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A History of RELAP Computer Codes

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The RELAP5-3D (Reactor Excursion and Leak Analysis Program—Three Dimensional) code is the state-of-the art member of a series of computer programs developed at Idaho National Laboratory (INL) for modeling nuclear power plants. Originally funded by the U.S. Atomic Energy Commission [today's U.S. Nuclear Regulatory Commission (NRC)] to model small-break loss-of-coolant accidents (SB-LOCAs) for pressurized water reactors (PWRs), the modeling capability and fidelity have grown with each successive release of the software.

The earliest forerunner of RELAP5-3D, FLASH-1, used the homogeneous equilibrium model (HEM) to model the fluid flow with explicit numerics for time advancement. Computer power was severely limited in the 1960s, so FLASH-1 used three control volumes to model the system: the pressurizer volume, which connected to the hot volume, which exchanged fluid with the cold volume (see Fig. 1). The secondary side was modeled as a constant heat transfer coefficient. FLASH-1 had a choked flow model for LOCA analysis.

In 1966, INL, known then as the National Reactor Testing Station operated by Phillips Petroleum Company, put the Advanced Test Reactor into operation for testing materials and generating isotopes, and RELAPSE-1 (or RELAP1) was created. A revised version of FLASH-1 for the IBM-7040 and CDC-660 computers, RELAP1 was written in FORTRAN IV to calculate pressures, temperatures, flow, mass inventories, reactivities, and power for PWRs during a reactivity event or LOCA.

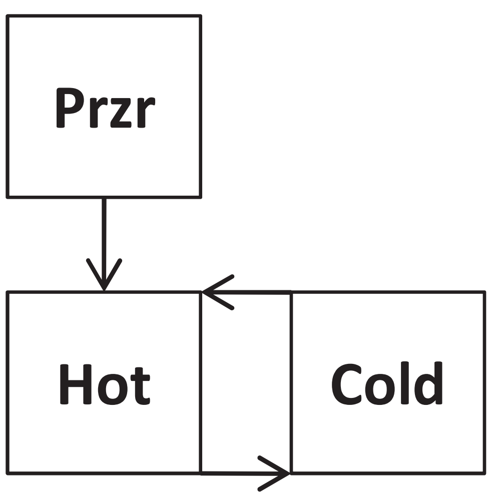

Fig. 1. FLASH-1, 1966.

RELAP1 represented the primary system as three lumped volumes with pressure-dependent coolant pumps and a flow-dependent heat exchanger (see Fig. 2). It also used point kinetics with several reactivity functions, a two-point heat transfer model with three modes, and interpolated steam tables from 1 to 3200 psia.

RELAP2 was released in 1968. It used the same three-volume system, same leak/fill capability, and same heat transfer as RELAP1; see Fig. 2. It incorporated bubble separation and other models for boiling water reactors (BWRs). Moreover, the program had improved stability, ran twice as fast as RELAP1 on the IBM and CDC computers, and was ported to other machines as well.

In 1970, RELAP3 evolved from RELAP2. It featured 20 volumes, trip logic, valves, pressure-dependent fill and leak, fuel pins/plates, a heat conduction model, and expanded heat transfer models (see Fig. 3).

Work continued on the RELAP series. In 1973, RELAP4/MOD1 was released. This code featured up to 100 control volumes, true one-dimensional (1-D) flow, a momentum flux term dP/dA and form losses, a two-fluid slip model, molecular nitrogen for the accumulator, representation of the secondary system as a flow network, and reflood heat transfer (see Fig. 4).

The heat transfer capability was expanded to include modeling of reflood and a fuel gap. The zirconium-steam metal-water reaction was incorporated. Also, implicit numerics were introduced for time advancement. Besides the ability to model SB-LOCAs for PWRs and BWRs, RELAP4/MOD1 could also model large-break LOCA (LB-LOCA) scenarios.

Eventually, there were 13 "mods" of RELAP4 written in the ANSI FORTRAN 1966 standard. In 1979, the first line of

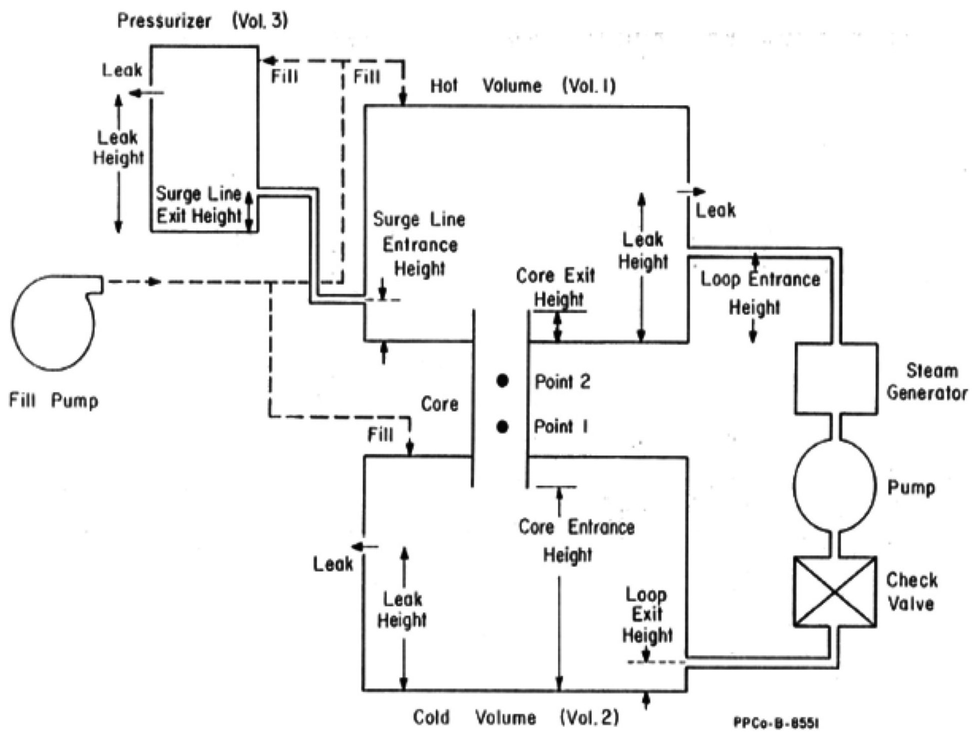

Fig. 2. RELAPSE-1 (RELAP1), 1966.

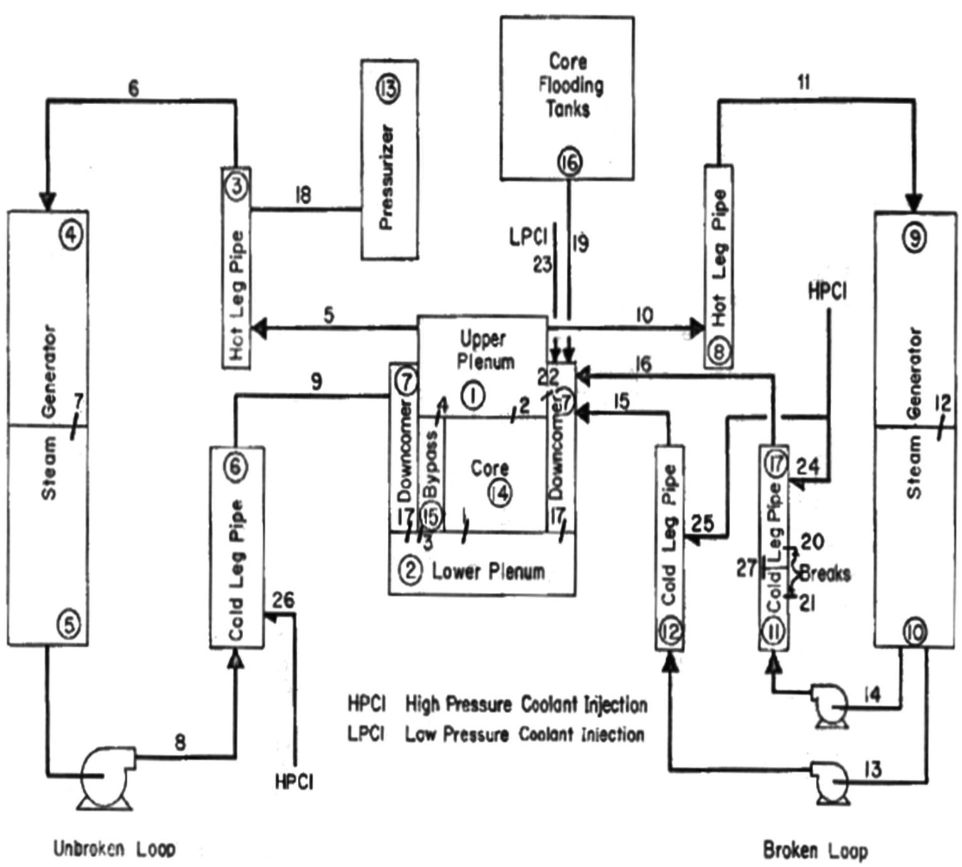

Fig. 3. RELAP3, 1970.

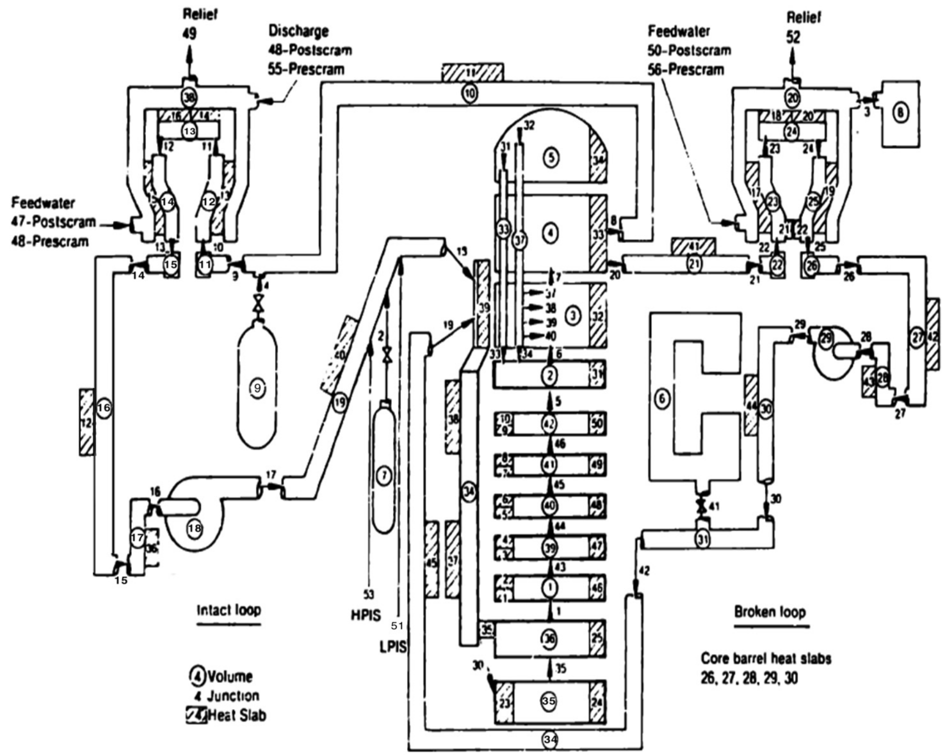

Fig. 4. RELAP4, 1973.

RELAP5 was written, and a pilot code, with no input processing, was used to demonstrate the new methodology.

The fundamental improvement difference between RELAP5 and all previous versions of RELAP was going from one-fluid HEM to a two-fluid model with a different set of governing equations for the liquid and gas phases. Other improvements were made as well. Interfacial momentum terms and mass and energy exchange terms were added. An important improvement to 1-D fluid flow was the addition of modeling cross-flow. A multichannel fuel rod model was incorporated. Many new models, correlations, trips, and controls were added. A new time-stepping scheme was put into place, using semi-implicit numerics for time advancement.

The ability to simulate SB-LOCAs and many operational transients was introduced in RELAP5 at the start with mods 0, 1, and 1.5. These had two mass equations, two momentum equations, but only one energy equation. With mod 2, the second energy equation was introduced. Other capabilities added since mod 2 include nearly implicit time advancement, a counter-current flow limiting (CCFL) model, mixture level, and thermal front tracking. Table I lists the various mods (versions) of RELAP5 and the dates they were released.

RELAP5 included many programming improvements over RELAP4, including conversion from FORTRAN 66 to FORTRAN 77, improvements to the input processing and error messages, expanded output, memory deallocation through a C-language memory removal procedure, many useful debugging features, vectorization, parallelization, and adaptation to a host of new computer platforms.

CREATION OF RELAP5-3D

Interest in RELAP5 grew with new organizations requesting that additional capabilities be incorporated into the code. These included the U.S. Department of Energy

TABLE I

RELAP5 Development Timetable

RELAP5/MOD 0	1979
RELAP5/MOD 1	1982
RELAP5/MOD 1.5	1982
RELAP5/MOD 2	1985
RELAP5/MOD 2.5	1989
RELAP5/MOD 3	1990
RELAP5/MOD 3.1	1993
RELAP5/MOD 3.2	1995

(DOE) Office of Nuclear Energy, other DOE national laboratories, and private companies such as Science Applications International Corporation (SAIC), which entered into a cooperative research and development agreement (CRADA) with INL to develop a real-time version of the program for use on operator training simulators. INL performed and directed these developments while also leading further development that it funded through long-term research initiatives (LTRIs) and laboratory-directed research and development (LDRD). By the mid-1990s, under INL sponsorship, RELAP5-3D was born. In the late 1990s, INL formed the International RELAP5 Users Group (IRUG) to organize and fund user requests for RELAP5-3D development and to license and distribute the code.

To avoid maintenance issues associated with having separate copies of the code that required identical updates, INL maintained only a single version but marked new coding with unique precompiler directives for each project so that it could be easily separated out by preprocessing tools. This was proven technology that had long been used with special coding for different computers.

The most important versions of RELAP5-3D are summarized in Table II. Note that RELAP5-3D/Ver. 0 and RELAP5/MOD 3.2 coexisted in the same source code for several years through precompiler directives. RELAP5-RT coexists in all subsequent versions for use on nuclear power simulators but is only created when clients request it. Version 1.0 introduced the RELAP5-3D Graphical User Interface (RGUI). Version 2.0 was the first adapted to the Windows operating system (while still running under Linux). RELAP5-3D/Ver. 2.4 was the final pure FORTRAN 77 code version and is still a standard of comparison; subsequent versions contain Fortran 90/95/2003 language constructs. RELAP5-3D/Ver. 3.0 was the beta-test release of the first fully Fortran 95 version, while Version 4.0 was the first release of RELAP5-3D that was validated with INL's developmental assessment process. RELAP5-3D/Ver. 4.3 is the most recent release and the most robust, verified, and validated product of the RELAP5 series.

TABLE II

RELAP5-3D Versions

RELAP5-3D/Ver. 0	1995
RELAP5-RT/Ver. 0[a]	1997
RELAP5-3D/Ver. 1.0	1997
RELAP5-3D/Ver. 2.0	2002
RELAP5-3D/Ver. 2.4[b]	2006
RELAP5-3D/Ver. 3.0	2010
RELAP5-3D/Ver. 4.0	2012
RELAP5-3D/Ver. 4.3[c]	2015

[a]Real-time (RT) coding is within RELAP5-3D.
[b]Special final FORTRAN 77 version.
[c]Most recent version.

RELAP5-3D ADVANCEMENTS

Over time, many new features and capabilities have been incorporated into RELAP5-3D that differentiate it from RELAP5/MOD3.2. Major physics improvements include

1. full three-dimensional hydrodynamics with rectangular, cylindrical, and spherical geometries
2. variable gravity to model moving systems
3. NESTLE incorporated for multidimensional neutronics with nodal kinetics
4. coupling with PHISICS for massively parallel neutron kinetics
5. one- and two-dimensional heat transfer including conduction, convection, and radiation
6. gas diffusion, radiological transport, and alternate heat conduction to fluids
7. new hydrodynamic components: ECC mixer, feedwater heater, and compressor
8. Godunov second-order-in-space boron tracking model
9. numerous working fluids; see Table III
10. numerous noncondensable gases; see Table IV.

In addition, the programming of RELAP5-3D has improved in many ways over RELAP5/MOD3.2. Rewritten in a modern language with a new data structure, the code runs faster and is much easier to read, modify, and maintain. One of the most important upgrades to RELAP5-3D is the ability to couple with other codes to solve complex problems through domain decomposition via R5EXEC. Some features include

1. code coupling via the R5EXEC program
2. synchronized integer-based time-step control
3. decoupled thermal-hydraulic and kinetic time steps
4. Fortran 95

TABLE III

Alternate RELAP5-3D Fluids

Water, light (H_2O)	Lead (Pb)
Water, 1984 light (H_2ON)	Lithium (Li)
Water, heavy (D_2O)	Lithium-lead (LiPb)
Water, 1995 light (H_2O95)	Molten salt 1 [LiF-BeF_2 (FLiBe)]
Ammonia (NH_3)	Molten salt 2 ($NaBF_4$-NaF)
Bismuth-lead (BiPb)	Molten salt 3 [LiF-NaF-KF (FLiNaK)]
Blood	Molten salt 4 (NaF-ZrF_4)
Carbon dioxide (CO_2)	Nitrogen (N_2)
DowThermA ([$C_{12}H_{10}O$]x.[$C_{12}H_{10}$]y)	Potassium (K)
Glycerol ($HOCH_2CHOHCH_2OH$)	R134A (CH_2FCF_3)
Helium (He)	Sodium (Na)
Helium, new (HeN)	Sodium-potassium (NaK)
Helium, new–Xenon, new (HeNXeN)	Vertrel ($C_5H_2F_{10}$)
Hydrogen (H_2)	Xenon, new (XeN)

5. strongly modular through structured programming
6. OpenMP parallel directives
7. fast hydrodynamic linear equation solvers for larger problems: BPLU and PGMRES
8. machine-independent binary fluid and plot files
9. RELAP5-3D Graphical User Interface.

TESTING, VERIFICATION, AND VALIDATION

Idaho National Laboratory applies very complete testing, verification, and validation before the release of every RELAP5-3D product. Each internal and externally released code version is tested on the standard installation test suites comprised of over 200 test cases and growing with addition of new features. For external releases, over 2000 more test cases are run and checked.

TABLE IV

Noncondensable RELAP5-3D Fluids

Air	Hydrogen (H_2)
Argon (Ar)	Krypton, SF (Kr)
Carbon dioxide (CO_2)	Oxygen (O_2)
Carbon monoxide (CO)	Nitrogen (N_2)
Helium (He)	Xenon (Xe)

Each internal and external version is also tested with the code's newly created and built-in verification capability, which identifies any changes in calculations between code versions to 32 decimal places on any of 195 test problems in the verification test suite. The test suite itself exercises over 190 different code features. It also verifies that the code restart and backup capability work correctly.

Code developmental assessment provides validation for nuclear power plant applications. Each external code release is run through a battery of 54 test cases and compared against data. The collection of input models is comprised of phenomenological tests, separate effects tests, and integral effects tests. Volume 3 of the RELAP5-3D manual records the results of these tests with plots of the code calculations against data and assessment of the comparison.

APPLICATIONS OF RELAP5-3D

Initially designed for analyzing SB-LOCAs for PWRs, the range of RELAP computer codes has expanded to include LB-LOCAs, operational transients, BWRs, test reactors, molten salt reactors, liquid metal reactors, high-temperature gas-cooled reactors, and supercritical fluid reactors. Most recently, RELAP5-3D is being applied to model small modular reactors and a traveling wave reactor. RELAP5/RT is installed in nuclear plant operator training simulators at many sites around the world.

Apart from nuclear power, RELAP5-3D is used for numerous other applications involving piping flow, from commercial steam flow, to cryogenic storage and delivery systems, to flow of coolant through rocket engines, and many more. RELAP5-3D is a truly versatile program.