Molten Salt Reactor Transients

How Power of The Future Performs In Accidents

Gavin Ridley, Dr. Alex Lindsay, Prof. Kathryn Huff
Advanced Reactors and Fuel Cycles Group

University of Illinois at Urbana-Champaign

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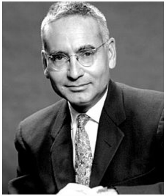
Outline

Energy for the future

Cheap and abundant nuclear energy is no longer a luxury; it will eventually be a necessity for the maintenance of the human condition. – Alvin Weinberg



Molten salt reactors offer a convincing solution to the problem of fossil fuels.

- Potentially much cheaper than normal nuclear
- Make meltdowns impossible
- Better natural resource utilization

MSR Comparison

Topaz Solar Farm

- 9.5 sq. mi of California desert
- Max output of 550 MW(e), on average makes 132 MW(e)
- $2.5B construction

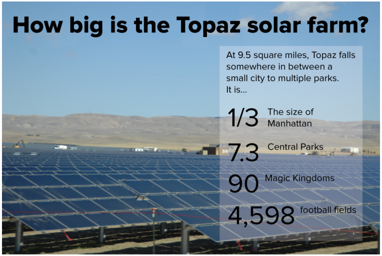


Figure 1: Topaz solar farm in California, credit GigaOM media

Terrestrial Energy IMSR concept

- About 300 MW(e) output, more than double Topaz farm
- Initial cost estimates rank IMSR cheaper than coal

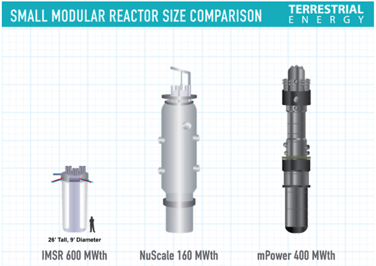


Figure 2: IMSR and some other small nuclear designs, credit Terrestrial Energy

Benchmark Case: MSRE

- Constructed at Oak Ridge National Lab, ran reliably 1965-1969 at 7.4 MW(th)
- Various tests proved theory and tech-readiness for full-scale power plants
- Stopped operation since all needed experiments were done

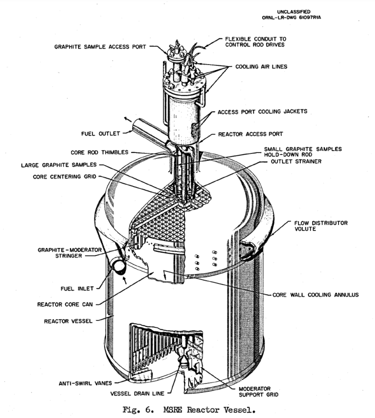
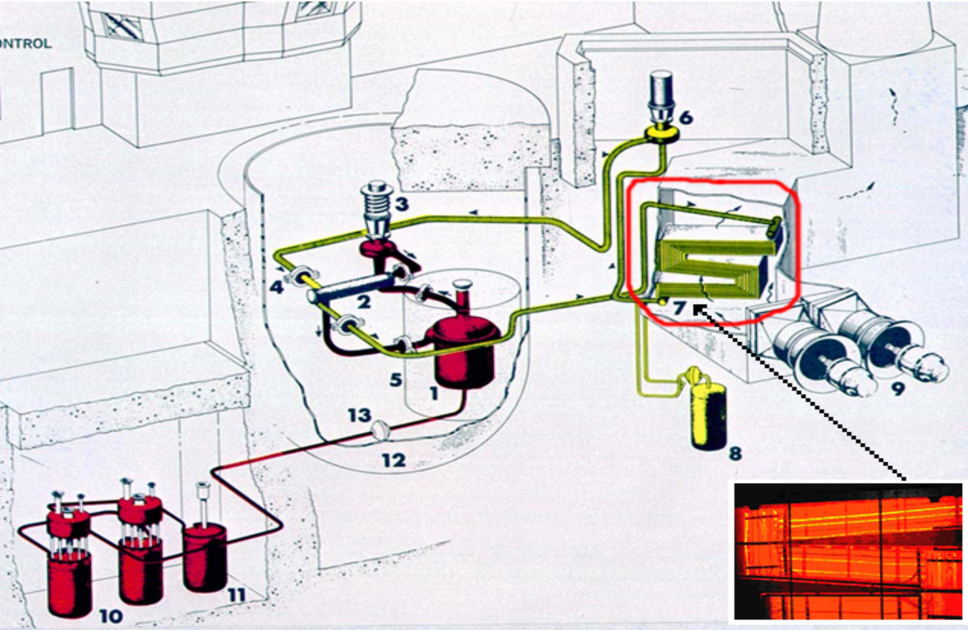


Figure 3: MSRE reactor core diagram from ORNL technical reports



1. Reactor Vessel, 2. Heat Exchanger, 3. Fuel Pump, 4. Freeze Flange, 5. Thermal Shield,

MSR Governing Equations

Neutrons' changing concentrations can be described approximately with coupled diffusion equations:

$$\frac{1}{v_g}\frac{\partial \phi_g}{\partial t} = \nabla \cdot D_g \nabla \phi_g + \sum_{g \neq g'}^{G} \Sigma^s_{g' \to g}\phi_{g'} + \chi^p_g \sum_{g'=1}^{G}(1-\beta)\nu\Sigma^f_{g'}\phi_{g'} + \chi^d_g \sum_i^I \lambda_i C_i - \Sigma^r_g \phi_g \tag{1}$$

Delayed neutron precursors are freshly split atoms that drift in the salt current, later emit neutrons.

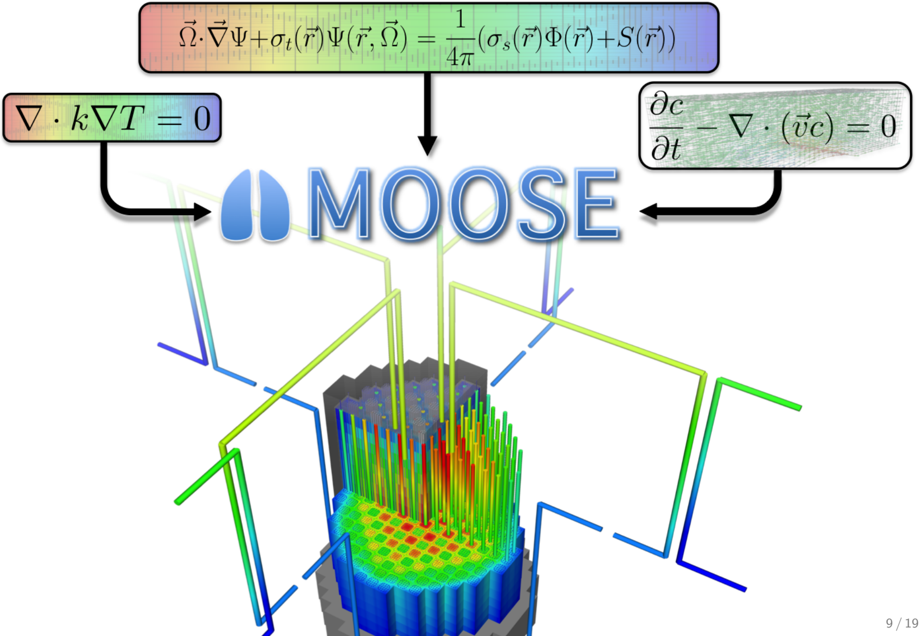
$$\frac{\partial C_i}{\partial t} = \sum_{g'=1}^{G} \beta_i \nu \Sigma^f_{g'}\phi_{g'} - \lambda_i C_i - \frac{\partial}{\partial z} u C_i \tag{2}$$

Heat changes coefficients in other equations.

$$\rho_f c_{p,f}\frac{\partial T_f}{\partial t} + \nabla \cdot (\rho_f c_{p,f}\vec{u} \cdot T_f - k_f \nabla T_f) = \sum_g \phi_g \Sigma_{f,g} E_{f,g} \tag{3}$$

Red values change with temperature. Green refers to delated neutron precursors. Purple indicates neutron flux.

Outline


$\vec{\Omega}\cdot\vec{\nabla}\Psi+\sigma_t(\vec{r})\Psi(\vec{r},\vec{\Omega}) = \frac{1}{4\pi}(\sigma_s(\vec{r})\Phi(\vec{r})+S(\vec{r}))$
$\nabla \cdot k\nabla T = 0$
$\frac{\partial c}{\partial t} - \nabla \cdot (\vec{v}c) = 0$
MOOSE

MOOSE Physics Representation

- Highly object-oriented code solves weak form of PDE using finite element method
- PETSc solves resulting system of nonlinear equations using generalized minimal residual method (GMRES)
- Some of the world's most cutting-edge numerical algorithms and scalable parallel computing are made painlessly accessible to the everyday user

MOOSE Example

In MOOSE, the term $D\nabla^2 u$ is easily represented by:

```
Real
GroupDiffusion::computeQpResidual()
{
  return _D[_qp][_group] * _grad_test[_i][_qp] *
         computeConcentrationGradient(_u, _grad_u, _qp);
}
```

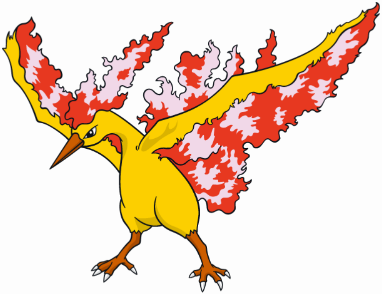
A vacuum boundary condition in neutronics calculations can easily be represented by:

```
Real
VacuumConcBC::computeQpResidual()
{
  return _test[_i][_qp] * computeConcentration(_u, _qp) / 2.;
}
```

Moltres

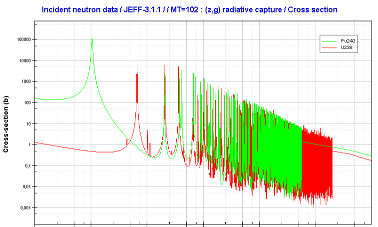
- github.com/arfc/moltres
- Publicly developed on github
- Continuous integration by Civet
- Includes detailed guide for contributing

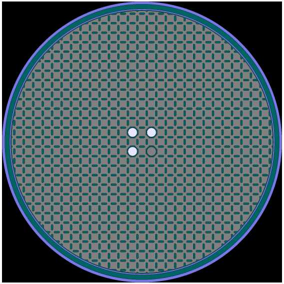
Most importantly: physics kernels, boundary conditions, and even capability to couple into MOOSE Navier-Stokes solvers provided to the moltres user

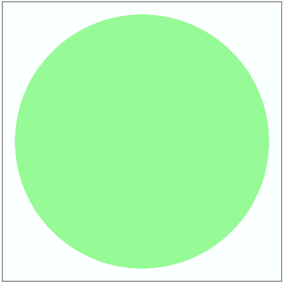


Group constant generation

- Where do coefficients like Σ, D, χ, ν come from?
- **Serpent 2 - Monte Carlo neutronics**
  - Continuous energy, meaning very close to first-principles physics
  - Trace millions of neutrons through reactor geometry
- *Behemothly* computationally expensive for transients, accuracy scales $\mathcal{O}(\sqrt{n}^{-1})$

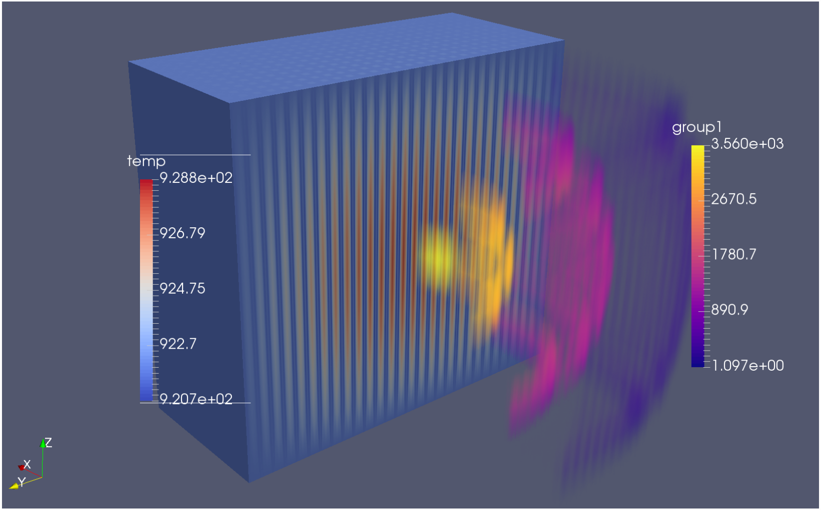




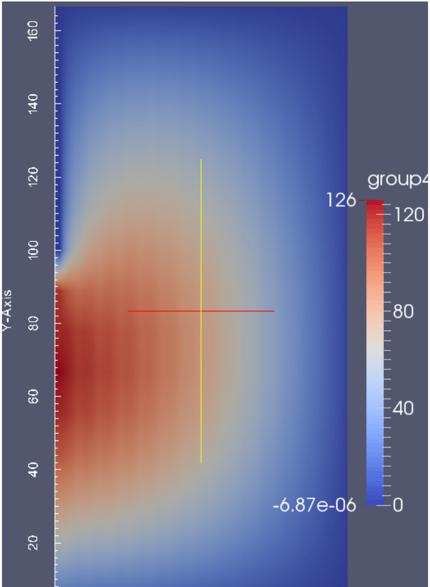


Outline

Results


temp
9.288e+02
926.79
924.75
922.7
9.207e+02
group1
3.560e+03
2670.5
1780.7
890.9
1.097e+00
Z
X
Y

More Results



- My code: adds ability to simulate control rod movement
- Future work will include making sure reactor power falls enough due to CR insertion in accidents

Conclusion

Moltres can contribute to building power for the future.

- Group constants generated for MSRE-like reactors, made public on github
- Work in progress to automatically model salt heat exchangers, salt loops

Future work

- Will build small research reactors, transport effects may dominate
- $\implies$ implement P_3 or so transport
- Include molten salt-specific thermalhydraulics models

Acknowledgement

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ENERGY IS COOL, KIDS