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DECAY HEAT STUDIES TO REDUCE ACTIVE COOLING TIME OF A NUCLEAR THERMAL PROPULSION SYSTEM

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Decay heating occurs within an Nuclear Thermal Propulsion (NTP) system after reactor shutdown due to fission products decaying and producing heat within the reactor. The decay heat is large enough during this period to cause the NTP system components to heat up past their temperature limits without sufficient cooling. If the temperature limits are surpassed, the NTP system could be damaged including the reactor core components. This is mitigated by the usage of both active and passive cooling stages after the NTP system shuts down. The active stage requires the expenditure of reactor coolant (also the propellant of the NTP) to cool the system. This coolant/propellant is contained within the NTP system and the more coolant/propellant needed translates to the higher mass and cost requirement of the NTP system. This motivates an effort to reduce the active cooling stage that in turn reduces system mass and costs. In this work, two design parameters are investigated for potential reduction of the active cooling stage length. These investigations are done by modeling a simplified NTP system using TRICORDER and it was found that the active cooling stage can be reduced by using high emissivity radiator coatings and the addition of radiator fins.

I. INTRODUCTION

After NTP systems shutdown, the reactor continues to produce heat through decaying of fission products. This decay heat initially produces 7% of the nominal heat (power) produced in the reactor and drops off exponentially over time. During the initial period of the decay heat production, active cooling is required until the mount of decay heat produced is below the passive cooling capacity (radiative cooling to the environment). The active cooling involves the coolant/propellent circulating and expending to the environment that impacts the amount of propellant needed for the entire mission. Thus it is desired to reduce this active cooldown period to reduce the amount of coolant needed for missions.

The purpose of this study is to use a modeling and simulation tool to investigate potential ways to decrease the period of active cooling required for an NTP system. Specifically, emissivity of the radiator surfaces and the addition of radiator fins are investigated.

II. METHODOLOGY

The methodology used in this analysis involves the simulation of heat transfer from the decay heat producing elements (fuel elements and tie tubes) to the outer vessel boundary using a finite element method based tool, TRICORDER. The following sections discuss TRICORDER, the geometry, meshing and boundary conditions, and post processing used for the study.

II.A. TRICORDER

The TRansient Investigation COde for Reactor DEvelopments and Research (TRICORDER) tool is a multiphysics design code for NTP systems involving steady state and transient analysis. TRICORDER is developed in the Multiphysics Object-Oriented Simulation Environment (MOOSE) Framework [1] and utilizes several MOOSE built-in modules. TRICORDER has the capabilities to simulate coupled heat transfer in solids, compressible flow in 1-D channels, and point reactor kinetics with future physics capabilities under development.

The TRICORDER heat conduction module was used to solve the steady state energy equation (Eq. 1) for solid media across a 2-D core. The axial conduction through the core and minimal convective contribution from the propellant were assumed to be negligible for this analysis.

$$\nabla k \nabla T + q''' = 0 \tag{1}$$

Where heat generation term, q''', is the contribution from the various reactor components producing decay heat.

The energy equation is solved using the Preconditioned Jacobian-Free Newton-Krylov (PJFNK) with continuous Galerkin finite elements. The Single Matrix Preconditioning (SMP) method was used for preconditioning.

II.B. Geometry of the NTP System

The NTP reactor geometry analyzed was a 2-D 1/12 slice at the axial center of the reactor core and is shown in Fig. 1 with the components labeled and listed in Table I. The main components of interest are the fuel elements, tie tubes, and reflectors with the reactor vessel forming the outer boundary of the model.

II.C. Meshing and Boundary Conditions

The meshing of the 2-D domain was created using a finite element mesher with each component of interest meshed individually. The shape functions used were first order, and an example of the mesh is shown in Fig. 2.

The boundary conditions are highlighted and labeled in Fig. 3. The inner boundary conditions (labeled, 'Symmetry') was symmetry boundary conditions (flux across the boundary was set to zero) to simulate the expected symmetry of the reactor core. The gap between the slat and the reflector was treated using the gap heat transfer capabilities of MOOSE with both conductive and radiative heat transfer considered. These boundary conditions were maintained constant for each study. The outer boundary condition (labeled, 'Dirichlet') was a Dirichlet boundary with a constant temperature defined using Eq. 2. The outer boundary temperature was changed based

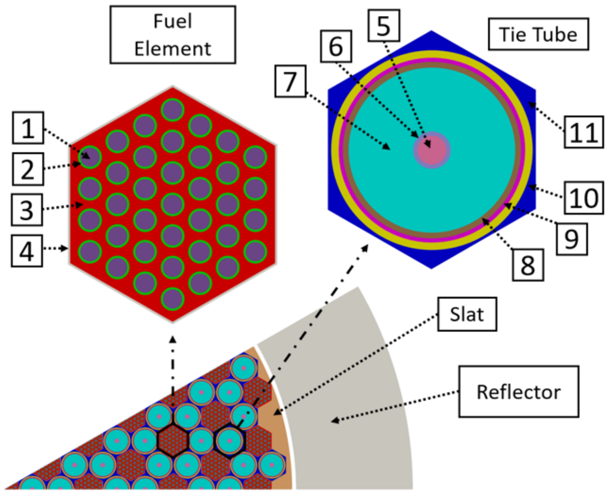

Fig. 1. 1/12 slice of NTP reactor core used for analysis.

TABLE I. Listing of NTP system components.

NTP System Components	Number
Fuel Coolant Channel	1
Fuel Tubing	2
Fuel Meat	3
Fuel Canning	4
Tie Tube Coolant Supply	5
Tie Tube Inner Metal	6
Tie Tube Moderator	7
Tie Tube Outer Metal	8
Tie Tube Coolant Return	9
Tie Tube Insulator	10
Tie Tube Structure	11
Slat	n/a
Reflector	n/a

on each decay heat, emissivity, and/or surface area specified for each simulation. The T_C was set to zero to reflect the expected environmental temperature and T_H was solved for using a baseline emissivity of 0.93.

$$\dot{q} = \epsilon\sigma(T_H^4 - T_C^4)A_{surf} \tag{2}$$

The heat sources (examples labed, 'Heat Sources') were varied based on the decay power of each simulation and the percentages of decay heat produced in each component was determined using a Monte Carlo tool.

For the radiator emissivity study, the emissivity in Eq. 2 was varied over a range from 0 to 0.99. For the radiator fin study, the fins were treated as an increase in surface area as part of solving for T_H. The surface area was nominally the outer surface area of the reflector and the added surface area of four fins. Each fin was treated as a flat plates that has the same core height and extends out approximately the radius of the core.

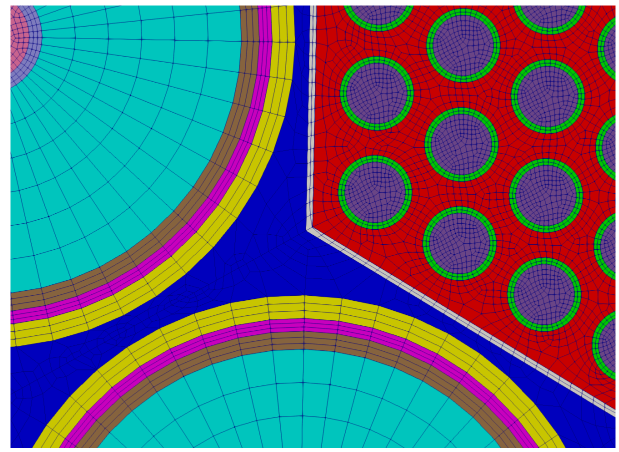

Fig. 2. Example of reactor core mesh used in the analysis.

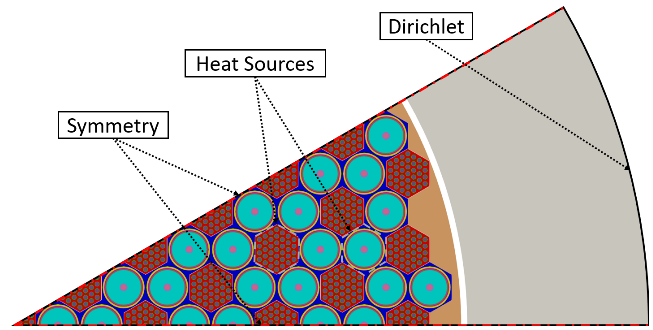

Fig. 3. Specification of boundary conditions on the computational domain.

II.D. Post Processing

For each simulation, the cooldown time was determined using Eq. 3 from ref. [2] by setting the decay heat equal to the decay power level. The ratio of the decay power, $P(t)$ to the initial power of NTP system, P_0, and the run time of the system, t_{fp}, are set by the nominal NTP system analyzed.

$$\frac{P(t)}{P_0} = 0.1104[t^{-0.2436} - (t_{fp} + t)^{-0.2436}] \tag{3}$$

This decay power correlation was used based on its development to describe decay power specific to an NTP system. The decay power correlation was developed using Serpent 2 in the same NTP system modeled in this paper.

The maximum temperature allowed for each study was conservatively selected to be $700K$ that corresponds to the maximum tie tube moderator temperature. The tie tube moderator, made of Zirconium hydride (ZrH), was considered the most limiting material before material degradation occurs for the purpose of these studies.

III. RESULTS

The results of each study are discussed in the proceeding sections with the baseline NTP system discussed initially. The baseline NTP system was run for several decay power levels over several orders of magnitude to simulate the exponent decay of decay heat. An example of the temperature distribution across the computational domain at a nominal decay power level is provided in Fig. 4. It is provided such that the reader understands where the maximum temperature was in the domain.

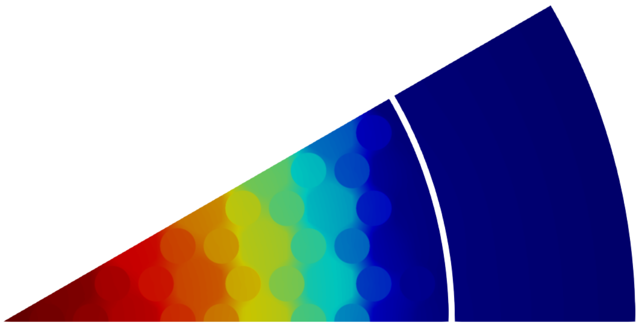

Fig. 4. Example of temperature distribution during cooldown for a nominal NTP system where red is hot and blue is cold.

III.A. Cooldown Time for Baseline NTP System

The cooldown time for different maximum temperatures corresponding to different decay power levels is shown in Fig. 5. The cooldown time is presented as a non-dimensional ratio of the cooldown time, t_{cd}, to the run-time of the reactor before shutdown, t_{fp}. The baseline ratio of cooldown time was determined to be 111.90 and was used for comparison in the preceeding studies.

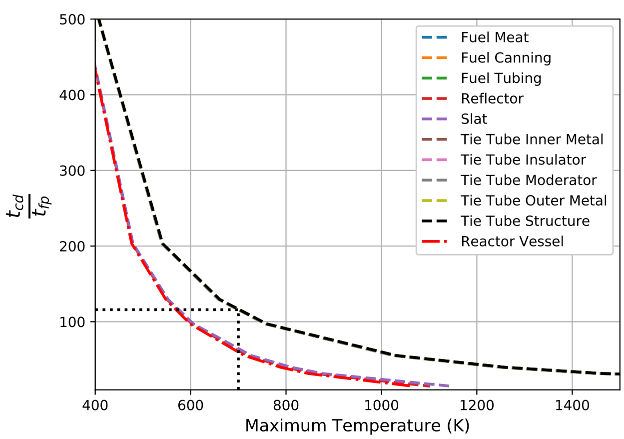

Fig. 5. Time to cooldown ratio for different components of a nominal NTP system.

III.B. Variation of Radiator Emissivity Study

The impact of varying the radiator coating emissivity was investigated through the method discussed in subsection II.C. In Fig. 6., the higher emissivity for the radiator coating shows a significant reduction of the ratio of cooldown time for the majority of potential emissivities. There is also an expected drop off after reaching an emissivity of 0.8 corresponding the relationship in Eq. 2. Due to the baseline NTP system having an emissivity of 0.93, the improvement by increasing the radiator coating emissivity to 0.99 is a maginal increase. This was quantified by a percent decrease of 2.57% of time to cooldown ratio. This increase of emissivity could yield a significant impact depending on the NTP system design, but it is not readily apparent in this study.

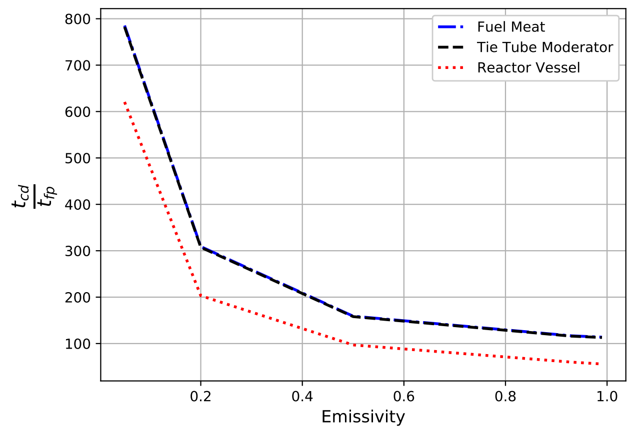

Fig. 6. Time to cooldown ratio for relevant components with varying emissivity.

III.C. Addition of Radiator Fins Study

The impact of adding radiator fins (additional surface area) was investigated through the method discussed in subsection II.C. The resulting maximum temperature of relevant components to the baseline NTP system without fins is shown in Fig. 7. The addition of fins (assuming perfect transfer of heat to the surrounding environment) enables a significant decrease of the time to cooldown ratio by 24.02%. This decrease could enable the design of an NTP system with a considerable reduction of hydrogen supply in favor of the added system complexity of radiator fins.

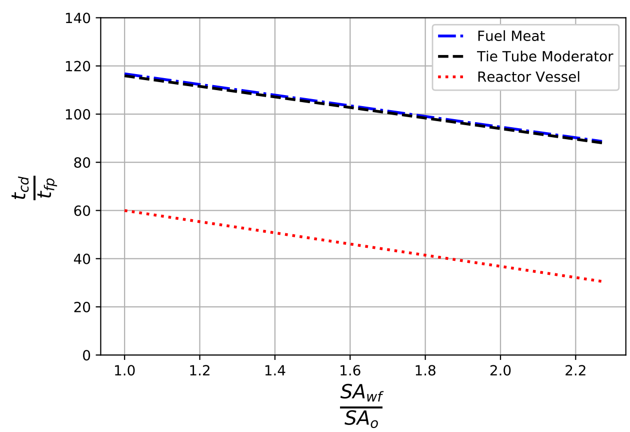

Fig. 7. Time to cooldown ratio for relevant components with increasing radiator surface area.

IV. CONCLUSIONS

The simulations of a baseline NTP system, a system with varying radiator emissivity, and a system with radiator fins were done using TRICORDER. The simulations were able to determine a baseline time to passive cooldown ratio and the impact of the aforementioned modifications. It was determined that using a baseline radiator emissivity of 0.93, marginal decrease (2.57%) in time to cooldown ratios could be achieved by increasing emissivity to 0.99. The addition of four modest sized radiator fins was found to decrease the time to passive cooldown ratio by 24.0%. It was determined that both studies yielded positive impact, but it will be ultimately up to the NTP system designers to determine the relevant impact.

V. NOMENCLATURE

NTP	Nuclear Thermal Propulsion
TRICORDER	TRansient Investigation COde for Reactor DEvelopment and Research
MOOSE	Multiphysics Object-Oriented Simulation Environment
k	Thermal conductivity of a material
ϵ	Emissivity of a surface
σ	Stefan-Boltzmann Constant ($5.67 \times 10^{-8} \frac{W}{m^2-K^4}$)
$\dot{q}$	Decay heat
q'''	Heat generation
T_H	Outer boundary temperature
T_C	Environmental temperature
A_{surf}	Outer surface area of the radiating surface
$P(t)$	Decay power
P_0	Initial power
t_{fp}	Run time of the NTP system
t_{cd}	Cooldown time of the NTP system
PJFNK	Preconditioned Jacobian-Free Newton-Krylov
SMP	Single Matrix Preconditioning

VI. ACKNOWLEDGMENTS

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REFERENCES

1. D. GASTON, C. NEWMAN, G. HANSEN, and D. LEBRUN-GRANDIÉ, "MOOSE: A parallel computational framework for coupled systems of nonlinear equations," *Nuclear Engineering and Design*, **239**, *10*, 1768–1778 (Oct 2009).
2. A. DENIG and M. EADES, "MONTE CARLO-INFORMED DECAY HEAT MODEL FOR A CERMET LEU-NTR," in "NETS 2019 Nuclear and Emerging Technologies for Space," .