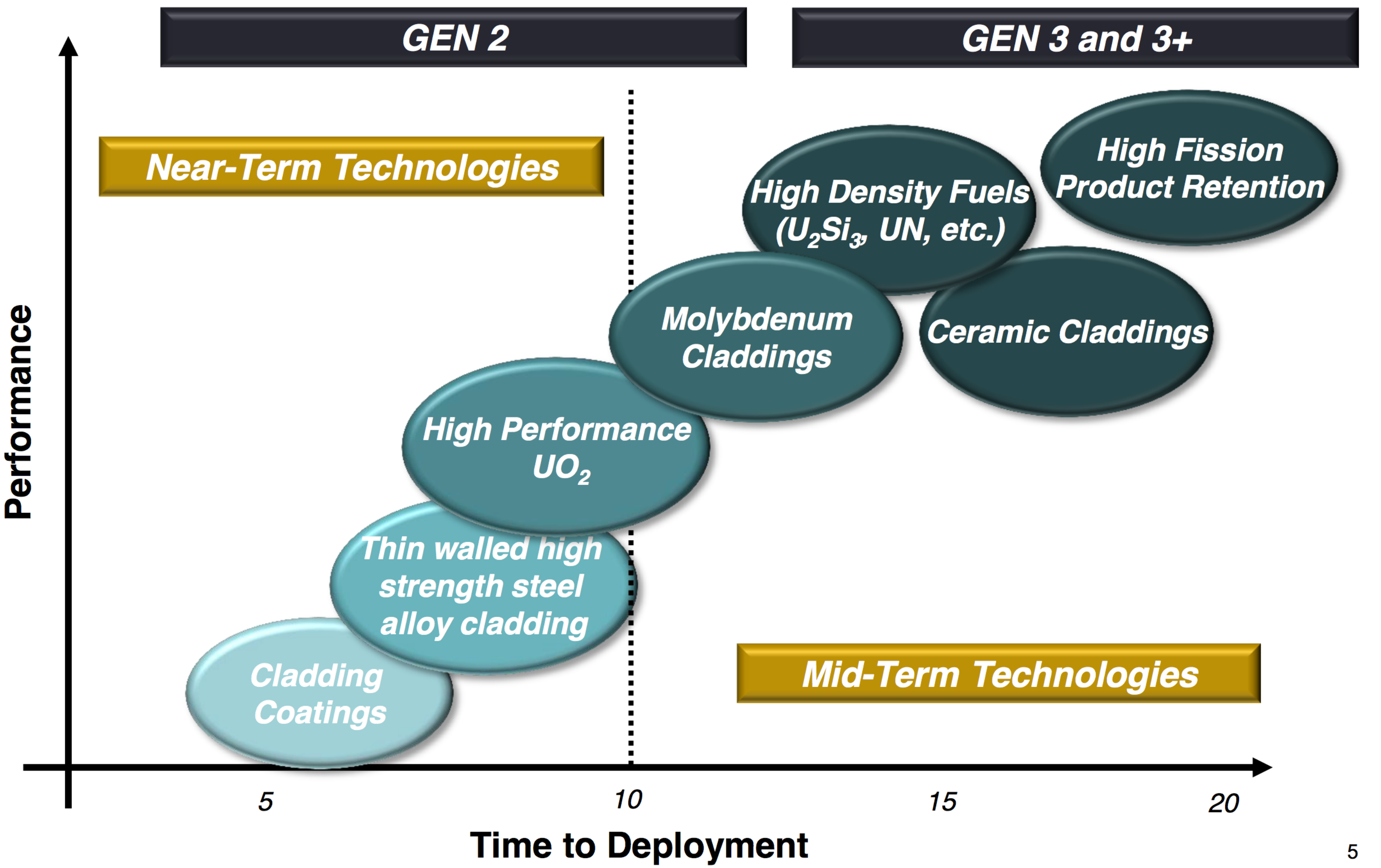
Higher payoff ATF concepts will take more time to develop than more incremental changes



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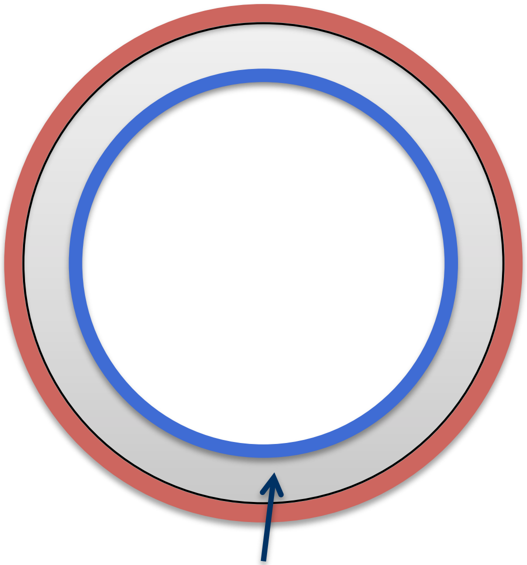
The simplest candidates for new cladding is to simply add coatings or sleeves to zircaloy

- Zirconium alloys have some very attractive properties
  - **Very low** absorption cross-section of thermal neutrons
  - High hardness and ductility

Cladding coatings
- Coatings protect the zircaloy from steam, without significant changes to the material
- Could have a rapid implementation time
- Various materials are being considered:
  - Ti_3SiC_2 or Ti_3AlC_2
  - SiC
  - MAX ceramic phase



Cladding sleeve
- Sleeves protect the inside of the cladding from oxidation and interactions with the fuel
- Lower potential benefit than coatings

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Completely changing the cladding material is also being considered

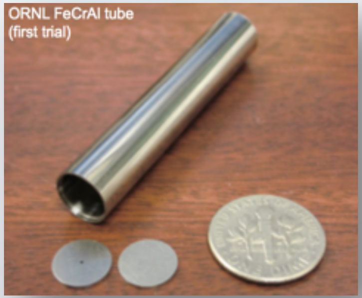
Silicon carbide composite

Strengths

- Low neutron cross section
- No high temperature creep
- Low activation

Disadvantages

- Expensive and hard to fabricate
- Difficult to add end caps
- Mass loss to for SiO_2 layer
- Possible microcracking resulting in fission product release



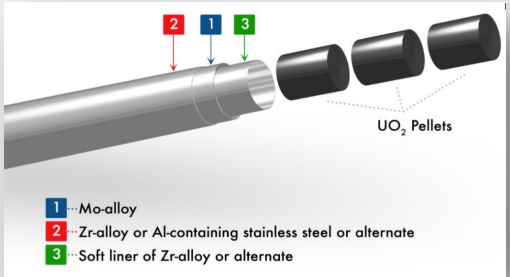
Advanced steel (FeCrAl)

Strengths

- High strength and ductility
- Corrosion resistant
- Low creep

Disadvantages

- Larger neutron cross section
- Optimal alloy still needs to be developed



Refractory metals (Mo)

Strengths

- High tensile and creep strength
- Can be made into tubes and welded

Disadvantages

- Larger neutron cross section
- Reacts with high temperature steam
- Susceptible to irradiation embrittlement

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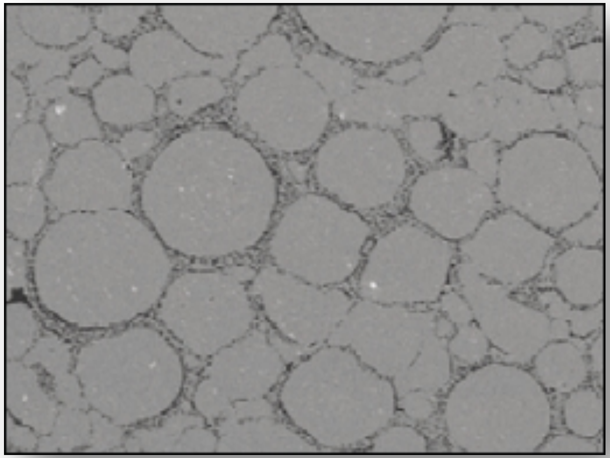
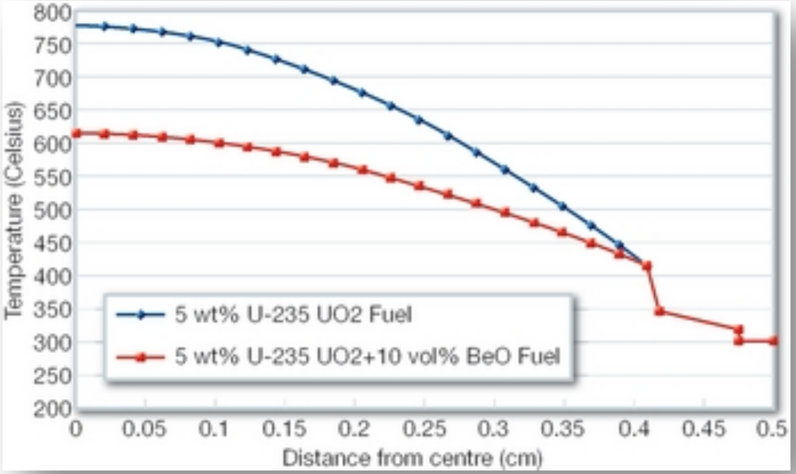
Simplest modification is to use additives in UO_2 to raise the thermal conductivity

- Potential additives include
  - SiC
  - BeO
  - Nano-diamond
- Advantages
  - Higher thermal conductivity lowers fuel temp, reduces fission product release, lower thermal stress
- Disadvantages
  - Reduced UO_2 density
  - More difficult fabrication
  - Could have negative side effects





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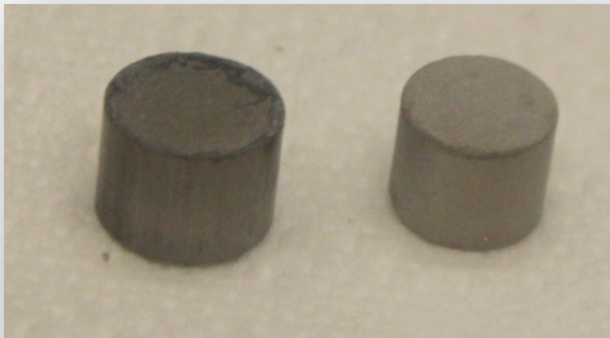
Other fuel types are also being considered



High density fuels

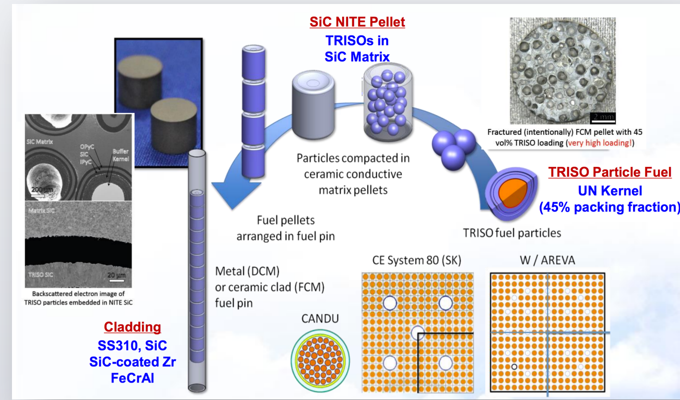
U metal, U nitride, U silicide, etc.

Strengths

- Higher fissile density to compensate for increased neutron absorption by clad
- Higher thermal conductivity

Disadvantages

- Large scale fabrication still has to be developed
- U Metal melting temperature is low
- U nitride reacts with water
- No clear understanding of reactor behavior



Microencapsulated fuel

Strengths

- High thermal conductivity
- Resistant to melting
- Excellent fission product retention

Disadvantages

- Expensive and difficult to fabricate
- Large reduction in fissile density

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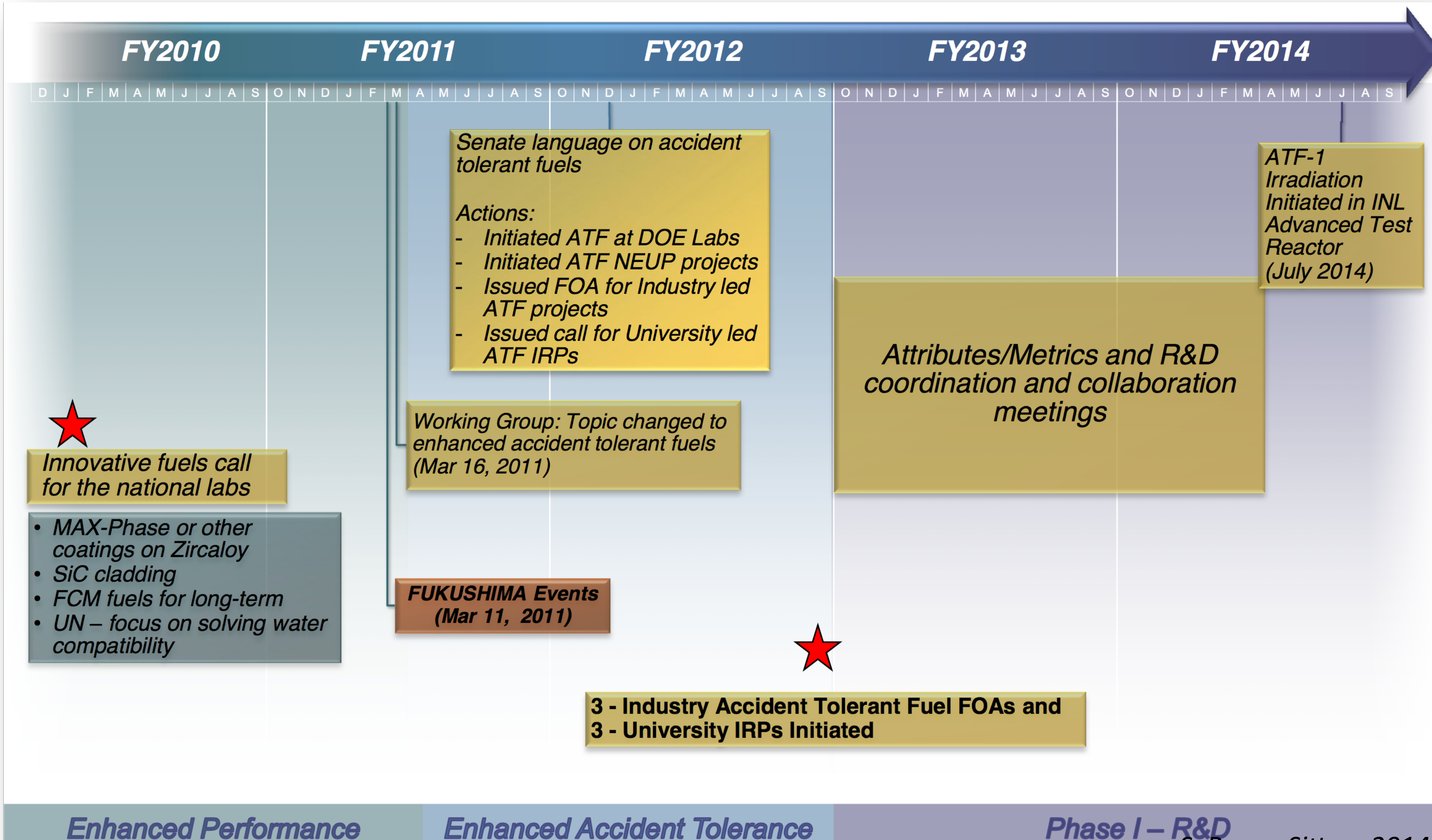
The US DOE advanced fuels campaign (AFC) has been developing accident tolerant fuel since 2010



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The DOE is funding a significant amount of accident tolerant fuel development

Lead Organization	Category – Major Technology Area	Additional Team Members
Oak Ridge National Laboratory	Fuel: Fully Ceramic Microencapsulated (FCM)-UO_2, UN FeCrAl cladding, SiC cladding	*Initial irradiation of all concepts at Idaho National Laboratory*
Los Alamos Nat. Lab. EPRI + LANL	Fuel: Enhanced UO_2, Composite Fuels Cladding: Molybdenum	
AREVA *(FOA, NEUP)*	High conductivity fuel (UO_2+Cr_2O_3, +SiC) Cladding: Protective materials, MAX phase	U. Wisconsin, U. Florida, SRNL,TVA, Duke **Includes work with AREVA France
Westinghouse *(FOA, NEUP)*	Fuel: U_3Si_2, and UN+U_3Si_2 fuel Cladding: Coated Zr and SiC	General Atomics, MIT, EWI, INL, LANL,TAMU, Southern Nuclear Operating Company **Includes work with WEC Sweden
GE Global Research *(FOA)*	Advanced Steel (Ferritic / Martensitic) Cladding	Global Nuclear Fuels, LANL, U. Michigan
University of Illinois *(IRP)*	Modified Zr-based Cladding (coating or modification of bulk cladding composition)	U. Michigan, U. Florida, INL, U. Manchester, ATI Wah Chang **UK contributions
University of Tennessee *(IRP)*	Ceramic Coatings for Cladding (MAX phase and multilayer ceramic coatings)	Penn State, U. Michigan, UC Boulder, LANL, Westinghouse, Oxford, U. Manchester, U. Sheffield, U. Huddersfield, ANSTO **UK and Australia contributions
Georgia Institute of Technology *(IRP, accident tolerant reactor design)*	Fuel: U_3Si_2, Cladding: FeCrAl Details TBD for fuel component – likely to adopt fuel developed under an above program	U. Michigan, Virginia Tech, U. Tennessee, U. Idaho, Morehouse College, INL, Westinghouse Electric, Southern Nuclear, Polytechnic U. Milan, U. Cambridge

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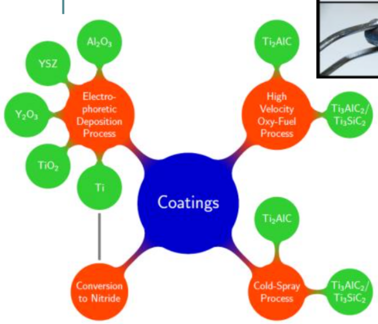
The DOE is also funding development by industry lead teams

AREVA

- Develop **coated Zr-alloy cladding** for improved accident performance
- Increased **fuel** pellet conductivity: Fuel with reduced stored energy that must be accommodated during DBE
- Additives achieved:
  - SiC powder or whiskers
  - Diamond
  - Chromia dopant

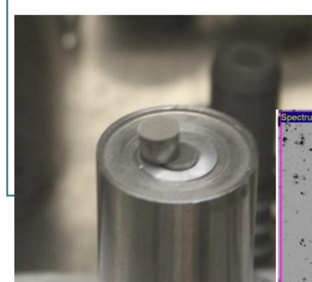


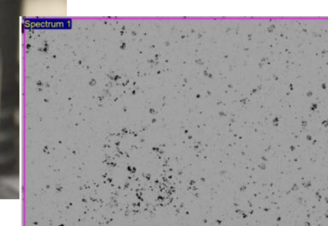
GE

- Develop advanced **ferritic/martensitic steel alloys (e.g., Fe-Cr-Al) for fuel cladding** to improve behavior under severe accident scenarios
- Objectives:
  - Characterize candidate steels
  - Study tube fabrication methods, neutronics, fuel economy, thermo-hydraulic calculations, regulatory approval path
  - Initiate ATR testing with UO_2 and two cladding materials.

Westinghouse

- Develop and test **cladding** concepts: **SiC** and SiC ceramic matrix composites; **coated Zr alloys**
- **High density/high thermal conductivity fuel pellets** (e.g., uranium nitride/silicides)
- First batch of U_3Si_2 pellets were sintered using finely ground powder
- Pellets were pressed using pressures of 6,000-10,000 psi and sintered at temperatures of 1400°C





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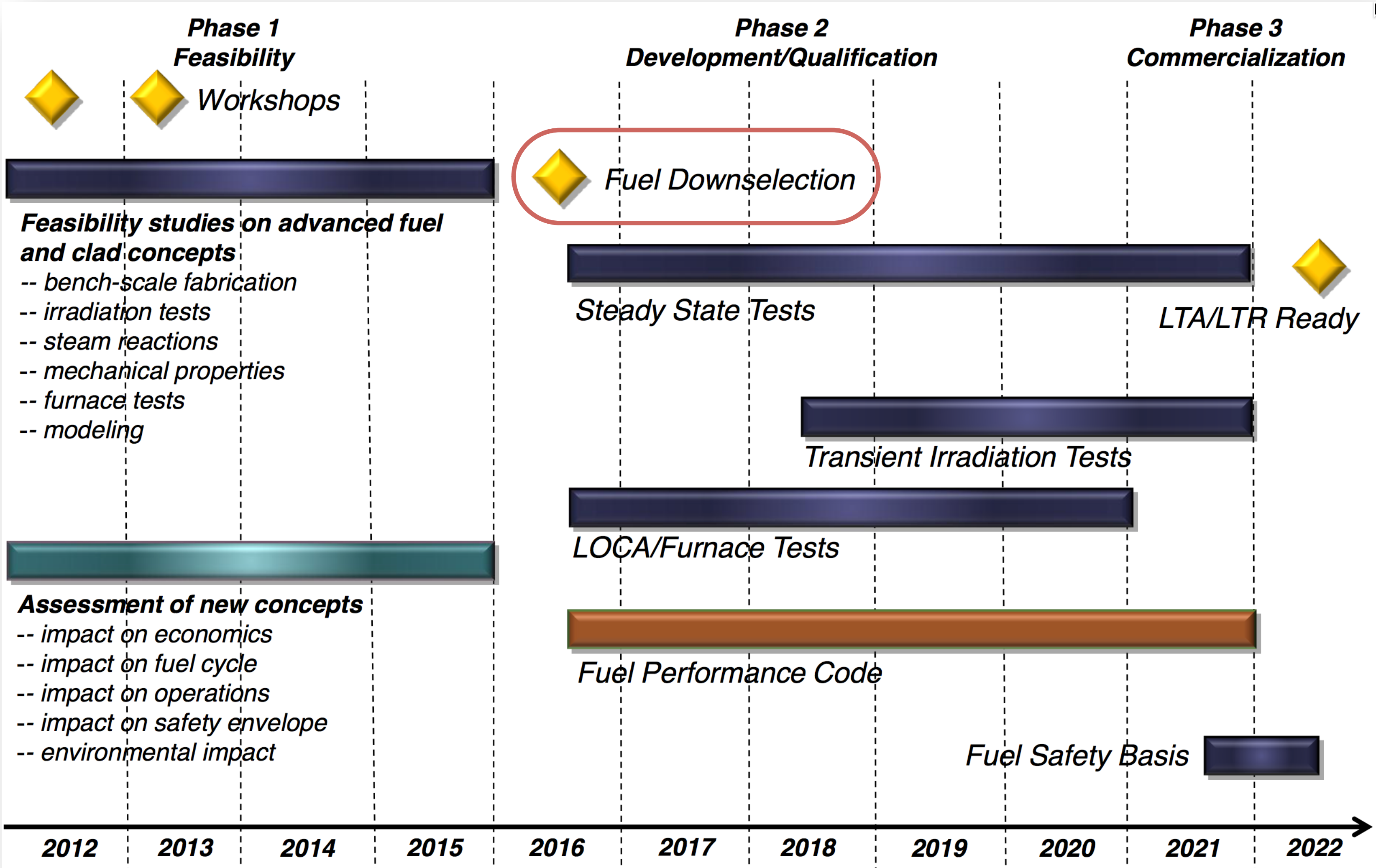
The AFC has set an aggressive timeline for accident tolerant fuel development



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There is still uncertainty if we can add any significant amount of time to cope with accidents

- ATF fuel will have a huge cost
- Industry must be convinced that ATF will results in some savings to offset this cost
  - Safety margins may be able to be reduced
  - NRC may provide regulatory benefit

Summary

- In loss of coolant accidents (LOCA), the fuel and cladding experience
  - Increases temperature
  - Decrease in coolant pressure
  - Fast, but not as fast as RIA
- The primary negative effects are
  - Embrittlement and ballooning of the cladding
  - Relocation and fission gas release in the fuel
  - Cladding can burst and release fuel fragments
- The accident tolerant fuel program is investigating different fuel and cladding materials to increase time before catastrophic behavior during an accident