Using RELAP5-3D to Design a Small, Factory-Built Reactor

Glenn Roth
Idaho National Engineering and Environmental Laboratory
P. O. Box 1625
Idaho Falls, ID 83415-3880, USA
Phone: 208-526-7226, Fax: 208-526-6971
Email: glenn.roth@usu.edu

Abstract

A novel 3rd generation nuclear reactor was conceived to lower the overall costs of construction and maintenance. The transportable design uses no pumps and is compact so that it can be built in a factory and sent by rail or motor-freight to the required location. RELAP5-3D, an advanced version of RELAP5, was used in the design process to verify functionality and identify configuration problems.

Keywords Reactor design, RELAP5, RELAP5-3D, Thermal-hydraulics

1 Introduction

RELAP5 has traditionally been used as a reactor transient analysis tool. It is ideal for analyzing Small-Break Loss of Coolant Accidents (SBLOCAs) and other reactor transients for safety considerations. The U.S. Department of Energy (DOE) has funded a Nuclear Energy Research Initiative (NERI) project at Idaho National Engineering and Environmental Laboratory (INEEL) in collaboration with NEXANT and Oregon State University to research the cost-effectiveness of smaller reactor designs. RELAP5-3D was used as a design tool to analyze the effectiveness of a naturally circulating primary coolant loop in a small reactor design.

The first step of the design process considered an 850 MW reactor design with four loops and four steam generators. The steam generators were oriented horizontally, so the VVER 440 was used as a model to scale from for the steam generator surface area. The reactor and containment were not transportable. The containment included water tanks to provide three days of decay-heat cooling. Extra convection cooling was provided to the containment by additional supplies of water around the outside of the containment. This entire system was modeled using RELAP5 to check the natural circulation properties. Though this design worked when considering the thermo-hydraulic requirements, it did not turn out to be a cost effective alternative to a full-sized reactor. By decreasing the size, it was hoped that the reactor cost could be reduced, thus producing more competitive electricity prices while maintaining a high level of safety and reliability.

Further design and development analysis indicated that a smaller reactor design, transportable by rail car or truck, might be more cost-efficient. The lower costs are the result of the assumed factory-style construction that would be possible for a transportable reactor. Costs are further lowered by the refueling versatility offered by an array of smaller-powered reactors compared to a single high-powered one. Refueling schedules could be arranged to shut down one reactor at a time for refueling. In this way, the majority of the power production is always available. Removing one reactor from the grid at a time for refueling saves the expensive shutdown costs in a larger reactor that must be completely removed from the grid. Finally, the elimination of expensive pumps in a naturally-circulating system lowers construction and maintenance costs still further.

2 Reactor Systems Development

The current version of this reactor design is called the Multi-Application Small Light Water Reactor (MASLWR). This reactor was designed to fit inside a single containment and be transported to an acceptable site by rail or truck. The transportability requirement imposed several size restrictions to the construction of the containment. The reactor containment can not exceed 4 m in diameter and is limited to 20 m in length.

All reactor coolant system pumps were eliminated, simplifying the construction as well as lowering construction and maintenance costs. To maximize natural circulation for reactor cooling, the elevation difference between the cold center and hot center must be maximized. The steam generator and other reactor components were therefore required to be as short as possible to give the longest possible segment of cold leg above the core. RELAP5-3D proved to be very useful in determining the viability of various designs and configurations.

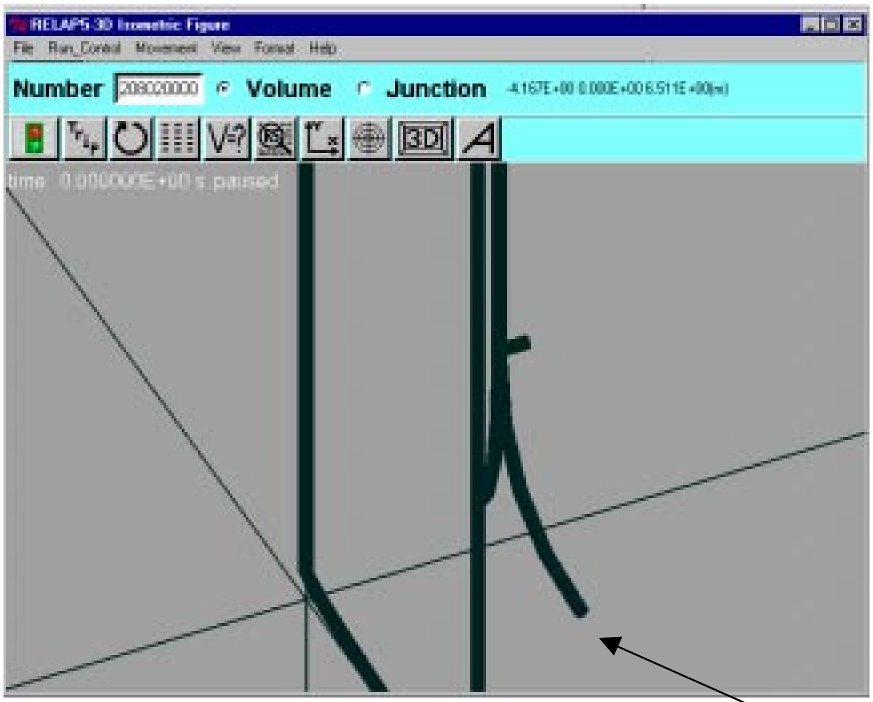
2.1 Steam Generator Development Using RELAP5-3D

The compact size requires that there be only one coolant loop and steam generator and a core of reduced size. The steam generator concept is a vertical once-through design. The tubes are twisted into a helical configuration to shorten the overall height. In one design, the steam generator was 7.407 m tall and required just a little over 1 complete rotation for the tubes on the descent. The length of the cold leg was 5.67 m for this particular design. All the available height in the containment was utilized when calculating the length of the cold leg. RELAP5-3D analyses showed that the reactor configured in this manner functioned as desired and expected. The length of the steam generator tubes was then reduced by 25% to further determine the reactor size constraints. RELAP5-3D showed that even with the reduced length, the heat transfer in the steam generator was sufficient to cool the reactor. The steam generator was therefore fixed at 5.556 m tall, with a tube rotation of approximately 300 degrees. The cold leg length for the reactor was then 7.52 m. Table 1 in Appendix A shows this development process. The 850 MW reactor data is shown, along with the data for the two MASLWR designs at 100 MW (thermal) each.

2.2 Power Output Analysis Using RELAP5-3D

The input deck was run several other times, at varying powers. Initially, the reactor design apparently functioned well when run at the desired operating point of 100 MW and 8.2 MPa. No voiding was apparent in the primary loop at powers as high as 130 MW. At 140 MW, however, the void fraction fluctuated between .074 and .003. This indicated undesirable boiling in the primary loop. Further analysis later showed abnormal fluctuations in the pressure drops across the steam generator and reactor core at 8.2 MPa and 100 MW power. Void fraction plots of the inlets and outlets for these sections showed small spikes, on the order of 3e-6. Such small spikes were not detected in initial analyses. Voiding was present, even though the fluid temperature was approximately 20 degrees Kelvin subcooled throughout the loop.

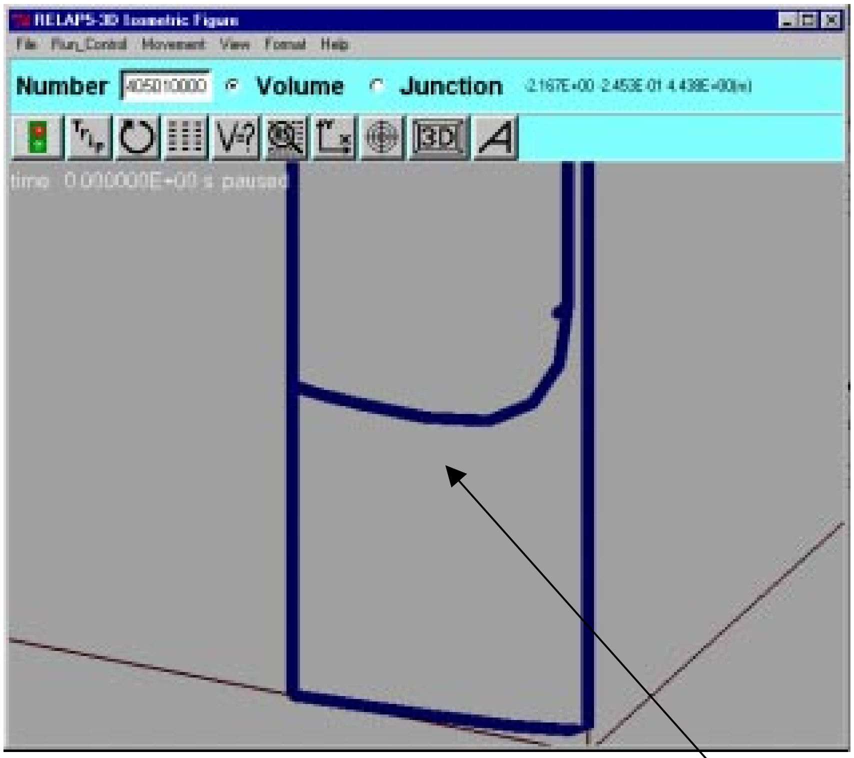
Eventual analysis proved that the flow rate was not sufficient to keep a thin film from boiling around the rods. The void condensed immediately upon leaving the vessel, so it was not detected in the other sections of the reactor. The voiding, though small, needed to be avoided. The pressure was increased to 9.5 MPa, and the voiding disappeared. Further runs showed that even at powers up to 120 MW the voids were eliminated. Table 2 in Appendix A shows the steady-state reactor data for the 8.2 MPa case at 100 MW and the 9.5 MPa case at varying power levels.



Number 208020000 ● Volume ○ Junction -4.167E+00 0.000E+00 6.511E+00(m)

time 0.000000E+00 s paused

Figure 1 Disconnected Surge Line



Number 405010000 ● Volume ○ Junction -2.167E+00 -2.453E-01 4.438E+00(m)

time 0.000000E+00 s paused

Figure 2 Correctly Attached Surge Line

2.3 RELAP5-3D Isometric Sketch as a Control

The RELAP5-3D Graphical User Interface (GUI) was also useful in determining misplaced connections in the input deck. The pressurizer for the MASLWR model was borrowed from the first RELAP input deck for the 850 MW reactor design. Figure 1 shows the end of the pressurizer surge line somewhere off in space, indicated by the arrow. The deck was consequently checked and corrected to show the isometric image shown in Figure 2. In this figure, the surge line is attached correctly, as shown by the arrow. This problem would not have been so obvious without the isometric drawing produced by the GUI. Repositioning the surge line point of attachment did not change the results significantly, since the pressurizer in this model only establishes initial conditions.

3 Current Reactor Design Parameters

The latest MASLWR design is shown in Figure 3. It fits in a containment 4 m in diameter and 20.2 m long.

3.1 Core Design

The core uses 24 fuel assemblies, each one with typical rod and spacer positions. The core is 1.2 m tall and 1.4 m in diameter. The typical PWR ratio of core height to diameter is one to one, so this core is well scaled. Allowance was made for 0.305 m of shielding around the core. Allowing for shielding, the reactor vessel is 2.7 m in diameter.

3.2 Steam Generator Design

The steam generator diameter was limited to 2.7 m, the same as the core, to allow space for the pressurizer and accumulators. The angled portion of the hot and cold legs places the steam generator to one side. The location of the accumulators and pressurizer with respect to the steam generator can be seen in the top view cross section shown in Figure 4. The steam generator is a 5.56 m (tall), once-through design. The tubes are rotated through 300 degrees in a helical fashion to shorten the overall height. The average tube length is 6.9 m.

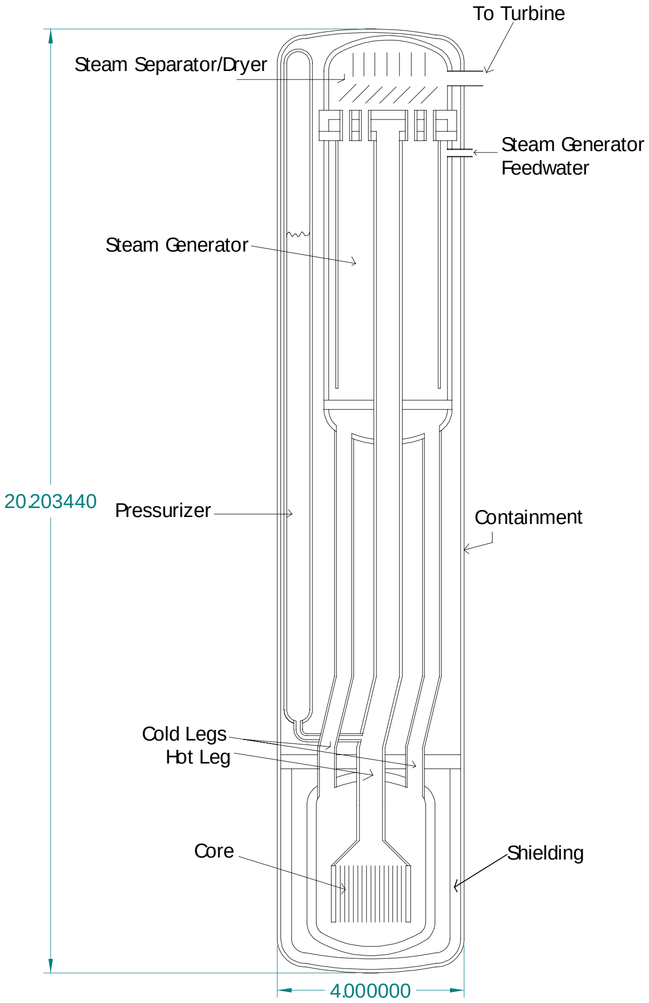


Figure 3 Current MASLWR Design

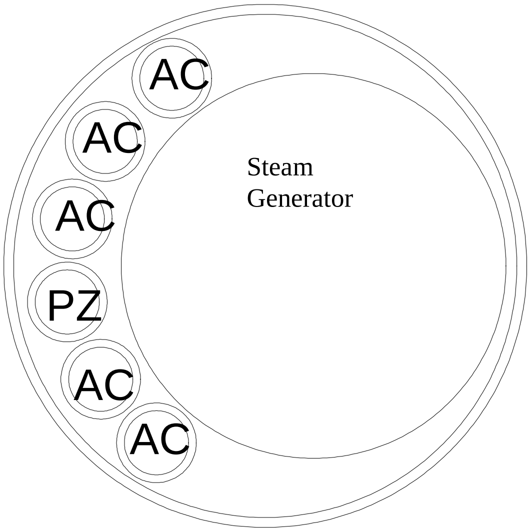


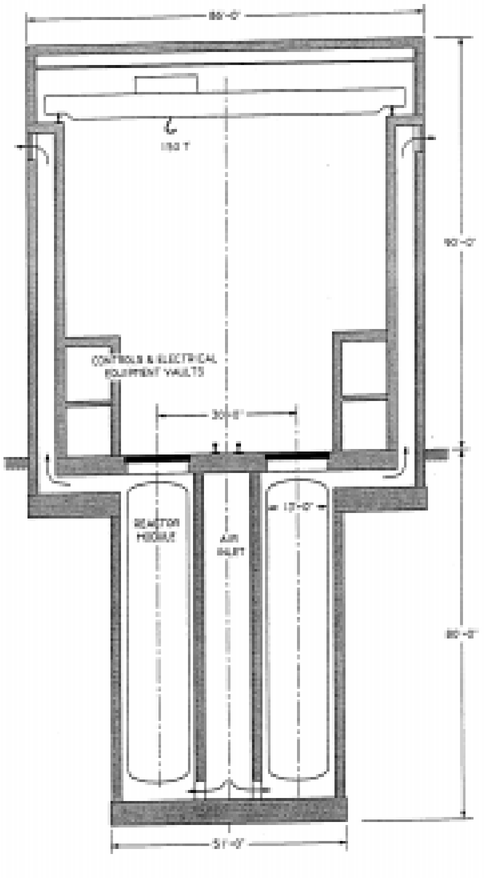
Figure 4 Containment Configuration (Top)

3.3 Accumulators

Five accumulators will be used, each having a capacity of 1.87 m^3 of water, for a total of 9.35 m^3. Six cubic meters are required to cover the core. The available volume in the accumulators will flood the core 1 1/2 times in the event of an accident. The available emergency water is not sufficient to cool the core during the phase of decay heating after an incident. Methods are being tested to cool the entire containment using airflow around the outside. Water may be used in place of air if it proves insufficient to cool the containment alone.

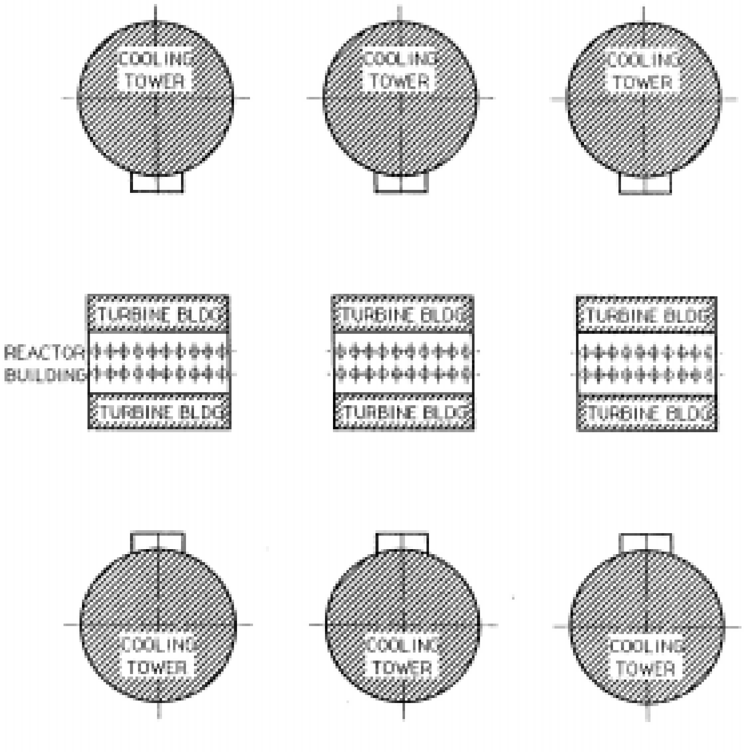
3.4 Plant Configuration

These reactors will be grouped together to increase the power output. Each reactor is capable of producing roughly 20 MW of electric power. A configuration of 30 reactors, each with a turbine and generator, would produce 600 MW of electricity. These reactors could be housed together in buildings designed to provide the appropriate air cooling in the event of an accident. A potential building interior is shown in Figure 5. Figure 6 shows a possible building layout at a site.



BNI – MASLWR/SMALL REACTOR PACKAGE
REACTOR BUILDING ARRANGEMENT

Figure 5 Building Interior Configuration



BNI – MASLWR/SMALL REACTOR PACKAGE
POWER BLOCKS ARRANGEMENT

Figure 6 Possible Building Configuration

4 Conclusions

A naturally-circulating reactor that will be transportable by rail or truck has been designed. Computer models have been tested, showing that natural circulation works for the MASLWR design. This reactor is safe at the required power levels and above. Current technology can be used as-is or modified easily to fit the requirements of this reactor design, reducing the overall costs. The lack of expensive and complex systems reduces the maintenance costs as well, yielding an overall cheaper reactor. RELAP5-3D has proved invaluable as a design tool in this process.

References

RELAP5 Code Development Team, "RELAP5/MOD3 Code Manual," NUREG/CR-5535, INEL-95/0174, Aug, 1995.

Mesina, G. and Galbraith, J., "RGUI 1.0, New Graphical User Interface for RELAP5-3D," proceedings of the 7th Intl. Conf. On Nuc. Engr. (ICONE-7), Tokyo, Japan, Apr 19-23, 1999.

Karkhov, A., "Methodology for Evaluations of the Overall Next Generation Systems Economics," proceedings of 8th Intl. Conf. On Nuc. Engr. (ICONE-8), Baltimore, MD, Apr 2-6, 2000.

O'Connell, J., Turk, R., and Matteson, D., "Report on NERI Research Project to Reduce Capital Costs and Plant Construction Time for Future Nuclear Power Plants," proceedings of 8th Intl. Conf. On Nuc. Engr. (ICONE-8), Baltimore, MD, Apr 2-6, 2000.

Bertel, E. and Hudson, C., "Can Nuclear Power Stay Competitive?," NEA Newsletter, 1998, Vol. 16, no. 1, pp 4-9.

Knief R., "Nuclear Engineering: Theory and Technology of Commerical Nuclear Power," Hemisphere Publishing Corporation, 1992.

Appendix A

Table 1 MASLWR Design Parameter Progression Table

	850 MW		100 MW Case 1		100 MW Case 2	
	SG scaled from VVER-440		SG scaled from VVER-440		SG Surface Area Reduced 25%	
No. of Steam Generators	4		1		1	
No. of 17x17 Fuel Assys	109		24		24	
Core Heated Length	3.31 m	10.86 ft	0.9 m	2.95 ft	0.9 m	2.95 ft
Core Flow Area	3.366 m^2	36.23 ft^2	0.9 m^2	3.05 ft^2	0.9 m^2	3.05 ft^2
SG Tube Active Height	1.032 m	3.38 ft	7.41 m	24.3 ft	5.56 m	18.24 ft
SG Tube Active Length	14.6 m	47.9 ft	9.26 m	30.4 ft	6.94 m	22.77 ft
SG Tube Spiral	N/A		1.1 rotations		0.83 rotations	
SG Tube Outer Surface Area	3013 m^2	32,435 ft^2	1095 m^2	11,786 ft^2	820 m^2	8,826 ft^2
Number of Tubes	4106		2352		2352	
Tube OD	.016 m	.63 in	0.016 m	0.63 in.	0.016 m	0.63 in.
Tube ID	.0132 m	.52 in	0.0132 m	0.52 in.	0.0132 m	0.52 in.
Distance between SG and Reactor Thermal Centers	33 m	108.3 ft	12.11 m		13.04 m	
Power	850 MW		100 MW		100 MW	
Steam header Pressure	5.4 MPa	783 psia	1.52 Mpa	220 psia	1.52 Mpa	220 psia
Secondary Mass Flow Rate	106.6 kg/s	234.5 lb/s	45 kg/s	99 lb/s	45 kg/s	99 lb/s
RCS Pressure	16.5 MPa	2,393 psia	8.20 Mpa	1190 psia	8.20 Mpa	1190 psia
RCS Sat Temperature	623.2 K	662.1 F	570 K	556.3 F	570 K	556.3 F
Hot Leg Temperature	615.5 K	648.2 F	552.6 K	535.0 F	551.3 K	532.7 F
Cold Leg Temperature	544.8 K	521.0 F	482.1 K	408.1 F	482.0 K	407.9 F
Loop Mass Flow Rate	2,000 kg/s	4,400 kg/s	295.4 kg/s	649.9 lb/s	301.2 kg/s	662.6 lb/s

* Per Steam Generator

Table 2 Current MASLWR Design Data Table

Power	100 MW		110 MW		120 MW		100 MW	
Steam header Pressure	1.52 MPa	220 psia	1.52 MPa	220.5 psia	1.52 MPa	220.475 psia	1.52 Mpa	220 psia
Secondary Mass Flow Rate	45.13 kg/s	99.5 lb/s	50.349 kg/s	111 lb/s	53.75 kg/s	118.5 lb/s	45 kg/s	99 lb/s
RCS Pressure	9.5 MPa	1378 psia	9.5 MPa	1378 psia	9.5 MPa	1378 psia	8.20 Mpa	1190 psia
Core Pressure drop	100 Pa	.015 psia	125 Pa	.018 psia	150 Pa	.022 psia	100 Pa	.015 psia
SG Pressure drop	-41725 Pa	-6.05 psia	-41070 Pa	-5.96 psia	-40415 Pa	-5.86 psia	-41640 Pa	-6.04 psia
RCS Sat Temperature	580.9 K	586.02 F	580.9 K	586.02 F	580.9 K	586.02 F	570 K	556.3 F
Subcooled margin	29.33 K	52.8 F	24.67 K	44.4 F	20.22 K	36.4 F	19.19 K	34.55 F
Hot Leg Temperature	551.62 K	533.25 F	556.29 K	541.65 F	560.7 K	549.6 F	551.3 K	532.7 F
Cold Leg Temperature	482.04 K	408.0 F	482.87 K	409.5 F	483.7 K	411.0 F	482.0 K	407.9 F
Core Mass Flow Rate	300.73 kg/s	663 lb/s	311.3 kg/s	686.25 lb/s	321.5 kg/s	708.85 lb/s	301.2 kg/s	662.6 lb/s