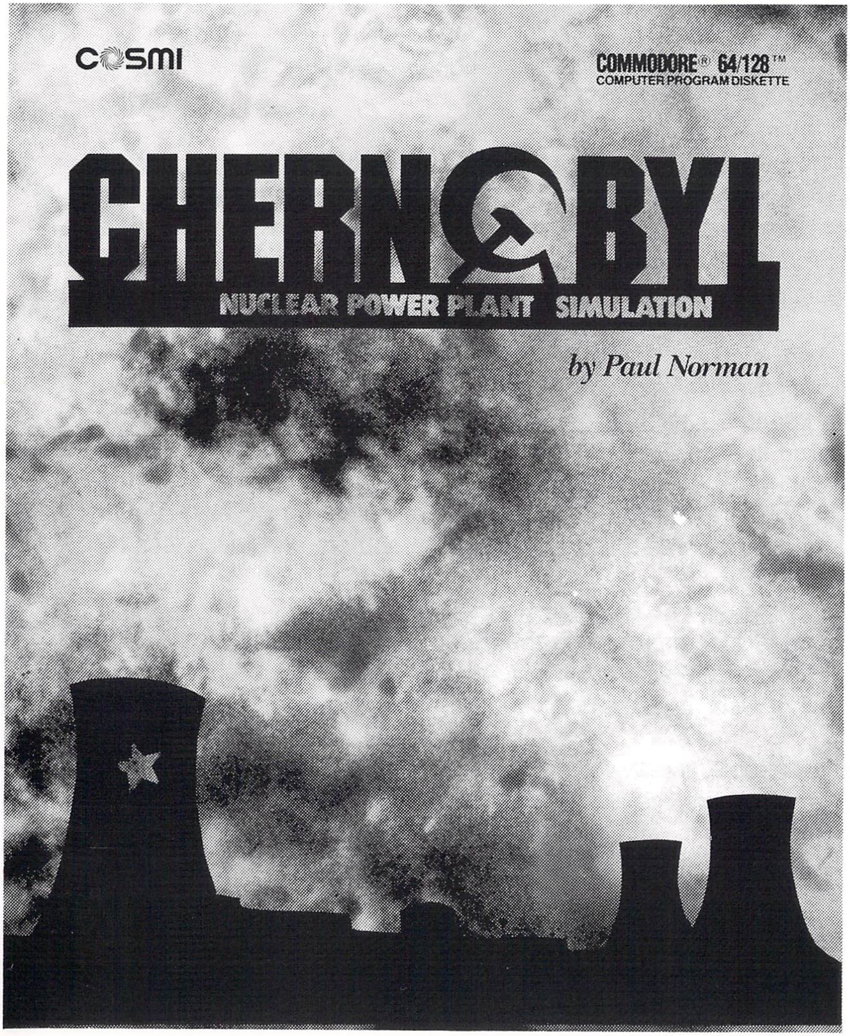
COMMODORE® 64/128™



COSMI

CD64-210

Chernobyl is an authentic computer simulation by Paul Norman, author of **Super Huey** Helicopter Flight Simulator series, and **Defcon 5**. In **Chernobyl,** the player's computer simulates being the central control room computer of a nuclear power plant. How you respond to each new crisis and in what sequence may determine the safety of millions of people, not to mention thousands of square miles of real estate! Remember, the reactor wants to live but its automatic defense mechanisms may be erroneous. A real-life dramatic challenge of stupendous proportions.

Commodore® 64/128™ are registered trademarks
of Commodore Business Machines, Inc.

CHERNOBYL

Following the accidents at Three Mile Island and Chernobyl nuclear power plants, the industry, the regulatory bodies and the public were obliged to take a new and critical look at the practicalities, in light of safety considerations, of nuclear reactors as viable energy sources. The public was very concerned. The nuclear industry found the events to be an excellent opportunity to launch a new campaign emphasizing safety.

It is now ten years later and nuclear plants have increased sixfold. While the essential elements of nuclear engineering have remained relatively unchanged, two factors have created one significant operation innovation. One factor being the exponential rise in computer technology, accompanied by an inversely proportionate fall in cost. The other factor is the decline in the average national level of literacy. These considerations, together with the acknowledgement that most nuclear incidents are the result of human error, have led to the obvious development of a plant operated much more by computers and much less by human beings.

On the surface, this seems a logical approach. In the event of accidents, computers can respond to crises in dispassionate and predictable ways, and even during normal operation, less personnel means less risk of radiation hazards to people.

One observation by technical people, usually voiced over a beer rather a conference table, is that computers, and computer programs, are also presided over by human beings.

NUCLEAR REACTOR POWER GENERATION

The following is a discussion of the theory and design of a nuclear power plant. The actual operating instructions are available on the computer by requesting the MANUAL.

A Pressurized Water Reactor consists of the reactor vessel in which the Uranium Oxide fuel in the form of thousands of thin rods are vertically grouped to compose the Core. The fuel rods are clad in zirconium tubes. Above the core is the Control Rod Drive Mechanism that controls the nuclear reaction by inserting or withdrawing rods of neutron absorbing material. A coolant, in this case water, is pumped through the core. A great deal of heat is produced by the reaction and this heat is transferred to the coolant passing through. The water in the reactor vessel is under very high pressure so that it will not boil. The superheated water passes out of the vessel into large boilers where the heat is transferred to unpressurized water that boils and produces steam. This heat exchange cools the Reactor water so that it can return to the core and repeat the process. The steam generated in the boilers is sent by pipes to the Turbine building where it is used to drive the turbine which turns the generators that produce electricity. The steam is then collected in condensers to liquify and be returned to the boilers. The reactor coolant system is closed from the steam generators because the water carries the radioactivity as well as the heat from the core. The steam generating system is also closed under normal operating conditions to prevent radiation leakage in the event of a pipe rupture. The reactor vessel and associated equipment (see Figure 1.) is housed in a large reinforced-concrete building called the Containment. This is the last barrier to prevent leakage to the atmosphere.

The safety systems for the reactor consist of the Emergency Control Rod system, which automatically drops all the rods into the core to significantly reduce the reactivity (a term that refers to the level or strength or amount of nuclear reactions occurring in the core). The automatic insertion of the Control Rods in an emergency is known as a SCRAM. The Emergency Core Cooling System (ECCS) is another automatic system that pumps new coolant into the reactor coolant system under high or low pressure depending on the nature of the emergency. The ECCS also includes other backup and ancillary equipment all dedicated to the same purpose; keeping the water and pressure levels in the reactor constant. Additional safety systems include a series of safety and relief valves that moderate levels at any point in the coolant or steam lines as well as the main vessels, heaters and sprayers located in many places to condense steam, regulate pressure, reduce radioactivity outside the system and so on. All safety systems are monitored by banks of indicators, gauges, annunciators and alarms all presided over by the main computer.

The computer regulates the entire power generation system up to and including the electrical output to the main grid. The plant operator monitors the computer to ensure that it is operating according to program and that actions taken produce the predicted results.

The need for a human operator is based on the fact that through a long series of nuclear power plant accidents of various degrees of severity, few as publicized as TMI and Chernobyl, the data collected maintains an uncertainty factor that cannot be programmed out of computer-moderated systems. Although in the majority of cases the escalation of the emergency was caused by operators making the wrong assumptions based on rapidly occurring events often unrelated or even contradictory but together constituting the actual picture of the condition of the system, there still remained that percentage of incidents where all the correct steps were taken and yet the theoretical result did not follow. In some instances this was because of a freak electrical anomaly that caused erroneous indications making true analysis impossible. These cases are where the only resort lies in illogical, unscientific and inimitable human imagination.

If a computer assesses all the pertinent data and takes all the programmed actions necessary and the result is not as predicted then two possible reactions occur. First, it may compute that all requirements have been satisfied and therefore no further action is necessary, in which case it will sit there and do nothing while the emergency grows, or, on the other hand, the computer may react moment to moment as if each event is a new and different incident to be dealt with based only on the immediate data. This could work in some circumstances but it could also be disastrous as it fails to appreciate the interrelated nature of the events.

This will be discussed further in the section on accident possibilities but for now the conclusion can be drawn that the computer is in effect just another automatic safety and control system that of course still requires a human operator to manage the machines.

REACTIVITY

The nuclear reaction that produces heat in the core is caused by atomic fission. Sub-atomic particles called neutrons collide with the atoms of the Uranium fuel causing them to break apart. The energy released by the collision is in the form of heat. The fission products, the particles from the struck atom, include more neutrons which in turn can cause subsequent collisions. While the original neutron is absorbed by the fission, an average of three neutrons is released so that a chain reaction is produced whereby neutrons and collisions increase by a power of three; the first collision produces three neutrons that cause three collisions which produce nine neutrons, then twenty-seven neutrons and so on...3x3x3x3x3...3^n. The time between collisions is approximately 309 millionths of a second and therefore a runaway nuclear chain reaction happens very quickly if no controlling factors are present.

The first natural restraint to fission is that less than 1% of the fuel is fissionable material, in fact, in order to produce the necessary reactivity, the Uranium must be enriched. The next factor is the control rods that are made of neutron absorbent material. For every neutron that is absorbed a collision is prevented. Additionally, the water coolant in the reactor contains Boron which is also a neutron absorber. All these factors make the fissionable material so diluted that no useable reaction could take place without the presence of water. The reason is that the water molecules slow down the neutrons and slower neutrons are more effective in collision.

A controlled rate of fission is maintained by these factors and by the mechanical movement of the Control rods. A reactor in this controlled state is called critical. A critical reactor is producing some positive level of reactivity. A sub-critical state means the fission rate is decreasing which is negative reactivity. The reactivity translates as the power level of the reactor that also means the amount of heat that is produced. This power level is normally controlled by the careful and measured movements in or out of the core of the control rods.

Various core conditions and phenomena contribute to the reactivity of the system. It is the operator's job to regulate the required changes in reactivity so that power is produced in a precise and controlled manner. It is the job of the computer to monitor the system so that it continues to function in a safe and efficient way.

THE MONITOR SYSTEM

The first line of indicators are the Annunciators, a labelled warning light for every controllable feature of the reactor and associated power-generating systems as well as the safety systems and electrical components. The Annunciators will show any change or malfunction in any part of the mechanism although in a somewhat general way. For example, an annunciator may light to show low pressure in the reactor or high temperature or radiation somewhere but it will not tell how low or how high. The Annunciators are useful for at-a-glance analysis when something is not working right.

For specific readings of temperature, pressure, radiation and so forth, the Gauges are required. A whole series of gauges is provided to read water levels in the reactor vessel, the boilers, the pressurizer and the several associated tanks and collectors. Radiation detectors are everywhere in the plant and there is a gauge for each section. There are also gauges for the power that the plant is producing that are associated with the Turbine and generators in addition to the electricity needed to run the plant itself.

The Control rod panel graphically displays the position of the rods in the core. This is one of the main operating panels since it is the control rods that regulate the power output of the system. An associated screen is the Reactivity graph that constantly displays the rate of fission going on in the core and can instantly record any nuclear excursions (sudden and significant changes in reactivity) that can affect the power output of the system.

The computer monitors everything and presents regular readouts on the state of the operation. The operator is informed, updated and prompted of any situation, normal or otherwise, that arises throughout the installation. The computer does not directly duplicate the Annunciators and Gauges but rather correlates the data into pertinent messages. Another function of the computer is to extrapolate based on events and data to offer the operator options when unusual situations occur. Since much of emergency response involves formulating assumptions based on what the indicators show the availability of logical alternatives can be very helpful and often time saving. Time is a major consideration in emergencies because power excursions can cause very rapid changes in reactivity, heat, pressure, all of which can exacerbate the problem.

Another monitoring system not directly related to the reactor is the security system. This consists of electronic plantwide scanners allowing detection of personnel anywhere and on any level of the plant. The system is also coordinated with the radiation detectors to show areas of abnormal levels in the plant and also major pipe ruptures and high temperatures indicating gas or steam leakage.

The access and operation of these and other monitoring systems is discussed in detail in the MANUAL available in the computer.

POTENTIAL HAZARDS OF NUCLEAR REACTORS

A loss of coolant can result from a pipe rupture, a relief valve sticking open, a control error or even a rupture of the reactor vessel. When the highly pressurized water escapes it explosively turns to steam. This is called a blowdown. The steam would be highly radioactive but if the rupture is not severe and the problem is dealt with promptly this hazard would be confined to the containment building. In a loss-of-coolant accident, several things happen in the core that affect reactivity. First, the density of the water around the fuel rods decreases. This causes less slowing of the neutrons making them less efficient and therefore reducing reactivity. However, coolant loss will also cause a rise in core temperature. This makes the fuel expand, perhaps even rupturing the zirconium cladding, which will increase reactivity. Additionally, with the lost water goes the boron density which also increases the fission process. This causes even more heat production so reactivity increases exponentially. With more heat, a greater pressure is exerted to push the water out and continue the process ever upward until the core is uncovered which will lead to meltdown.

Loss of coolant is automatically dealt with by the ECCS (Emergency Core Coolant System) which injects fresh coolant under high pressure into the reactor whenever the level falls below a prescribed point. If the rupture is checked the ECCS will maintain the proper level. If the rupture is in a pipe it is usually cut out of the system by closing appropriate valves and rerouting the coolant flow. The coolant must continue to move through the system so that collected heat can be dispensed. Standing water in the core would continue to heat up with the fuel until the pressure exceeded the tolerance of the vessel and a massive steam explosion destroys the reactor releasing major amounts of radiation. If the explosion was strong enough it could even rupture the containment allowing the radiation to escape to the atmosphere. If the rupture is significant but the reactor vessel remains intact the reactor may have to be SCRAMed (the control rods automatically inserted into the core to dramatically reduce reactivity). The ECCS will have to continue to keep the core covered because the temperature will remain very high even after the SCRAM and could cause a partial meltdown. Also, there is additional heat generated by reaction byproducts (this is called afterheat) which must be controlled to prevent core damage.

The steam released during a loss-of-coolant accident is primarily dealt with by water sprays in the containment. The spray condenses the steam back into water which then drains into collection tanks along with much of the radioactive elements. Once the reactor has been shut down and the heat is brought to a manageable level the coolant flow can be stopped to make repairs to the system.

A power excursion is any sudden and significant change in the rate of reactivity. It can be either positive or negative. A negative power excursion will result in a substantial drop in reactor power output but since heat and pressure are the primary destructive forces involved it is unlikely any damage or hazard could come from a loss of reactivity. On the other hand, a positive excursion is potentially much more dangerous than a loss-of-coolant incident. Because of the very high rate of the fissioning process a power excursion can occur extremely rapidly, 1/500 of a second, with an accompanying sudden increase in temperature and pressure that could result in reactor vessel rupture strong enough to breach the containment followed almost immediately by core meltdown. This would allow vast quantities of lethal radiation to escape to the atmosphere. In such a drastic situation the ECCS would be of little or no help since a meltdown would transform the fuel into an uncoolable molten mass at temperatures exceeding 5000 degrees Farenheit, which is the melting temperature of Uranium Oxide. The Control Rod Drive Mechanism is programmed to insert all the rods into the core (SCRAM) within 1 second of an excursion. If the event is relatively slow this action should prevent rupture and meltdown by instantly reducing reactivity to almost zero. However, if the excursion is sudden enough the core could begin to deteriorate immediately and change the structure of the core in such a way to prevent full insertion of the rods. Or, a violent surge in power could create such pressures within the vessel as to blow the head of the rod housing and the rods would be explosively ejected from the core. The rods could act as missiles in this instance to breach the containment dome.

A power excursion can be caused by several circumstances. A loss of coolant, if severe and rapid enough, could trigger an excursion. A steam valve closing, which can occur during a turbine trip (the turbine malfunctions and stops turning), that causes a change in the rate of coolant flow which increases the density of water in the core and therefore reactivity. A control rod malfunction, such as a breaking off of one or more rods which then fall out of the core. A coincidental malfunction of steam or relief valves that might create pressure changes in a confusing manner such that the computer and operator take steps that worsen the situation. For example, the relief valve on the pressurizer sticks open causing the water in the reactor to lose pressure and start to boil. The ECCS would automatically start pumping coolant to maintain level. Because the leak is at the top of the pressurizer, it would begin to fill (this is

In fact, almost any event that disturbs the normal operating parameters of the reactor, can conceivably cause a power excursion. An earthquake could loosen the support structure of the core changing the core position making the control rods inoperable. A valve could malfunction by accident or mistake and introduce fresh, cold water into core from a closed off loop. This sudden coolant temperature mismatch could cause a tremendous pressure surge in the reactor and greatly increase reactivity.

There are also effects called autocatalytic where a single source of reactivity increase can build upon itself exponentially producing a strong, rapid power excursion of potentially explosive force. Such autocatalytic effects include fuel rod distortion caused by overheating in which the fuel elements are brought closer together, increasing reactivity, increasing heat and thereby compounding the problem. Another is when the coolant rises causing it to expand. Since the water is already under high pressure and cannot escape (though, normally, the relief valve would deal with this) the density of the coolant increases. This increases the neutron-slowing effect because the water molecules are closer together and so causes increased fissioning. More reactivity produces more heat producing more pressure and so more reactivity and on and on up to an explosive excursion.

Although all the safety systems are designed to prevent or at least interfere with the processes, the loss of one system requires an entirely new approach to be invented on the spot and while this is being devised the situation is becoming more complicated very quickly. The operator must appreciate the time intervals involved to see that power excursions need to be prevented rather than reacted to. The excursion is the result of exponential growth in the rate of fission which is occurring at 30 million per second at a one-to-one ratio. Since the fissioning process is self-propagating, the rate of reactivity is constantly being multiplied by an ever growing factor. If conditions are allowed to develop where a power excursion could eventually result, that event will probably happen instantaneously and the damage done and the aftermath of that damage will often be catastrophic.

Another cause of potential trouble is a power-cooling mismatch. In this case, there is an imbalance in distribution of nuclear reactions in the core that causes excess reactivity only at certain points in the fuel arrangement, or hot-spots. This can be caused by nonuniformity in the arrangement of the control rods. Since each rod can be individually controlled the withdrawal of rods in an irregular or random pattern will contribute to irregular heating patterns in the core. These hot-spots could not be as efficiently cooled and might lead to fuel damage, producing temperatures that endanger the surrounding fuel and could eventually cause a meltdown. Also, a SCRAM of the reactor would not be as effective in reducing reactivity when it is concentrated in small areas.

Precise Control Rod operation is discussed in the MANUAL.

Pump or valve failure anywhere along the heat chain can lead to coolant overheating and increase pressure. Briefly, the heat chain proceeds as follows: the reactor coolant collects the heat of fissioning and is pumped out to the boilers (steam generators). There, it exchanges heat with the water in the boiler, a process whereby the reactor coolant loses heat while boiling the boiler water. The boiler water turns to steam and is sent to the Turbine. After serving as power to turn the turbine the steam goes to condensers to be turned back into water. This is done with cooling tubes supplied with water from an outside source (a river). The condensed steam, water, is returned to the reactor building and stored as feedwater for the boilers. All along this chain are pumps and valves positioned at crucial points along the miles of piping. Since the system, regardless of its size, is normally closed, a fault anywhere can interfere with the normal cooling process. For example, if the turbine stops (a turbine trip), valves will automatically close to cut off steam to it. This causes a break in the chain and must be dealt with by rerouting the steam to the condensers or terminating the steam generating process temporarily while still maintaining core coolant flow. In this case, emergency steam venting may be required to control pressure in the steam leg of the system since the heat exchange is still active from the reactor. Steam venting from the boilers is considered an emergency action because this steam would be released into the containment where steam pressure would build. Normally, boiler steam is not radioactive and can be vented to the atmosphere, however if the action is taken during a reactor incident, careful monitoring of the containment must be made to determine if radiation is present and if so, containment seals cannot be broken and the steam would have to remain confined. If the overall situation were not resolved, the steam pressure in the containment could grow to explosive proportions, threatening outside contamination.

One of the major considerations is at what power level the plant was operating when the incident occurs. Since a SCRAM will often happen immediately upon the detection of trouble the actual power level will be reduced to almost nothing. So if the operating level was rather low the heat remaining in the core should be manageable. However, if the plant was running near full power then even after a SCRAM there will be substantial afterheat from residual fission products. If a loss of coolant were involved the afterheat could be high enough to initiate fuel damage or even meltdown.

The production of Hydrogen during core overheating can have disastrous consequences. If the core temperature gets high enough materials in the core react with coolant water and produce Hydrogen. A bubble of hydrogen grows in the top of the reactor vessel and if the pressure is not relieved the vessel could rupture. However, venting the Hydrogen into the containment presents several possible safety problems.

Any venting from the reactor vessel releases radiation, therefore the containment must remain sealed. If the reactor is not brought under control, Hydrogen will continue to be produced building up pressure against the containment dome. Also, the Hydrogen is highly combustible. An electrical spark could cause an explosion strong enough to blow the dome off the containment building releasing massive amounts of radiation into the air. Another reaction that can cause an explosion is Hydrogen coming in contact with Oxygen. When these two gases combine to form water molecules they do so very violently. In any case, once the containment is breached there is simply no way to prevent radiation from escaping and endangering the public.

MELTDOWN

The worst-case scenario in a nuclear reactor is a meltdown. Whatever the cause—a loss of coolant, power excursion, or vessel rupture—once the core temperature exceeds the melting point of Uranium there is nothing that will stop the destruction of the fuel assembly. The fuel will become molten and burn through the zirconium tubes. At these temperatures the zirconium will burn in the coolant water and produce Hydrogen. The molten fuel mixes with the water creating explosive steam. The steam also acts as an insulator between the remaining coolant and the fuel mass so that the heat rises even faster. Initially the melting fuel collects into an uncontrolled mass so that reactivity shoots up (a strong power excursion) but after the fuel burning the reactivity begins to decrease because of a process called negative reactivity feedback that is due partly to the deterioration the fissionable material in the fuel. Even though reactivity declines, and so the reactor power output, the heat produced by the event is more than sufficient to completely destroy the reactor vessel and the containment in the form of steam pressure or hydrogen.

All possible measures should be taken to bring the reactor under control long before meltdown. The reactor should be shut down, presumably by an automatic SCRAM, and the residual heat in the core should be lowered as quickly as possible. Reactor pressure should be relieved in the safest possible manner depending on the nature of the emergency. If even a partial meltdown should occur, there is little left that can be done except try to contain the radiation which will be substantial enough to threaten the lives of hundreds of thousands of people if it is released to the atmosphere. If the meltdown is caused or creates a loss of coolant the heat will be strong enough to allow the fuel mass to burn through the bottom of the reactor vessel and possibly the floor of the containment. If this mass were to come in contact with cold ground water it would produce a catastrophic steam explosion blowing huge amounts of radiation into the air. This has been called the "China syndrome."

STARTUP PROCEDURES

All operating procedures all continuously available to the operator by requesting the MANUAL. After loading and signing on to the program the station control screen will appear. From this screen press the logo key (c=) to access the MANUAL.

To load the initial program insert the disk and type:

LOAD "CS", 8, 1 (return)

When the sign-on screen appears enter your name and press return. Then enter the time of day followed by am or pm (1242pm). If the time is before 10:00 am include a leading zero in the number (0900am). Do not include spaces or a colon.

After the time, followed by a return, enter the following station number code:

BNL104–PN

and press return.

When the control screen appears the first thing a novice should do is access the MANUAL and begin familiarizing themself with operating procedures.

When the operator feels comfortable the station can be taken control of by typing:

ON LINE (return)

The simulation can be terminated at any time by typing:

OFF LINE (return)

When the station starts up it will be under the control of the computer and the operator will act as monitor. This is a good way to learn the normal operation of the station and how various events are dealt with. Whenever the operator wishes to take complete control type: OVERRIDE (return). The computer will relinquish command. All regulatory and safety systems will continue to operate automatically in reacting to abnormal events but it will become the responsibility of the operator to make all decisions regarding the maintenance of the plant and the generation of power.

In emergency situations the computer will analyze and collate data and offer information and alternative courses of action. The operator must review the events and make judgement based on study and experience as to how the crisis should proceed to a safe conclusion.

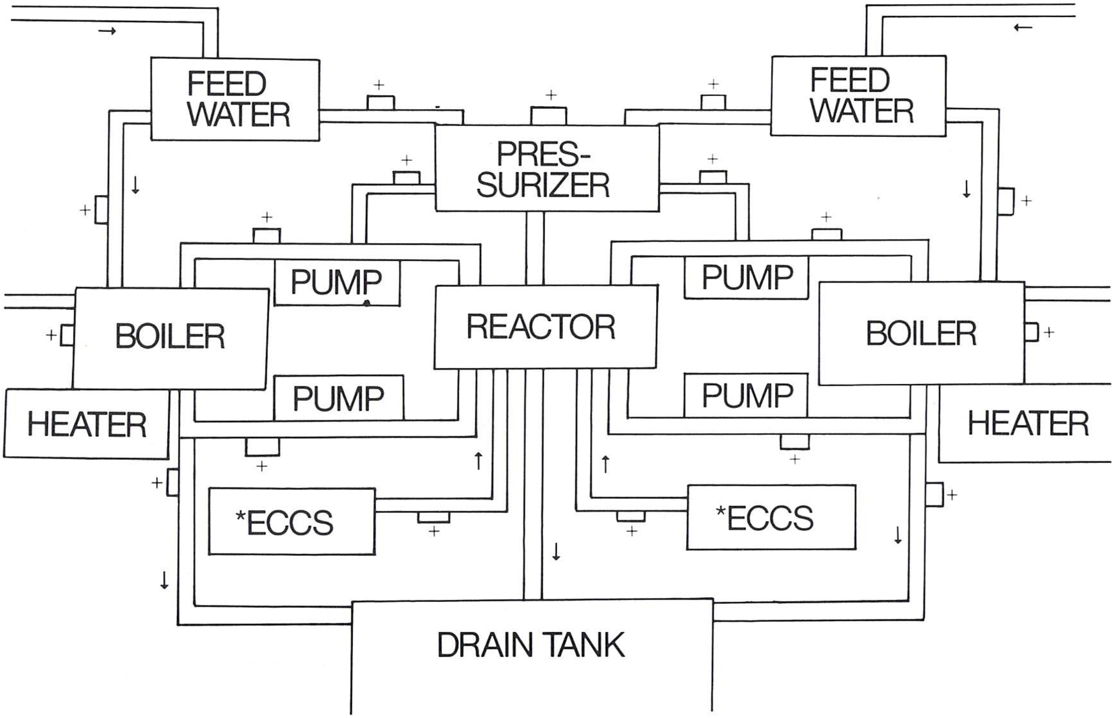


Figure 1. Simplified Block Diagram of the Reactor System and Function

The reactor vessel contains thousands of uranium fuel rods arranged vertically in bundles. Above the fuel assembly is the Control Rod Drive Mechanism that inserts and withdraws neutron-absorbent control rods in between the fuel rod bundles. Control rod movement regulates the rate of fission in the reactor that produces power in the form of heat. The reactor is full of water that acts as both a coolant to the fuel and a medium to transfer the heat out of the reactor and into the Boilers. In the boilers, the heated coolant water passes through internal tubes that take the heat from the water, cooling it, and passing it on the water in the boilers. This water boils and turns to steam. The cooled reactor water returns to the reactor to repeat the process. The steam is piped out of the boilers and sent, under high pressure, to power the Turbine. The Turbine, turned by the steam injection, turns the electrical generators that provide power. After the steam does its job it is condensed back into water and returned to Feedwater tanks that replenish the boilers. The Pressurizer keeps the reactor coolant under great pressure so that it will not boil. The Emergency Core Cooling System (ECCS) maintains the water level.

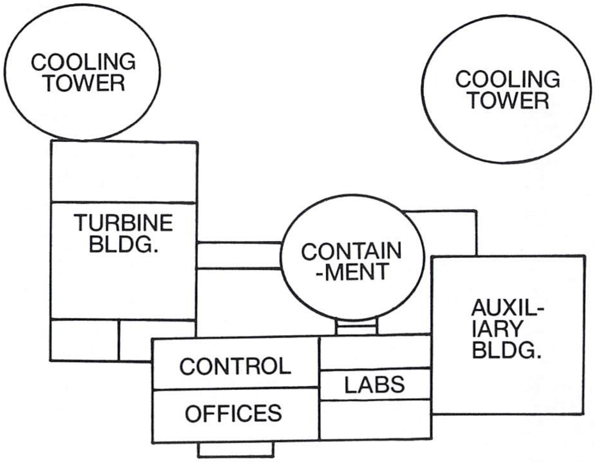
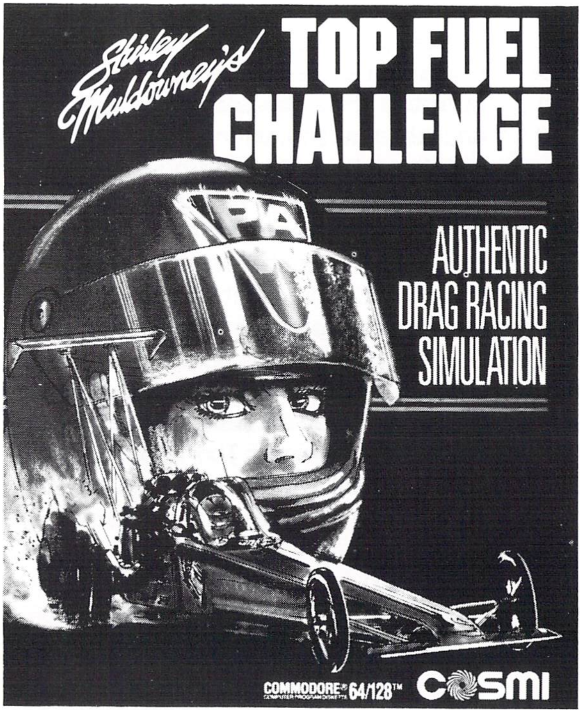


Figure 2. The Plant Layout

The Control Room contains the control, power production, and monitoring equipment as well as the computer and operator. There are associated offices and labs that contain the analysis labs, radiation labs and Health-physics labs. The Containment is a large reinforced concrete domed structure that houses the reactor, the boilers and related equipment. The Containment is the main barrier against escaping radiation. The Auxiliary building contains storage tanks, pumps, filtering systems and condensers that are part of the power generation and safety system but do not have to be close to the reactor or turbine and do not need to be sealed from the outside world. The Turbine Bldg. holds the turbine, the generators, and power transmisison equipment as well as the main power source and cable junctions for the plant.

New Thrilling, Authentic Simulations

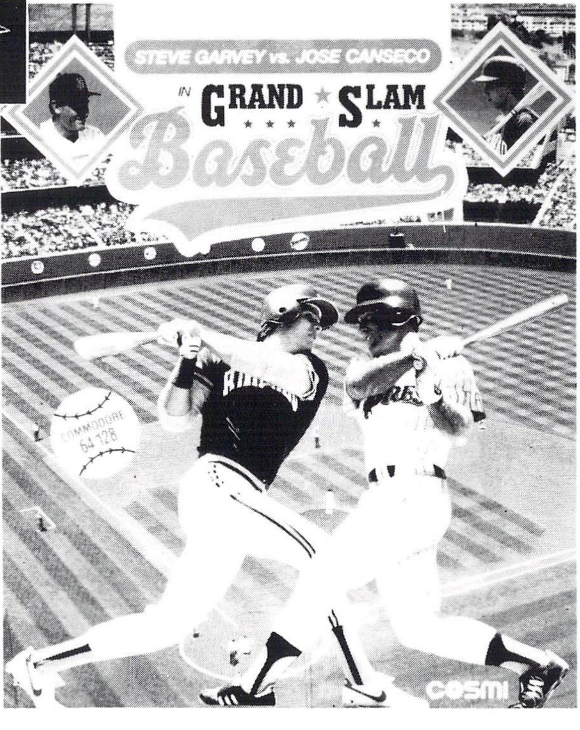
SPORTS • RACING • ADVENTURE • BUSINESS



Shirley Muldowney, three time world champion in Professional Top Fuel Dragsters, has helped design this exciting, authentic 3D drag racing simulation. Surrounded by all the drama and action of NHRA competition you select your equipment, qualify, burn in your tires, stage your dragster, watch the christmas tree lights, pop the clutch, hit the throttle, watch your tach, lean out your fuel, shift just right and maybe when you pop your chute you'll have beaten Shirley in one of her actual races during her three winning years. Don't red light, smoke your tires or blow your engine . . . it's a long season.

LIST: **24.95**

C 64/128



Steve (iron man) Garvey and Jose (Rookie of the year) Canseco take you to the ballpark in a Grand Slam Double-header. First, you have a regular baseball game with all the "real-time" action, sliders, curves, squeeze plays, defensive shifts, scrolling outfield screens, batter's-eye view of the pitcher, instant replays . . . all the exictement, color and sound, PLUS a dynamic new variation in which only grand slam homeruns can score points for your team. The action and strategy are intense as you, Steve and Jose match power and skill.

LIST: **24.95**

C 64/128

COSMI

415 N. Figueroa St., Wilmington, CA 90744 • (213) 835-9687
800-843-0537 Outside CA • 800-654-8829 In California