Evaluation of Downstream Sump Debris Effects in Support of GSI-191

Westinghouse Owners Group
B&W Owners Group

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GSI-191 Downstream Effects Evaluation

Program Objective:

- Provide licensees with data, methods and templates to evaluate effects of debris ingested into:
  - Emergency Core Cooling System (ECCS)
  - Containment Spray System (CSS)

  during post-accident operation when realigned to recirculate inventory from the containment sump
- Address all US PWR designs
  - B&W
  - CE
  - Westinghouse

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Elements of this program

- Multi-disciplinary, multi-pronged approach that included
  - Systems and component assessments for all PWR designs
  - Use of available test data (component and debris)
  - Collaboration with vendors (pumps and valves)
- Scenario
  - System responses and alignments
  - Mission time evaluation
- Debris
  - Characterization
  - Depletion
- Equipment
  - Abrasive – erosive wear modeling
  - Pump rotor dynamics analysis
  - Pump assessment by Westinghouse and vendor
  - Various component evaluations and analyses

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Components Included:

- Pumps; ECCS and CSS
- Safety Related Valves; ECCS and CSS
- Heat Exchangers; ECCS and CSS (if applicable)
- Orifices
- Containment Spray Nozzles
- Piping and instrumentation tubing (as applicable)
- Reactor Internals
- Fuel

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System Assessment

- Evaluation of scenario progression
- Flow paths for each ECCS and CSS for each NSSS design
  - Identified components in alignment
  - Identified flow areas in alignment
- Evaluation of mission times for equipment
- Identified equipment designs
  - Pumps
  - Valves
  - Heat exchangers
- Objective was to understand the systems, system alignments and affected components

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Mission Times

- Amount of time a given component is required to fulfill its safety function post-LOCA
- Mission times evaluated for
  - Residual Heat Removal/Low Head Safety Injection Pumps
  - Centrifugal Charging/High Head/Intermediate Head SI Pumps
  - Containment Spray Pumps
  - Heat Exchangers

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Debris Modeling

- Establish the following
  - Amount of debris that passes through sump screen
  - Make-up of that debris
  - Depletion of debris due to settling and capture
- Sets the boundary conditions for wear and abrasion evaluation

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Debris Ingestion

- Initial amount of debris at sump screen - from NEI 2004-07 guidance
- Key assumptions
  - Insufficient fiber to build a continuous fiber bed (no continuous fiber bed)
  - Dimensions of particulates passing through a passive sump screen:
    - Thickness and/or width of particulates limited to sump screen hole size plus 10%
    - Maximum length of particulates equal to 2 times flow hole diameter
  - Individual fibers and small groups of fibers:
    - Pass through the sump screen
    - The maximum width and thickness of small clumps of fibrous debris is limited to the sump screen hole size plus 10%
  - Maximum length of fibers taken as larger of thickness of fibrous insulation or 4 inches
  - Generally applicable to an active sump screen
    - Specific information regarding the effect of the active components may be available from the sump screen vendor

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Debris Ingestion

- Key assumptions (continued)
  - Particulate debris and clumps of fibrous debris that are 10% larger across their minimum dimension than the size of the sump screen hole do not pass through
  - Once in solution, size of debris, both particulate and fibrous, remains constant
  - Debris is assumed to be homogenously distributed in the recirculating fluid throughout recirculation
  - Concentration of the debris in the recirculating fluid is sufficiently dilute that there is no interaction among individual pieces of debris, either the particulate or fibrous debris, in the recirculating coolant itself
  - Settle-out and retention of debris in the containment sump pool is conservatively neglected
  - Concentration of debris in recirculating fluid taken as equal to or less than 0.1% based on:
    - Work performed to close out Unresolved Safety Issue USI A43
    - Recent work performed by NRC contractors
    - Licensees to confirm debris concentration

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Debris Settle-out Model

- Based on first principles
- Force balance for settle-out
- Mass balance on flow
  - Flow through the reactor coolant system
  - “Bypass” flow out the break

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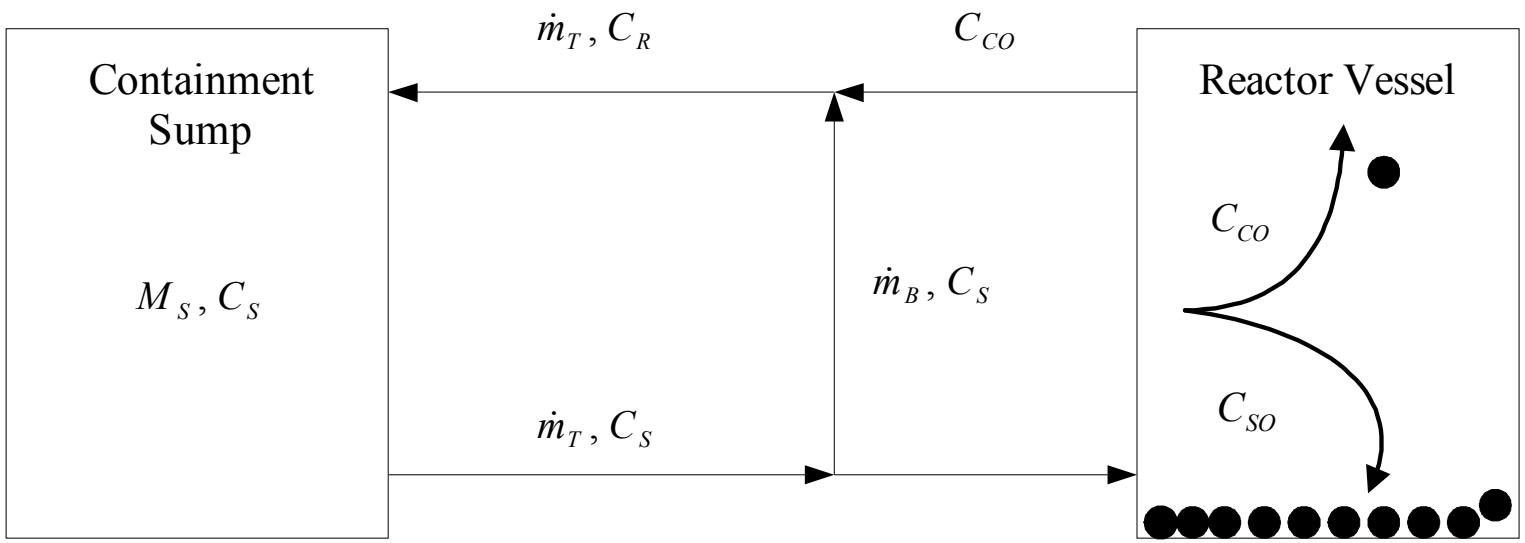
Particulate Debris Concentration Depletion



$$C^*(t)_P = C^*_{CO} + C^*_O \exp\left[\left(\frac{\dot{m}_B}{\dot{m}_T} - 1.\right)\frac{\dot{m}_T}{M_S}t\right]$$

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Fibrous Depletion Model

- Based on ratio of:
  - Open screen area
  - Closed screen area
- Assumptions
  - No debris capture at a 100% open screen
  - No debris passes at a closed screen

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Fibrous Debris Concentration Depletion

- Sump screen will collect fibrous debris
  - For a passive screen design
    - Collection effectiveness expressed as function of the ratio of open flow area to closed or blocked area
  - For an active sump screen
    - Likely to be a function of the design
    - Use vendor supplied behavior

$$C^*(t)_F = C^*_{SF} + C^*_{LF} \exp\left[-\frac{\dot{m}_{SCREEN}}{M_S} \times \eta \times t\right]$$

where:

$$\eta = (1 - \textit{Fraction of Open Screen Area})^2$$

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Component Evaluation Basis:

- For wear and abrasion
  - Use of available test data
    - Westinghouse pump test data
    - NRC data (for example, USI A-43 data)
    - Public data and technical papers
  - Characterize material behavior in abrasive and erosive media
  - Used as input to wear model
- Dynamic analysis of pump rotors (by vendor)
- Hydraulic evaluation of pumps
- Wear evaluations
  - Wall thinning
  - Orifice enlargements
- Plugging/blockage

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Pumps

- Three aspects of pump operability considered
  - Hydraulic performance
    - Performance of the pumps is impaired to the point where the pump does not provide the required flow to the systems and components it serves
  - Mechanical shaft seal assembly performance
    - Debris buildup in the shaft seal package interferes with normal operation such that actual wear of the seal surfaces is accelerated
  - Mechanical performance (vibration) of pump itself
    - Some multistage pump designs depend on the wear rings between each stage to provide bearing support for the rotating assembly
    - For these pumps, the support stiffness for the shaft is reduced if the clearances in the wear rings open up
    - If these pumps operate at speeds near the natural frequency for the rotating assembly, additional dynamic loading on the shaft associated with operation at/near resonance may result in shaft damage

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Evaluate Valves for Plugging

- Gate Valves (Manual or Power Operated)
  - Open gate valves not a concern, provided valves are >1 inch nominal size
- Butterfly Valves (Manual or Power Operated)
  - Full open or closed butterfly valves are not a concern
  - Throttled < 20 degrees open and < 4 inch nominal size vendor guidance for flow areas needed
- Check Valves including Stop Check Valves
  - If valve is > 1 inch and minimum velocity requirements are met, valve will pass debris
  - If minimum velocity is not met or the valve is 1 inch or less, vendor input may be required

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Evaluate Valves for Plugging (continued)

- Globe Valves
  - Globe Valves (Not throttled and Body Guided)
    - Are either full-open or full-closed
    - If valves > 1 inch nominal size and valves are not hermitically sealed - not a concern
    - For < 1 inch valve or hermitically sealed valves
      - Vendor input may be required for port size and flow area
      - Evaluate for compliance with IN 96-97
- Globe Valves (Not throttled-Cage Guided)
  - Evaluate to ensure that the cage holes can pass the debris and compliance with IN 96-97
- Globe Valves and Needle Valves (Throttled)
  - Vendor input to confirm flow area through valve needed

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Heat Exchangers

- Tube plugging
  - Tube inner diameter > anticipated particle size, plugging not an issue
  - Generally true, no plugging of tubes is expected.
  - If heat exchanger tubes < largest expected particle size, perform a plant-specific evaluation
- Debris settling in tubes
  - Tube velocity is generally between 3 and 15 feet/sec
  - This is greater than the sump velocity; settling not expected
- Tube failure
  - ASME formulas and debris concentration used to assess required wall thickness
  - Tubes will not fail if erosion does not reduce wall thickness below required thickness

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Orifices

- Plugging
  - If orifice hole size > anticipated particle size, plugging is not be an issue
  - For plants with orifice bore diameters < largest expected particle size, perform a plant specific evaluation
- Abrasive wear
  - Same model as for heat exchangers
- Neither plugging or abrasive wear expected to be a concern for orifices

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Containment Spray Nozzles

- Plugging
  - Most plants use a nozzle with an orifice size of 3/8"
  - Internal geometry suggests plugging is not a concern
  - Reasons similar to those for orifices
- Abrasive wear
  - Results are similar to orifices
- Plugging and erosion are generally not a concern

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Instrument Tubing

- Considered only instruments used post-accident
- Plugging
  - No direct flow path into instrument lines; they are water solid
  - Therefore, plugging not generally a concern

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Reactor Internals Evaluation

- Reviewed post-accident flow path through reactor internals components for several internals designs
  - Lower Support Plate
  - Core Support Plate
  - Upper Support Plate
  - Upper Plenum Cross Section
- Essential flow paths through the reactor vessel identified and dimensions reviewed
- In all cases, flow path dimensions of internals larger (1-inch or greater) than particulate debris size
- Therefore, blockage due to particulates in upper and lower internals flow paths not being a concern

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Fuel Evaluation

- Both cold-leg recirculation and the hot-leg recirculation flow paths
  - Cold leg recirculation supplies water to the core from the lower plenum
  - Hot leg recirculation is implemented to preclude boron precipitation, supplies water via the hot leg

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Comment on Fuel Design

- Designs for fuel for LWRs incorporate rods and grids
  - Traps debris during normal operation causing fuel cladding failures
  - NRC has challenged fuel vendors to improve operating fuel performance
- Debris capturing devices for fuel to minimize fuel failures
  - Improves fuel performance under normal operating conditions
  - Perform the same function under accident conditions
- NRC expressed concern for debris capture for accident conditions
  - Reduced core flow
  - Elevated core temperatures
- Relaxing debris capturing capabilities of fuel not considered reasonable
  - If needed, alternatives to mitigate effect of debris capturing fuel features considered
  - Capturing debris at the core inlet is considered preferable to in the core

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Fuel Blockage Evaluation Method

- Identify the following:
  - Limiting flow dimension in fuel, debris capturing devices
  - Particulate debris characteristics; size, density, shape
- Using ECCS flow rates and lower internals dimensions:
  - Use Stokes Law to calculate debris size carried to fuel
  - Assess changes in thermo-fluid properties on debris sizes carried to fuel (long term cooling)
- Evaluate potential for transported particulates to block core:
  - If particulate dimensions are smaller that the limiting flow dimension, blockage will not occur
  - If particulate dimensions are larger, consider alternate evaluation

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Hot Leg Recirculation

- May be needed to address boron precipitation
- Concerns:
  - Potential introduction of particulate debris in ECC fluid to the top of the core
  - May block flow into top of fuel, possibly approaching boron solubility limits
  - If sufficient debris is introduced, debris bed may form that insulates fuel from ECC coolant.
- The conditions associated with hot leg recirculation are plant specific and include:
  - The time following the event that hot leg recirculation is initiated
  - The hot leg recirculation flow rate
- The amount of debris that is large enough to result in the blockage of flow into the fuel is shown to decrease fairly quickly
  - Within about three (3) hours, about one-half of debris large enough to cause blockage may settle out
  - Debris depletion is plant dependent and is based on the total volume of water available to the containment sump

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Fibrous Debris

- Evaluate potential fuel blockage by fibrous debris in ECC flow using the method describe as "Partial blockage of the flow path into the fuel"
- Calculate the depletion of fibrous debris by the following components:
  - The sump screen
  - Debris filtering features of the fuel located below the active length of the fuel
  - Support grids within the fuel
- Assess impact of a mixed bed of fiber and particulate debris on head loss
- The following is suggested for plants having both fiber and particulate debris ingested into the ECC:
  - Assume ingested fiber and particulate uniformly mixed within the ECC flow
  - Treat first fuel obstacle (debris filtering device, lowest support grid for cold-leg flooding, the top support grid for hot leg recirculation) as filter or screen
  - Evaluate the potential blockage of fuel by fibrous debris introduced by flow into the lower plenum, "Partial blockage of the flow path into the fuel"
  - Use flat plate head loss correlation in NEI 04-07 for mixed (fibrous and particulate) debris and evaluate head loss across the fiber-particulate debris bed

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Post-accident chemistry effects

- Corrosion products not currently addressed in evaluation methodology
- Will be addressed upon availability of information from ongoing NRC/Industry Integrated Chemistry Effects Test (ICET)
  - Characterization of particulates
  - Characterization of suspended solids

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Summary

- Evaluation method developed for downstream effects
  - Addresses all components in ECC and CS System flow path
  - Uses publicly available information
- Document status
  - Industry review complete
  - Comments being addressed
- Chemistry effects will be addressed when data is available

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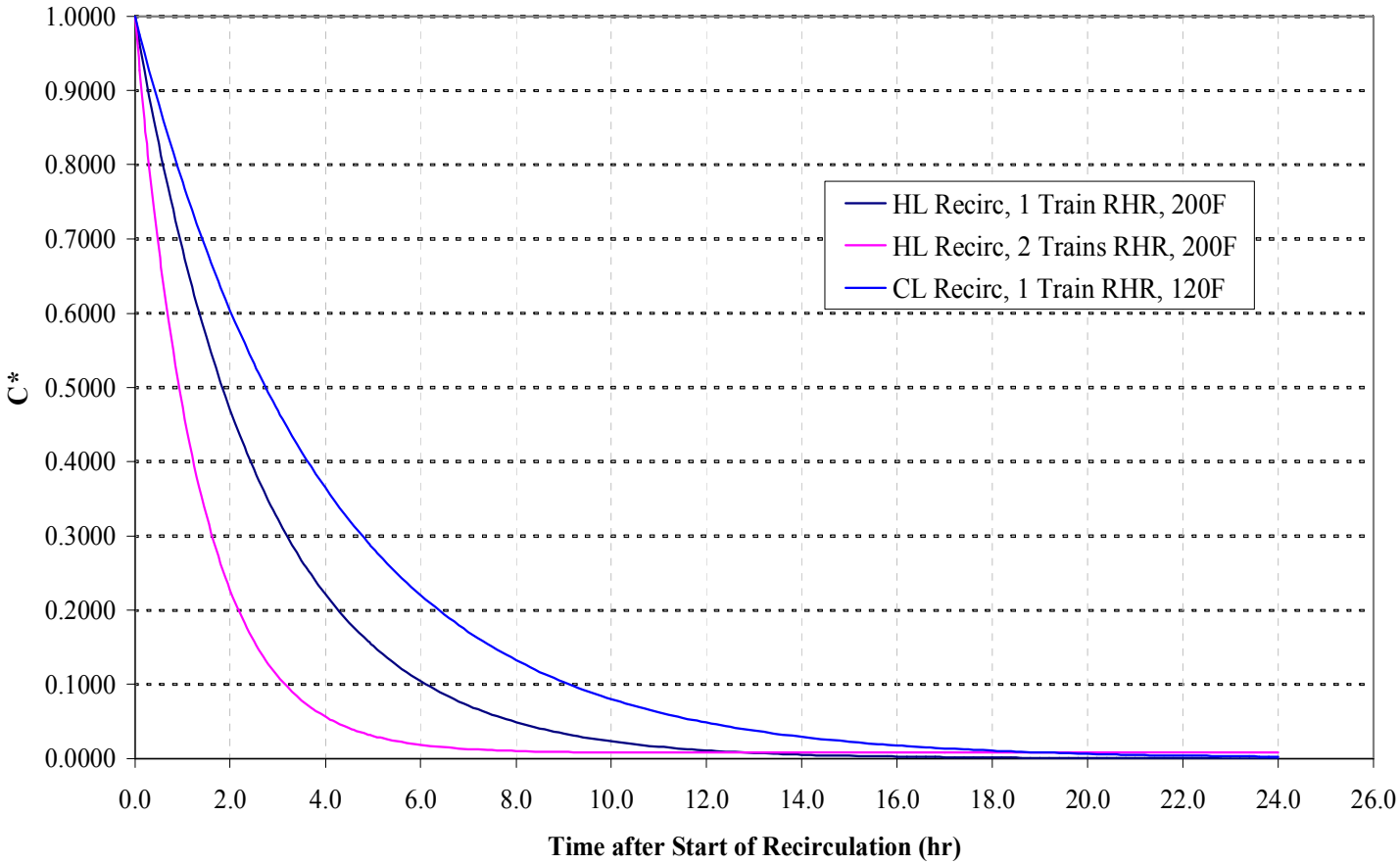
Particulate Debris Concentration Depletion

Illustrative example; does not relate to any specific plant or debris type



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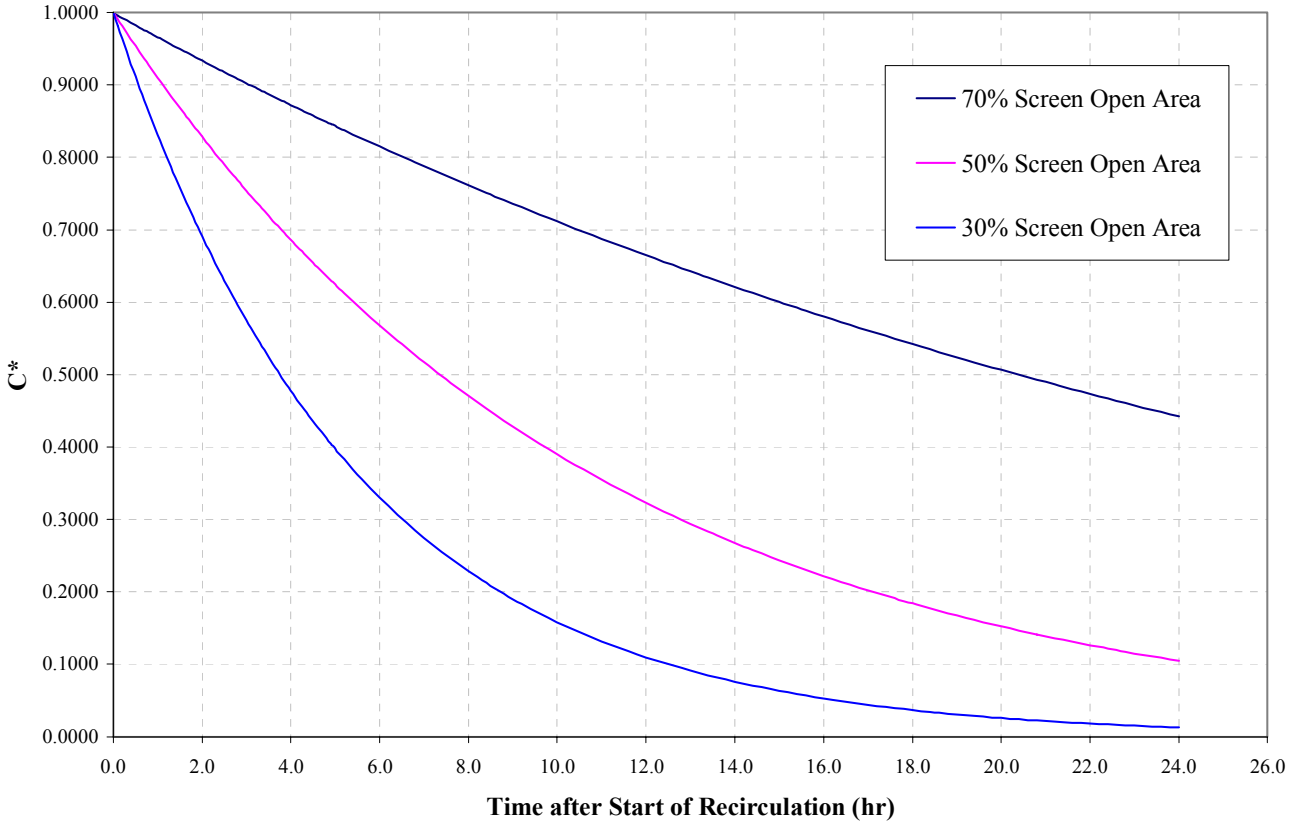

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Alternate Evaluations

- Evaluation of Alternate Flow Paths
  - From the cold legs through short steam generator tubes into upper plenum
    - ECCS pumps must have sufficient head capability to drive fluid
    - Assessment performed on a plant-specific basis
  - From baffle/barrel region and/or the spacing between fuel assemblies and fuel assemblies to the baffle
    - If available, may be applicable for both cold-leg and hot-leg breaks
    - Flow paths must be greater than debris filtering devices limiting dimensions
  - Confirm long-term cooling criteria of 10 CFR 50.46 are satisfied
- Partial blockage of the flow path into the fuel
  - Calculate amount of particulate debris to pass through sump screen
  - Calculate amount of core blockage resulting from particulate
  - Determine the coolability of the fuel with blockage
  - Confirm long-term cooling criteria of 10 CFR 50.46 area satisfied

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Hot Leg Recirculation (continued)

- Following method recommended to evaluate the potential fuel blockage by particulates during hot-leg recirculation
  - Identify
    - Plant-specific time to initiate hot-leg recirculation
    - Hot-leg recirculation flow rate
  - Calculate amount of particulates depleted (deposited into the lower plenum) during cold leg recirculation only
  - Subtract the depleted particulate debris from the total amount of particulate debris that passes through sump screen
  - Determine particulate debris delivery rate to top of core due to hot leg recirculation
  - Calculate amount of particulate debris introduced to the fuel by hot-leg recirculation
  - Determine height of particulate debris that would be deposited in the fuel, assess impact on cooling of fuel