Mitigation of Severe Accident Consequences Using Inherent Safety Principles

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Authors:
Roald Wigeland
Idaho National Laboratory
James Cahalan
Argonne National Laboratory

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Idaho National Laboratory

Introduction

- Fast reactors have been studied, designed, and operated since the beginning of nuclear power
  - Desired for their ability to breed new fissile material, especially when uranium resources were believed to be scarce
- It was recognized very early that fast reactors have safety challenges that need to be addressed
  - High power density
  - High heat removal requirements
  - Power variation due to neutron leakage at the core boundaries resulted in the need for ducted assemblies and control of coolant flow
  - Fuel is not in the most neutronically reactive configuration in the reactor core
    - Relocation of fuel has the potential to significantly increase reactivity, including exceeding prompt critical

Fast Reactor Safety Development

- Fast reactor safety was typically based on the concept of "defense-in-depth", i.e., where multiple redundant safety systems are used to lower the probability of accident occurrence
  - Example such as two independent scram systems and backup heat removal systems for decay heat removal
- Even with such measures, accidents with severe consequences dominated licensing discussions for projects such as CRBR
  - Even though probability of occurrence was very low, about 10^{-5} per reactor year, usually associated with failure of the reactor scram systems and considered to be beyond the design basis, the consequences were potentially very large, posing a risk to the public
  - Many of the safety-related issues were unresolved at the time the project was ended
- Mainly during the 1980's and 1990's, new efforts were undertaken to find better approaches to safety, including the development of the concept of 'inherent safety'

Fast Reactor Inherent Safety

- Inherent safety was developed as an approach that would protect the reactor during severe accident conditions when the engineered protection systems had failed without requiring the functioning of any active system
  - Typical accident conditions such as the unprotected (unscrammed) loss-of-flow (ULOF), unprotected loss of the main heat sink (ULOHS), and unprotected inadvertent withdrawal of reactor control rod(s) resulting in a transient overpower event (UTOP)
  - Fundamental phenomena were considered for inherent safety mechanisms, such as thermal expansion, buoyancy-driven flow, and gravity
- The focus of inherent safety is to address three main conditions for safe operation of the reactor
  - Avoid large increases in core reactivity
  - Maintain sufficient cooling of the reactor core
  - Prevent rearrangement of fuel that would lead to energetic events

Inherent Safety Principles

- To meet the goals of inherent safety, there are three basic principles that are used
  - Favorable reactivity feedback
  - Sufficient natural circulation cooling
  - Containment of reactor fuel even with fuel pin failures
    - May require favorable dispersion of failed fuel
- Research was conducted in each of these areas leading to developments that could substantially improve the safety of a fast reactor
  - Concepts were developed and demonstrated by testing
  - Not all results were favorable, but identified where additional measures would be needed to succeed
- The first two principles are important for ULOF, ULOHS, and UTOP accidents, and if inherent safety is properly engineered into the reactor, there are no serious consequences from these events
  - Fuel failure does not occur; no release of radioactive materials

Reactivity Feedback

- Reactivity feedback is created by several major mechanisms
  - Fuel Doppler
  - Coolant density
  - Axial fuel expansion
  - Radial core expansion
  - Control rod driveline expansion
- It is important to note that overall reactivity feedback is determined by all of the reactivity feedback mechanisms, not just one
- It is also important to recognize that larger is not necessarily better for all accident conditions
  - The same reactivity feedback mechanism can provide favorable reactivity feedback in some cases and unfavorable feedback in others
  - The key is to achieve the proper balance of reactivity feedback so that a benign termination of the accident can be achieved

General Comments on Reactivity Feedback

- Higher Doppler feedback is beneficial for reducing the power rise if reactivity is added as a result of the accident conditions
- Lower Doppler feedback is beneficial if the core power needs to be lowered in response to accident conditions
- Lower sodium density worth is beneficial in accidents where the coolant temperature increases
- Higher expansion coefficients can be beneficial where coolant and structure temperatures rise during an accident if properly designed
- Lower average fuel temperature is beneficial for accidents where reactor power needs to be reduced in response to accident conditions
  - Reducing core temperature can produce positive reactivity feedback
- The capabilities of inherent reactivity feedback have been demonstrated by tests in the EBR-II and FFTF reactors

Natural Circulation Cooling

- The capability to remove shutdown decay heat with natural circulation provides a means to maintain reactor component temperatures at acceptable levels even in the event of loss of all off-site and emergency on-site power supplies
  - Sodium-cooled fast reactors can be configured to take advantage of buoyancy-driven flow due to the favorable variation of density with temperature for sodium
- The key design parameters are
  - a relatively free-flowing fluid natural circulation path
  - sufficient elevation difference between the heat source and the heat sink
- Depending on the accident conditions, either the normal heat removal path through the IHX (intermediate heat exchanger) or auxiliary decay heat removal systems can be used
- Shutdown heat removal through an auxiliary cooling system has been demonstrated in the pool-type EBR-II reactor

Containment of Reactor Fuel

- In more severe accidents, beyond the traditional ULOF, ULOHS, and UTOP events, the initiating conditions are so severe that fuel melting and fuel pin failure can't be avoided
  - Probability of occurrence for these accident initiators is less than 10^{-6} per reactor year, and probably much less
  - Examples include a ULOF with no flow coastdown, possibly as a result of a very large seismic event, or a UTOP event where all control rods are withdrawn from the core with failure of any rod motion limiters as well
- The magnitude and timing of the events is such that even inherent reactivity feedback is unable to prevent core temperature increases that result in coolant boiling, fuel melting and fuel pin failure
  - The outcome of these events is determined by the behavior of the molten fuel outside of the fuel pin
    - Favorable dispersal is required to prevent energetic recriticalities

Very Low Probability Events – Oxide Fuel

- Analyses and experiments of the behavior of an oxide-fueled core for the conditions where the severity of the accident leads to rapid overheating, coolant boiling and fuel pin failure (as in the ULOF presented earlier) demonstrate that the consequences are large
  - Sodium coolant boiling causes a power rise from unfavorable feedback and overheating of the fuel pins due to loss of cooling
  - Fuel pin cladding fails, either mechanically or by melting
    - Molten cladding and/or fuel relocates to cooler areas above and below the core, freezing and preventing further coolant flow in the assembly
    - Cladding failures are near the core mid-plane, so that fuel movement toward the core midplane is likely
    - Material motions result in a series of power excursions, with peak power far exceeding nominal power (100's – 1000's)
  - Failure in a single assembly will propagate to neighboring assemblies due to the high temperatures of molten fuel and clad
    - Process continues to whole-core involvement

Very Low Probability Events – Oxide Fuel (cont'd)

- The core becomes a "contained" mass of molten fuel and steel
  - repeated recriticalities to many (hundreds to thousands) times nominal power
  - accident termination is by an energetic disassembly of the core
    - a large power excursion to mechanically disperse the core
    - likely failure of the reactor vessel
    - containment structure mitigates releases to the environment
- Designing a containment for such an event is feasible but may become difficult for large power reactors
  - Very large uncertainties about the magnitude of the event
- The cause is the very high melting point of oxide fuel
  - Little early fuel dispersal while power and temperatures are low
  - Molten oxide fuel (T > 3000 °C) is difficult or impossible to cool with liquid sodium that has a boiling point of about 900-1000 ºC
    - Molten fuel and steel readily forms blockages above and below the core region
  - Molten oxide fuel (T > 3000 ºC) rapidly melts through hexcan materials, facilitating propagation and whole-core events

Very Low Probability Events – Metallic Fuel

- Analyses and experiments of the behavior of an metallic-fueled core for the conditions where the extreme severity of the accident leads to coolant boiling and fuel pin failure demonstrate that the consequences are small
  - Sodium coolant boiling leads to a power rise and overheating of the fuel pins, starting in the highest power/flow fuel assemblies
- The relatively low melting point of the metallic fuel and the interaction with cladding allow for some early fuel pin failures
  - Spatial and temporal incoherence among subassemblies limits early failures and allows time for mitigating feedback effects
  - Molten fuel (likely alloyed with clad) exits into the coolant channels, often with some liquid sodium present
  - Cladding failures are near the top of the fuel pins, so fuel motion out of the pin generally provides negative reactivity feedback
  - Subsequent motion of the molten fuel/clad alloy is upwards and out of the core region, removing substantial reactivity from the core early in the accident, shutting down the reactor

Very Low Probability Events – Metallic Fuel (cont'd)

- Boiling sodium coolant moves the fuel upwards and out of the core
  - Later in the accident, it is possible that the remaining fuel can move downwards, but only under decay heat power since there isn't enough fuel left in the core to sustain the fission reaction
- Only a small amount of fuel needs to be removed from the core (1 or 2 assemblies) to shut down the reactor
- The result is some core damage, but no reactor damage
  - Fermi-1 experienced a metallic fuel melting accident, and was reloaded and subsequently operated before being shut down
- The favorable response to even the most severe accidents is due to the thermophysical properties of metallic fuel
  - Relatively low melting point and high thermal conductivity
  - Compatibility with liquid sodium coolant, even when molten
  - The key is limited early fuel pin failure and fuel removal from the core

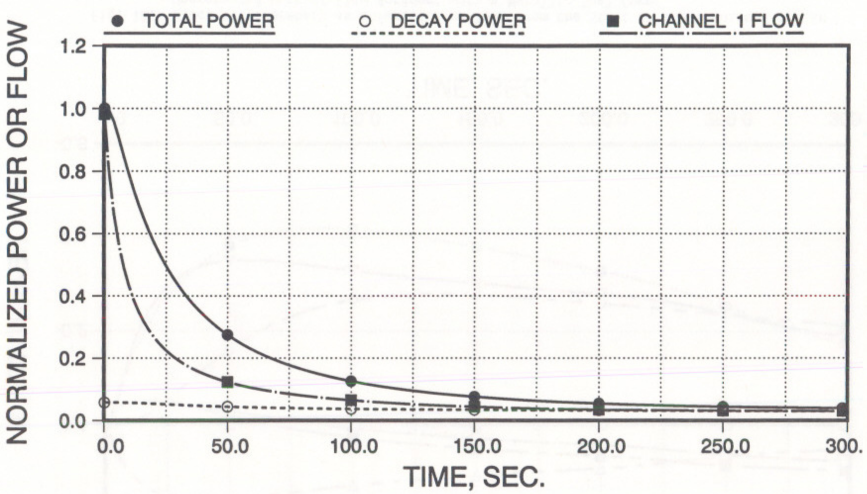
Integrated Inherent Safety Approach

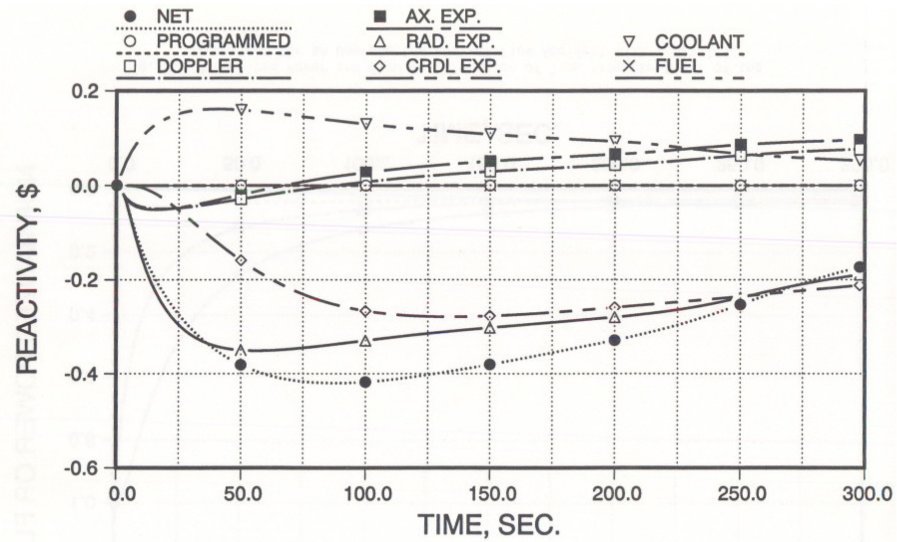
- Using inherent safety principles, a reactor can be designed that has a benign termination for UTOP, ULOF, and ULOHS events
  - a balance of reactivity feedback mechanisms for favorable response
    - one may also have to rely on design features that limit the severity of the accident initiator to ensure a benign termination
      - control rod motion limiters to restrict the amount of reactivity that can be introduced into the core from an inadvertent control rod withdrawal
      - extending the inertial coastdown of the coolant pumps to provide sufficient time for the inherent reactivity feedback to reduce core power and limit the mismatch between the coolant flow and core power
- If these and other similar considerations are included at the design phase of the reactor, it is possible for the reactor system to respond to a wide range of potential accident initiators without resulting in core damage or more serious consequences.

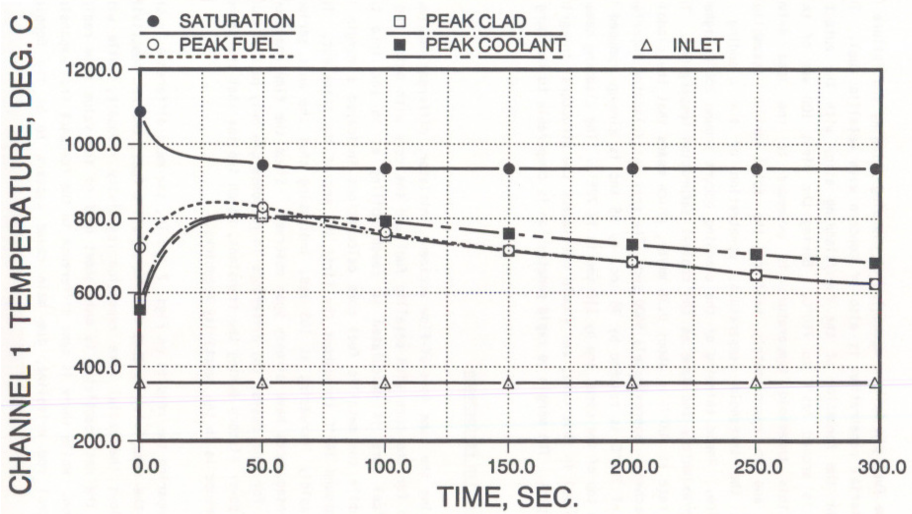
ULOF Accident Example – Metallic Fuel

- A large reactor, 3500 MWth, is used for the analyses
  - Pool-type reactor, reactor vessel about 19 m diameter, 21 m high
  - Core height about 1 m, diameter about 4.5 m
- Sodium void worth with metallic fuel is 7.26$
- Accident initiator is loss of power to the coolant pumps with failure to scram the reactor
  - Inertial pump coastdown has a flow halving-time of 6 seconds
- Reactivity feedback is sufficient to limit the rise in core temperatures
  - No coolant boiling and no fuel pin failures, eventual transition to natural circulation cooling occurs
- Dominant favorable feedback is from radial core expansion and control rod driveline expansion
  - Similar calculation for an oxide fuel core results in coolant boiling and fuel pin failures, mainly due to unfavorable Doppler feedback, and a longer flow coastdown can mitigate these effects

Unprotected LOF – Metallic Fuel



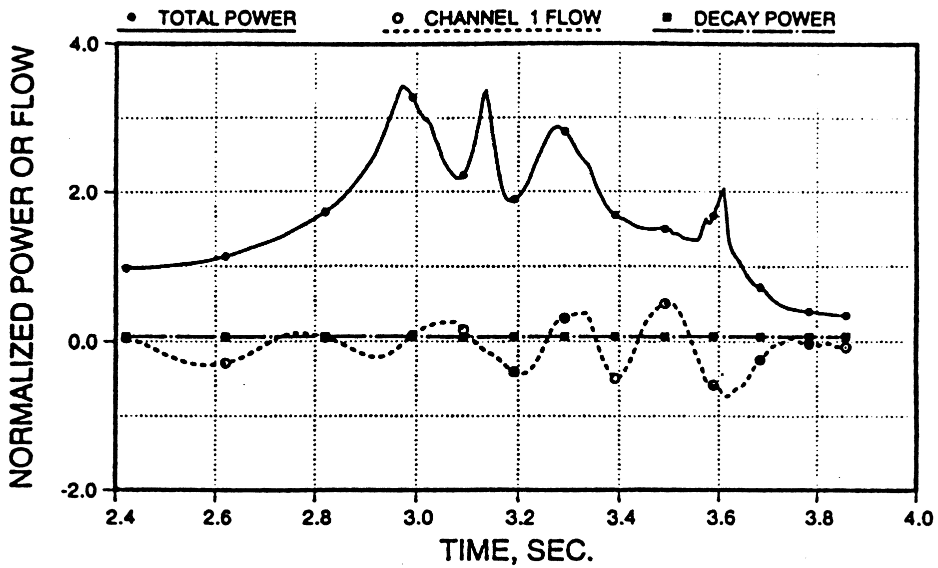


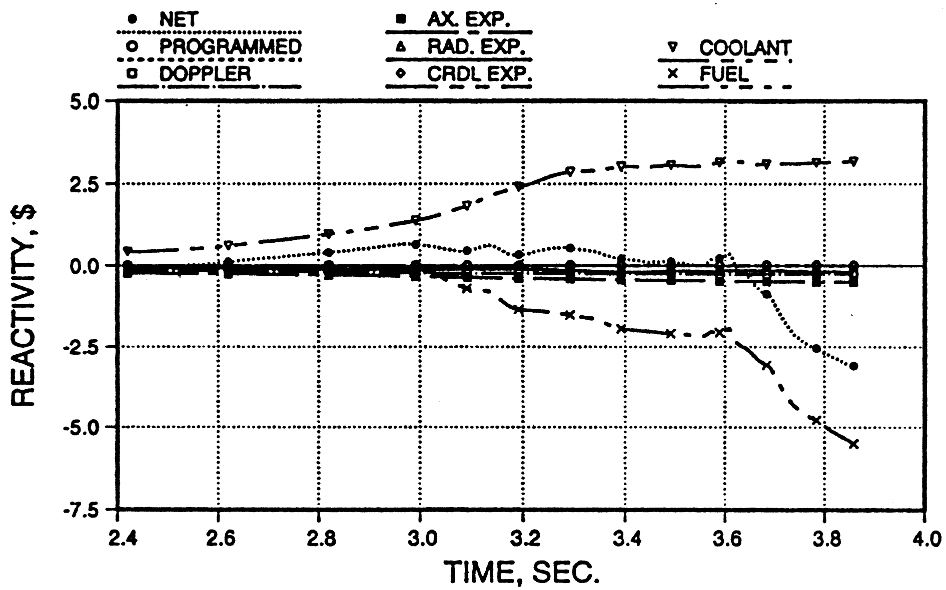


Instantaneous ULOF Example – Metallic Fuel

- A medium-sized 900 MWth reactor with metallic fuel is analyzed
  - Still has a large positive sodium void worth, about 5.4$
- The accident initiator is an instantaneous stoppage of the coolant pumps, coolant flow stops in about 0.25 seconds or so
  - No flow coastdown
  - Insufficient time for reactivity feedback to reduce core power and keep core temperatures below failure thresholds
    - Coolant boiling
    - Fuel melting
    - Fuel pin failure and molten fuel relocation in a few subassemblies
- Favorable dispersive fuel motion upwards and out of the core region introduces very large negative reactivity feedback
  - Quickly reduces power
  - Coolable geometry is maintained
  - Core damage is limited, but primary system integrity is maintained

Instantaneous ULOF – Metallic Fuel





Conclusions

- Inherent safety principles can be effectively used to mitigate consequences of severe accident initiators
  - Favorable reactivity feedback
  - Natural circulation cooling
- Even for extreme accidents, the ability to have inherent fuel dispersal can prevent energetic events, maintaining the primary coolant system integrity
  - No release of fuel or other radioactive materials to the containment
  - Containment is not challenged
- With proper design choices, including continuing with the desing philosophy of defense-in-depth, it may be possible to virtually eliminate the accident-related radioactive releases from a sodium-cooled fast reactor plant
  - Currently this appears achievable with metallic fuel, and it may be possible with other fuel types