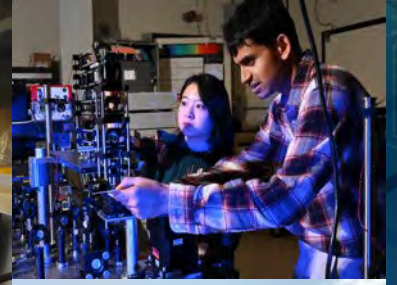




May 2026

Dr. George Mesina
RELAP5-3D Team

RELAP Code Series Perspective

Battelle Energy Alliance manages INL for the
U.S. Department of Energy's Office of Nuclear Energy

Idaho National Laboratory

INL/CON-XX-YYYYY

Agenda

1. Past
2. Present
3. Future

RELAP Series from the Past

51 Nuclear Reactor Expts at INL (NRTS) 1946 – 1961

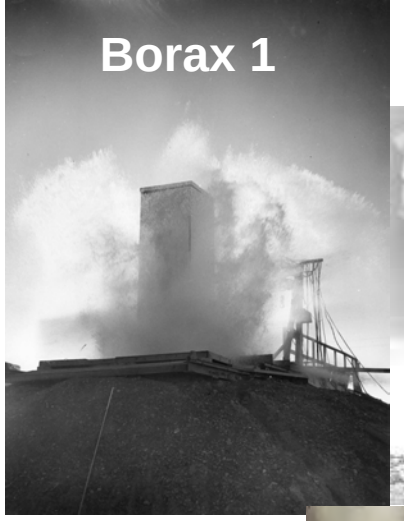
1. BOiling water ReActor eXperiment (BORAX)
2. Special Power Excursion Reactor Test (SPERT)
3. Transient REActor Test (TREAT)
4. Loss Of Fluid Test (LOFT)
5. Semiscale

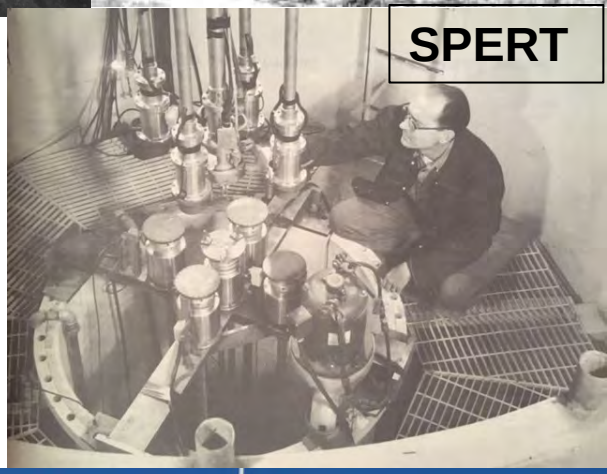
Industry had built 17 very different commercial plants by 1965

Experiments

1. Took too long to build
2. Were very costly
3. Did not cover all the needs of power plant builders

Enter COMPUTER CODES and the RELAP Series to be able to model different kinds of reactors

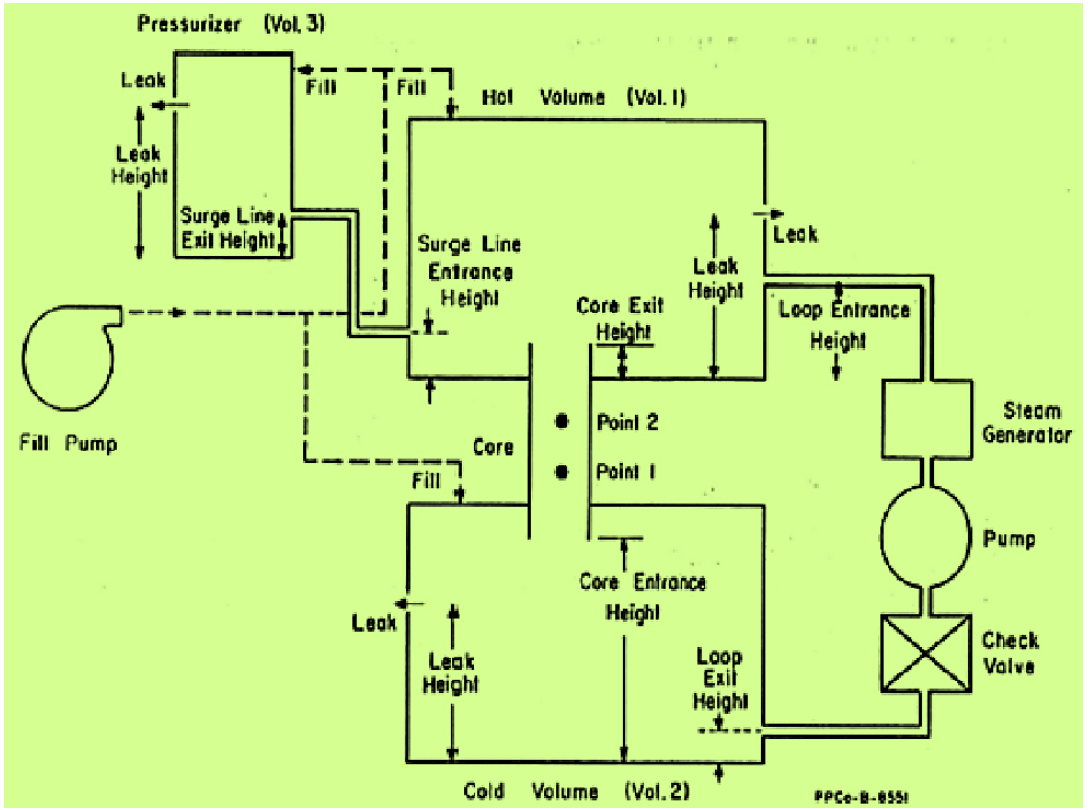




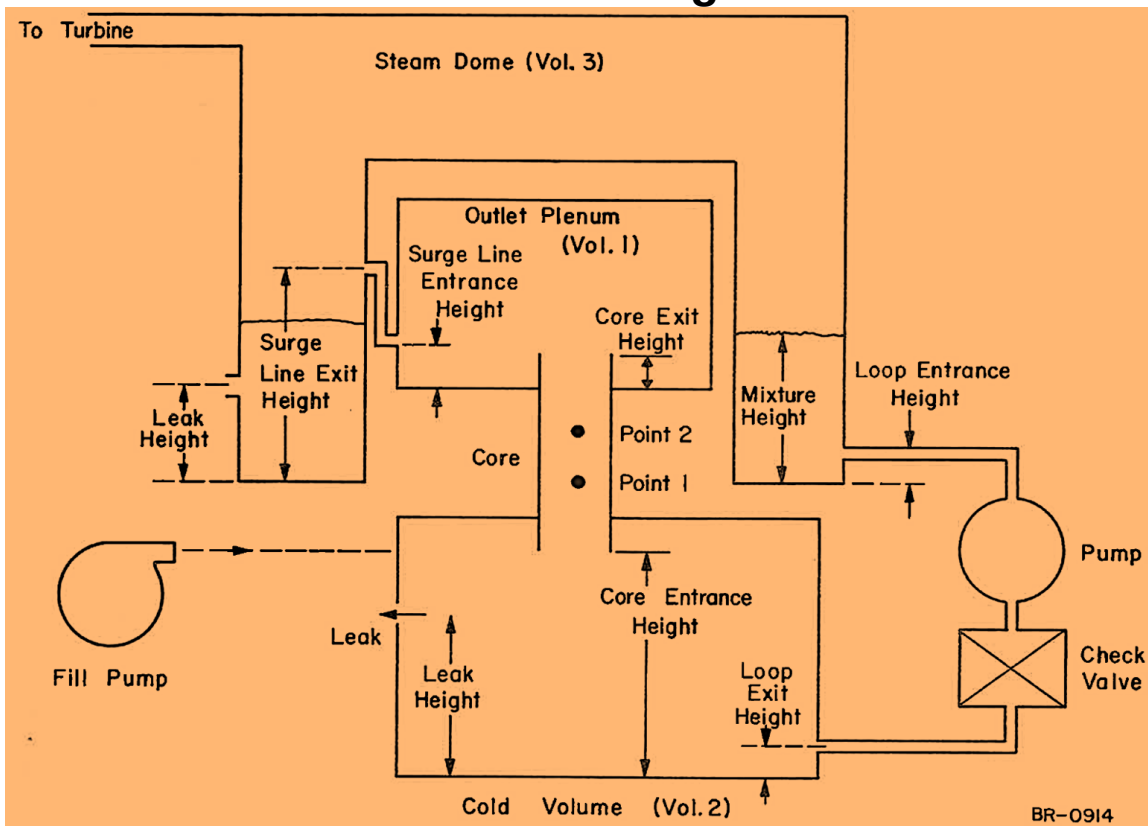
RELAPSE (RELAP1) and RELAP2

1. RELAP1 (1966) and RELAP2 (1968) had only 3 control volumes
    1. Hot volume, Cold Volume, Pressurizer
2. 3 PDEs: Mass, Momentum, Energy
3. 1 ODE for 2-phase separation
4. This clearly could not model all the different kinds of reactors that industry needed

RELAP1 and 2 model of Pressurized Water Reactor

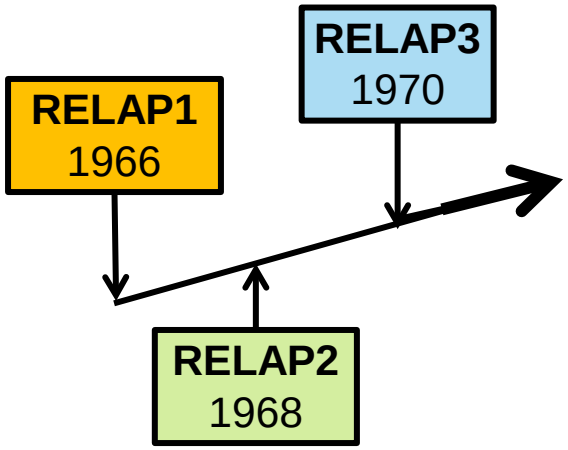


RELAP1 and 2 model of Boiling Water Reactor

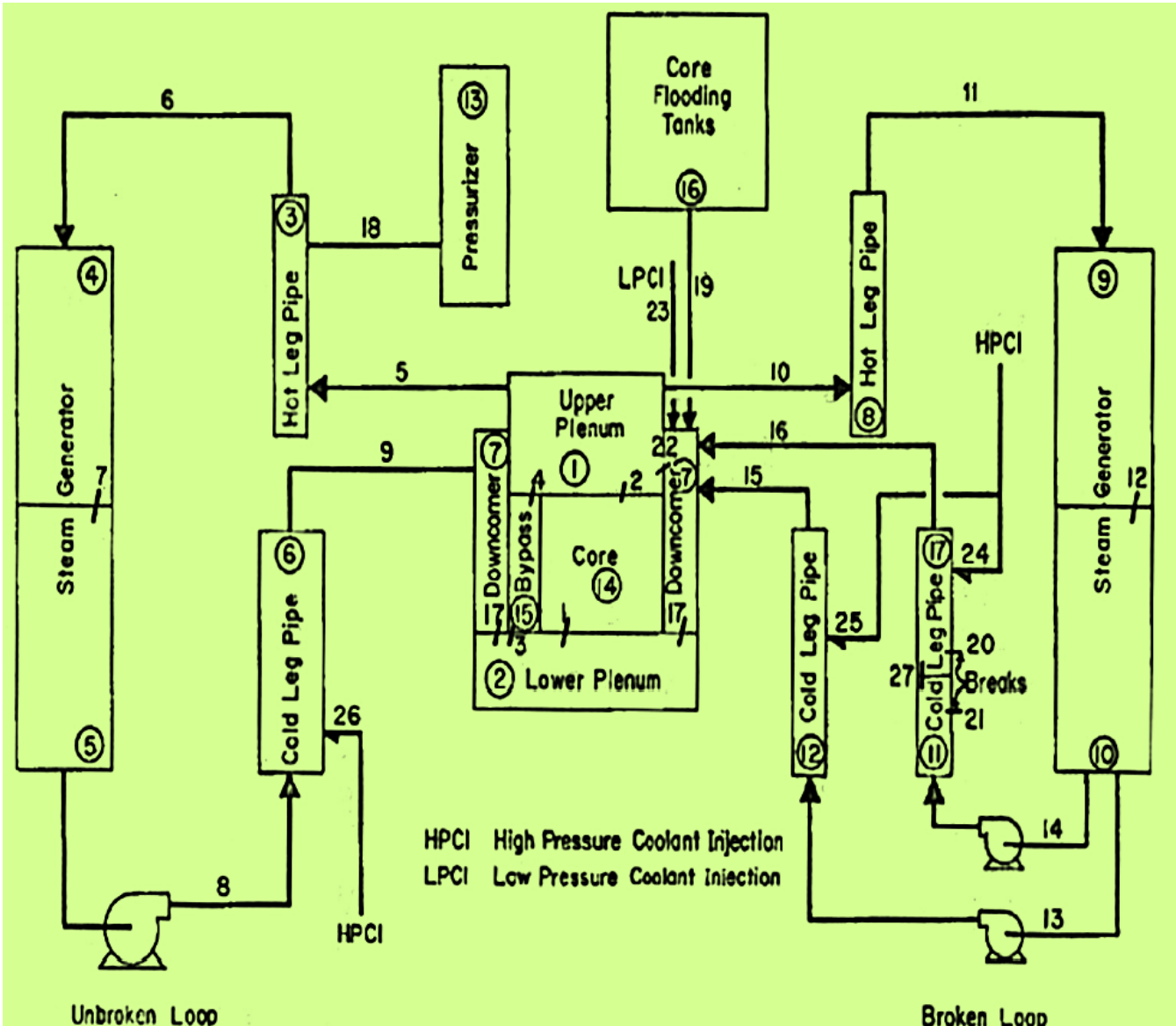


RELAP3

- RELAP3 (1970) improvements over RELAP2
  - 20 volumes
  - trip logic
  - Valves
  - pressure-dependent fill and leak
  - fuel pins/plates
  - heat conduction model, and
  - expanded heat transfer models

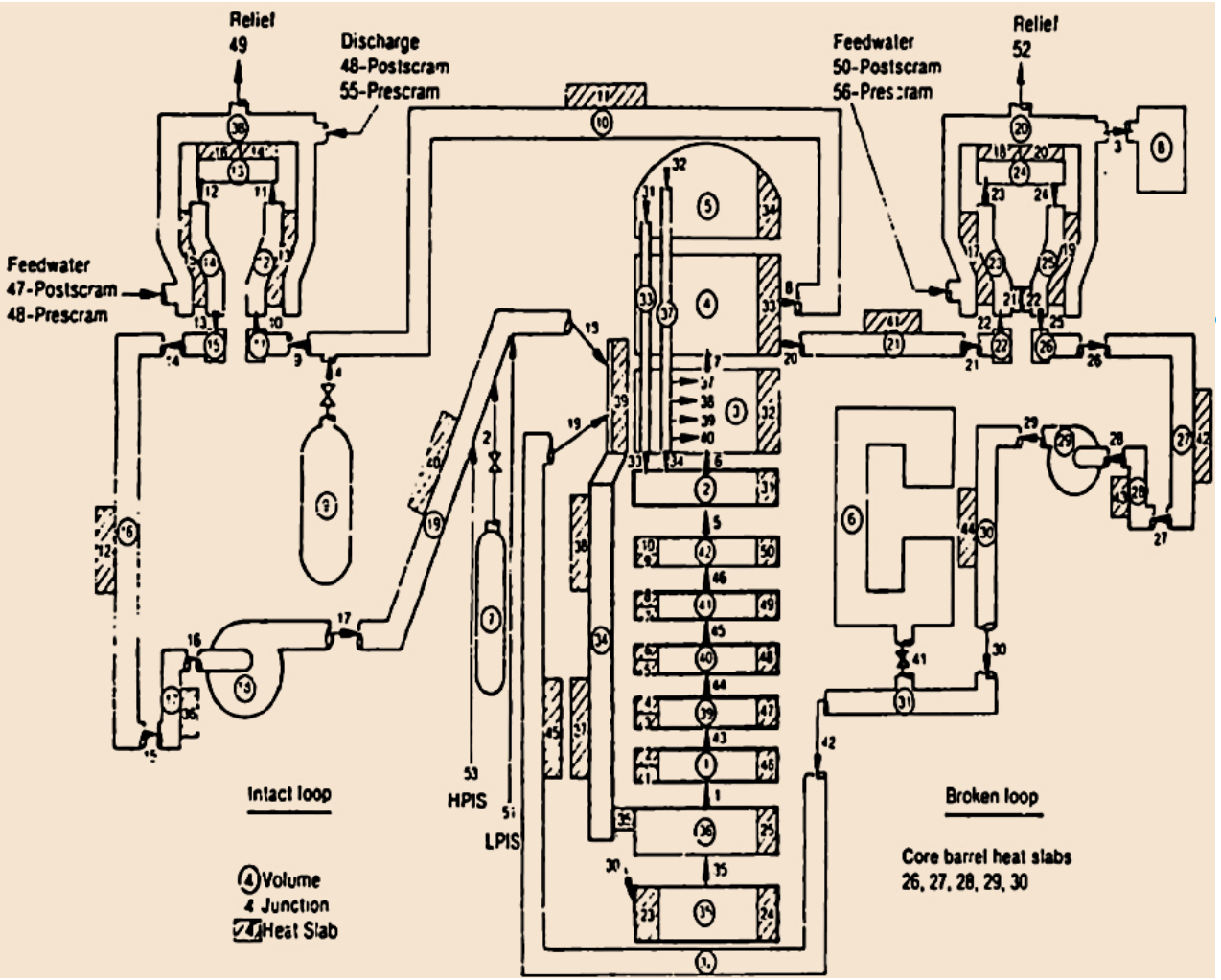


RELAP3 model of Pressurized Water Reactor



RELAP4

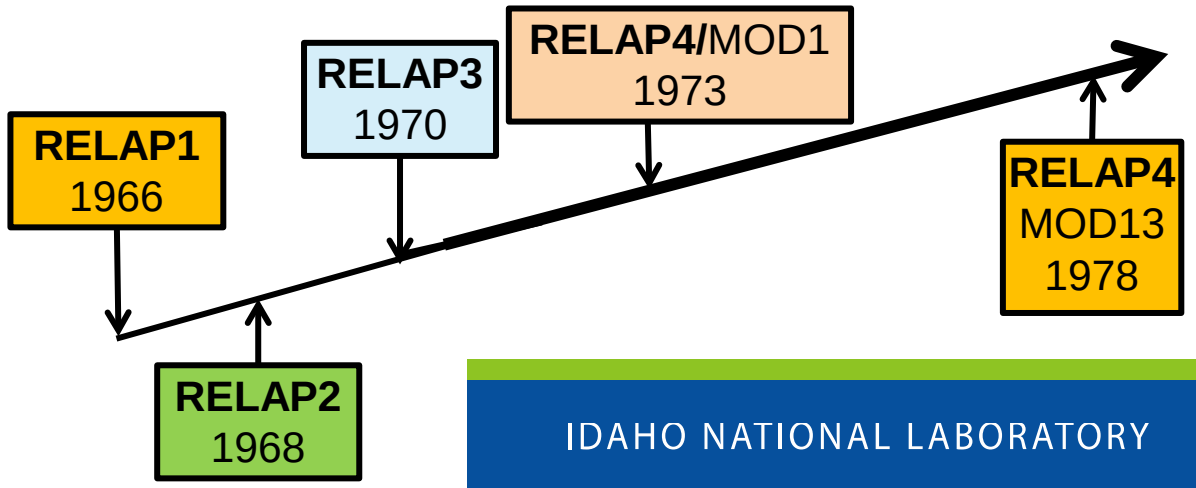
RELAP4 model of Pressurized Water Reactor



- RELAP4/MOD1 (1973) to RELAP4/MOD13 (1978)
  - Up to 100 control volumes
  - MOD1 could model SB-LOCA scenarios
  - MOD6 – Reflood modeling
  - MOD7 – Self-initialization
  - MOD 10 – Momentum flux term *dP/dA &* form losses
    - True 1D flow, 2-fluid slip model
  - Molecular nitrogen for accumulator
  - Secondary system as a flow network

By Mod 13

- The heat transfer capability included
  - Better reflood and fuel gap modeling
  - Zr-steam metal-water reaction
- Implicit time advancement
- Could model SB & LB-LOCAs for PWRs & BWRs



RELAP5 / MOD 0, 1, 2

RELAP5/MOD 0 (1979) LBLOCA code

- No essential limit on control volumes
- First well-posed 2-fluid nonequilibrium set of equations (1975 Pilot code)
- 2 mass, 2 momentum, 1 energy eqn. gas phase fixed at saturation

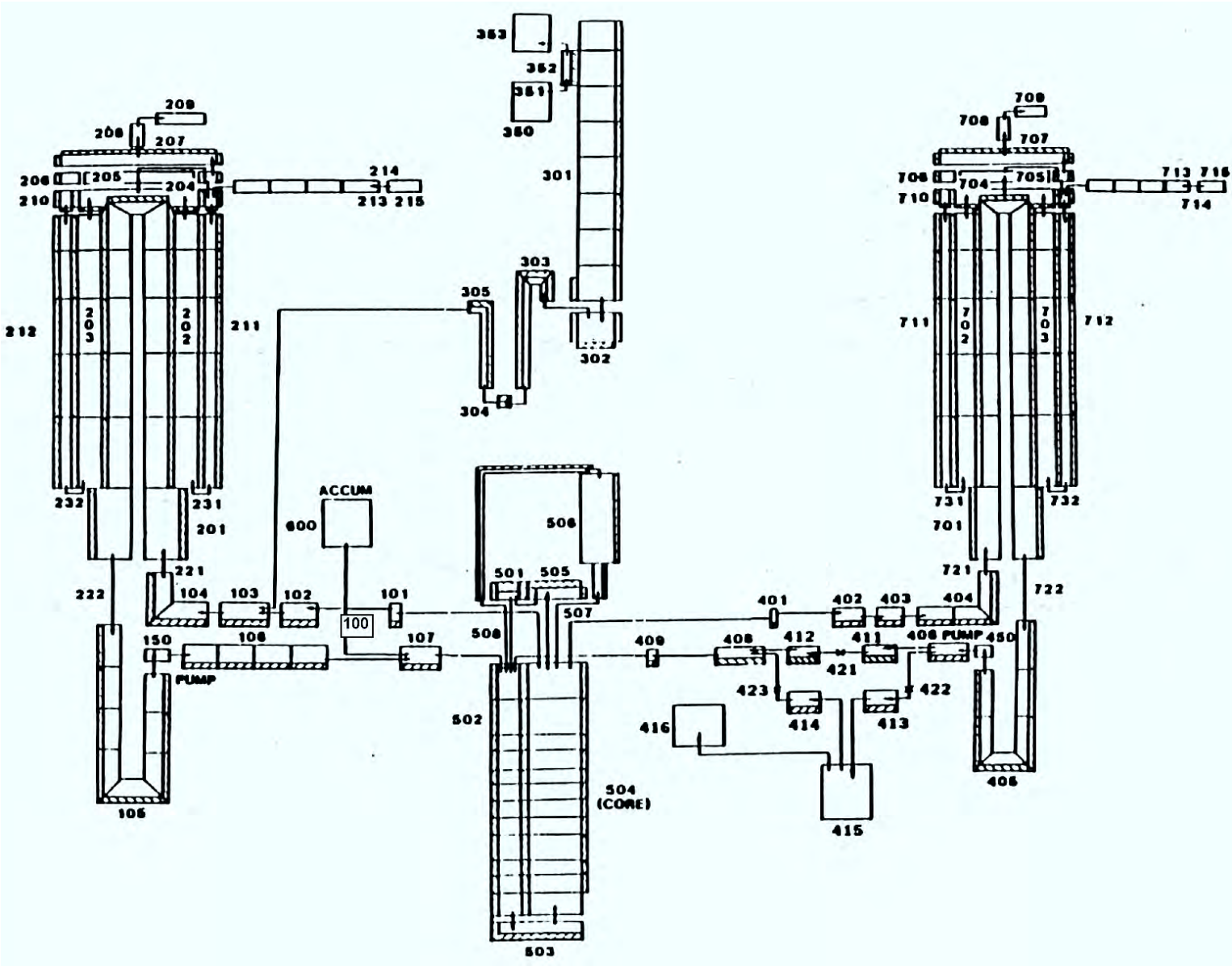
MOD 1 (1980) SBLOCAs

- reactor kinetics,
- Same 5 2-phase Eqns. stratified flows
- secondary system components
- control systems crucial to system dynamics, faster

MOD 2(1982)

- complete LWR simulation code
- 2 mass, 2 momentum, 2 energy eqns. more components, faster

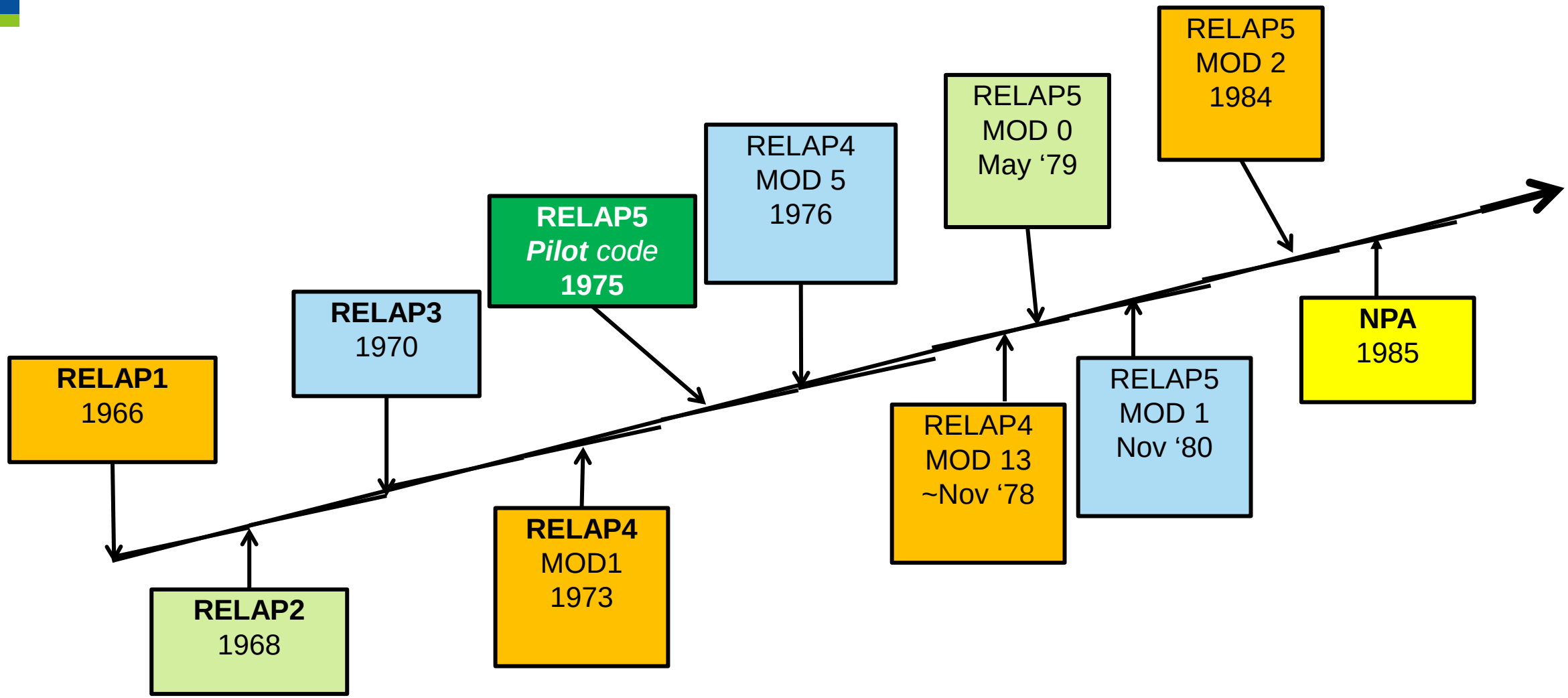
RELAP5 model of Loop Blowdown Investigations (LOBI) test facility



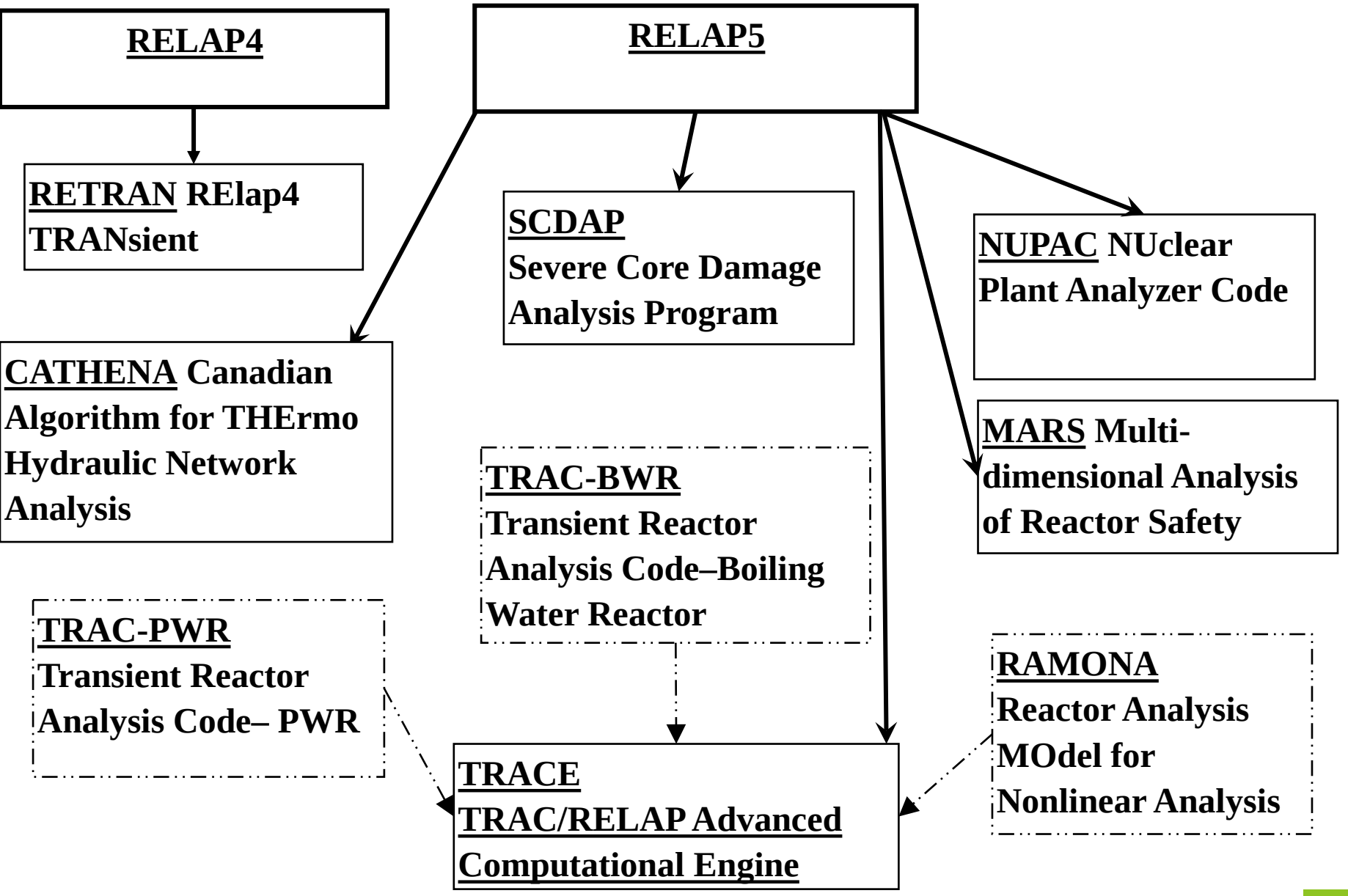
RELAP Series 1985 to 1999

- Nuclear Plant Analyzer (1985) – 2D preprocess
- MOD 2.5 (1988) much faster, vector & parallel, more components
- MOD 3.0 (1990) Fortran 77, radiation enclosures, level tracking, more components
- MOD 3.1 (1992) adapted to dozen computer systems and compilers
- MOD 3.2 (1995) much, much faster runtime (v/p)
- MOD 3.2.1.2 (1997) final INL version before break w/ NRC
- RGUI (Relap5 Graphical User Interface) (1999) post-process in 3D

RELAP Series Timeline



RELAP Series Family Tree



Long Lasting System Codes

- Minimum 25 years
- TRAC-BWR, -PWR, and RAMONA gone

Non-RELAP-related

- ATHLET (German only)
- CATHARE (French only)
- APROS (Finland)
- MELCOR

Majority of Long-Lasting System Successful Codes Descend from RELAP series

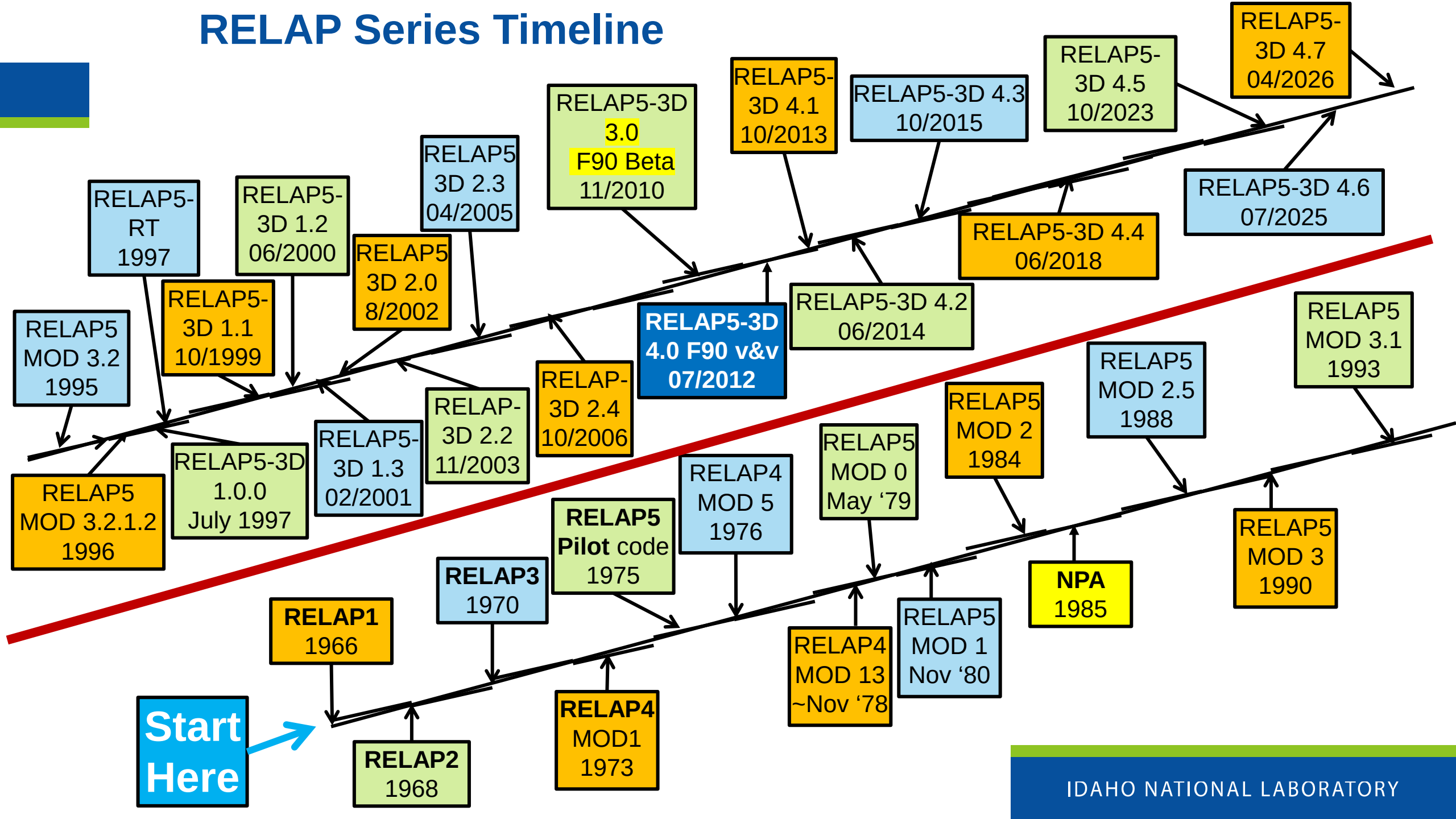
RELAP Series – RELAP5-3D (1997 - 2025)

- Names used (temporarily) included:
  - ATHENA (Adv. Them. Hyd. Energy Network Analyzer)
  - ATHENA-3D
- RELAP5-3D Versions 1.0.0 to 4.6.2
  - 3D hydro
  - 3D kinetics
  - Better data-matching correlations for more experiments & reactor types.
  - 31 fluids
  - Magnetohydrodynamics
  - Variable gravity
  - Dissolved gas model

RELAP Series – RELAP5-3D (1997 - 2025)

- RELAP5-3D Versions 1.0.0 to 4.6.2
  - Molecular diffusion
  - Faster Solvers
  - Appendix K
  - Sequential verification
  - Code coupling: Interactive variables, PVM, disk files, memory-to-memory direct
  - Training Simulator Adaptation
  - F90/ 95/ 2003/ 2008/ 2018
  - GNU & Intel Fortran

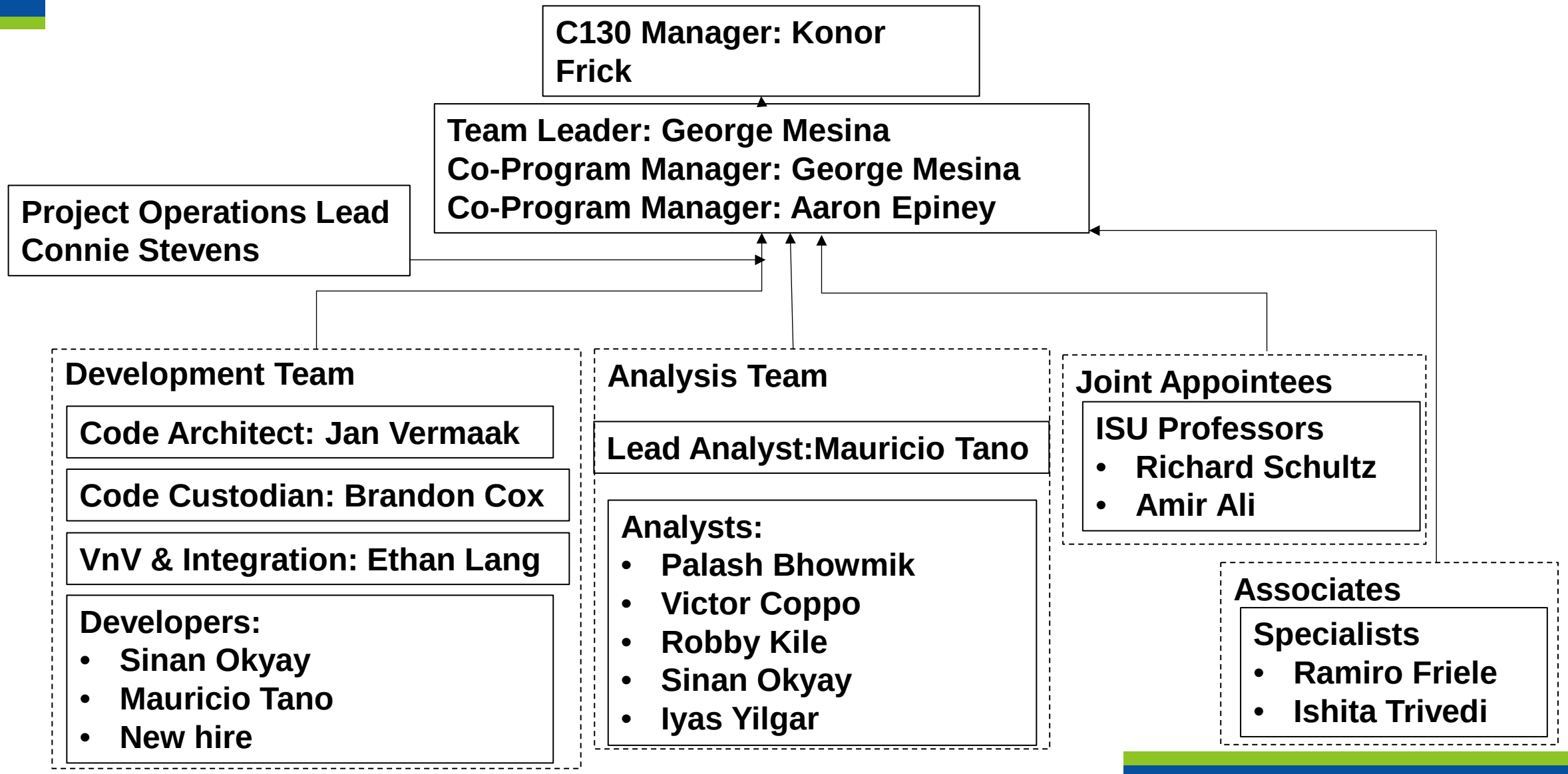
RELAP Series Timeline



Present Day – RELAP5-3D is shifting into *High Gear!*

1. Improved version control – GIT
2. Continuous Integration – CIVET
3. Improved build system – CMAKE based
4. Internal INL funding – Modernization
5. Internal INL funding – Program Development
6. Annual new code releases
7. ANS-NT Special Edition on RELAP5-3D in 2026
8. New RELAP5-3D Team

The RELAP5-3D Team Organization Chart



Fun projections for the RELAP5-3D Future

Why should RELAP be restricted to only one kind of power generation?

Practical Short Term Future: Fusion

- **R5-3D Nuclear Fusion Modeling**
  - Restore Magnetohydrodynamics
  - Fluid properties for plasmas
  - Specific physics for Tokamaks
  - Specific physics for cold fusion
  - Obtain Experimental data, VNV
  - Develop CRADAs, SPPs, etc.

- **NRC is gearing up for fusion.**
  - 2024 Advanced Nuclear for Clean Energy Act changed law concerning fusion research and allowable materials

  https://www.nrc.gov/materials/fusion
  - Regulatory Framework for Fusion Machines NRC-2023-0071

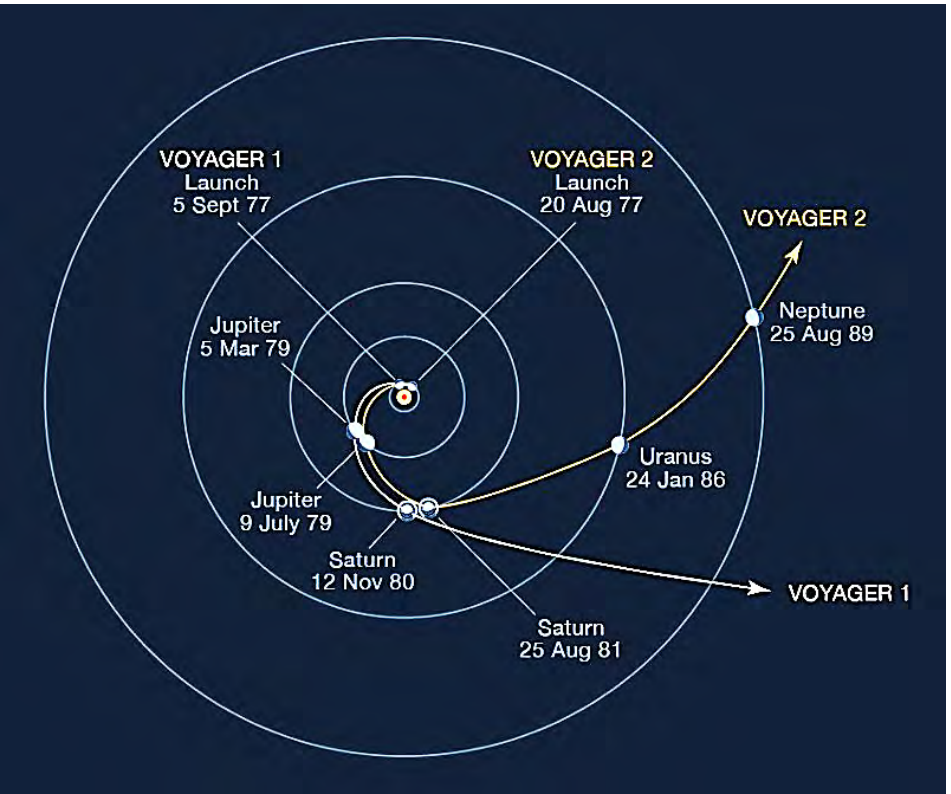
  https://www.nrc.gov/reading-rm/doc-collections/rulemaking-ruleforum/active/ruledetails?id=2185

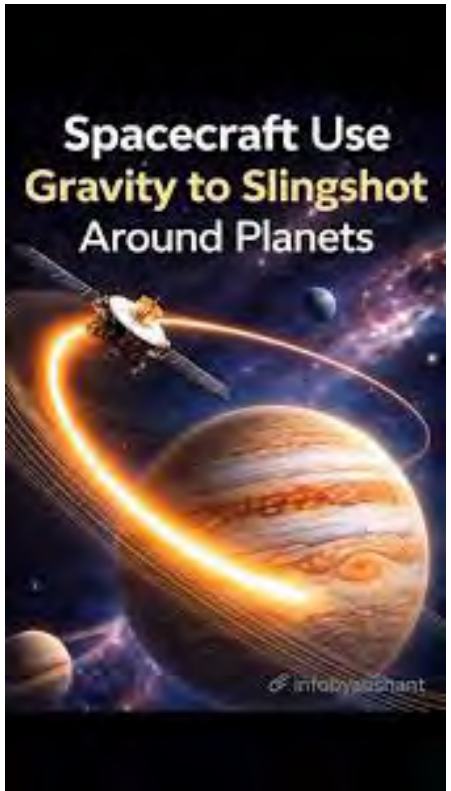
Every fusion startup that raised over $100M

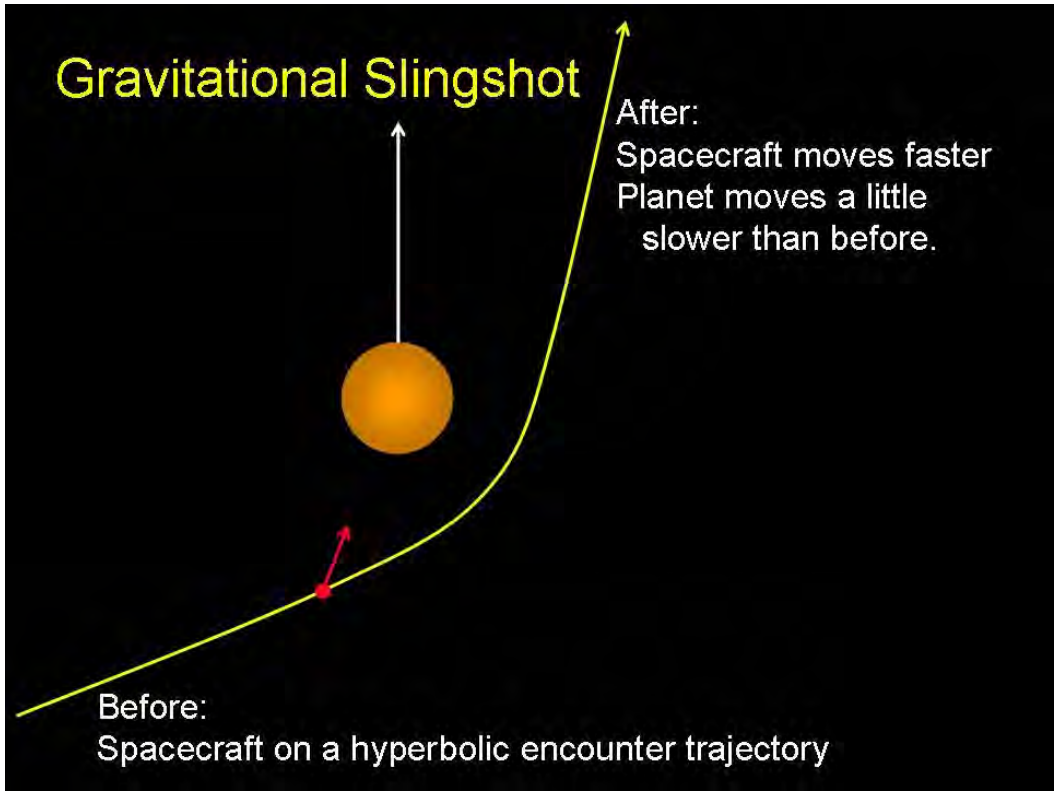
1. Commonwealth Fusion Systems (CFS) - $3B
2. TAE Technologies
3. Helion – Electricity production by 2028
4. Pacific Fusion – $900M – 2 TW / 100 nanoseconds
5. Shine Technologies – med. Isotopes, radioactive recycle
6. General Fusion – $600M (Bezos, and 4 other investors)
7. Inertia Enterprises – only fusion expt. Surpassing breakeven
8. Tokamak Energy – Compact Tokamak, less magnets, cheaper
9. Zap Energy – electric current zaps/compresses plasma, surrounding coolant heats up, uses heat exchanger
10. Type One Energy – 350 MWe mid-2030s
11. Proxima Fusion – *Stellarator* Wendelstein 7-X reactor (Germany)
12. Kyoto Fusioneering – B.O.P for fusion reactors
13. Marvel Fusion – lasers compress structures to plasma to ignite
14. First Light Fusion – Inertial confinement compress fuel pellets to ignite
15. Xcimer – Brand new design based on National Ignition Facility.

Fun Future Projection: *Relativistic RELAP*

- **A.K.A. RELAP in <u>Space</u>**
  - **Physics for relativistic speeds for interstellar missions**
    - **Reactor must handle massive acceleration and deceleration**
    - **Rapid gravity assist (Voyager or Cassini) to 25% speed of light or higher**
  - **Couple with codes for containment, I&C, navigation, biosphere, etc.**







Fun Future Projection: Distant Future

High-energy RELAP in Space

Why stop with fission and fusion?

- **Models for generation of antimatter**
  - **Physics of antimatter**
  - **Physics of anti-matter generation**
- **Matter-antimatter Interaction**
  - **Physics of matter-antimatter annihilation**
  - **Physics of conversion to usable energy forms**
- **Physics to model such Power Generation**
- **Space: Model high energy Warp drive**
  - **Does not violate speed of light**
  - **Alcubierre Metric Equation & drive (1994**
  - **Natario drive (2001)**
- ***For RELAP, the sky's NOT the limit!***