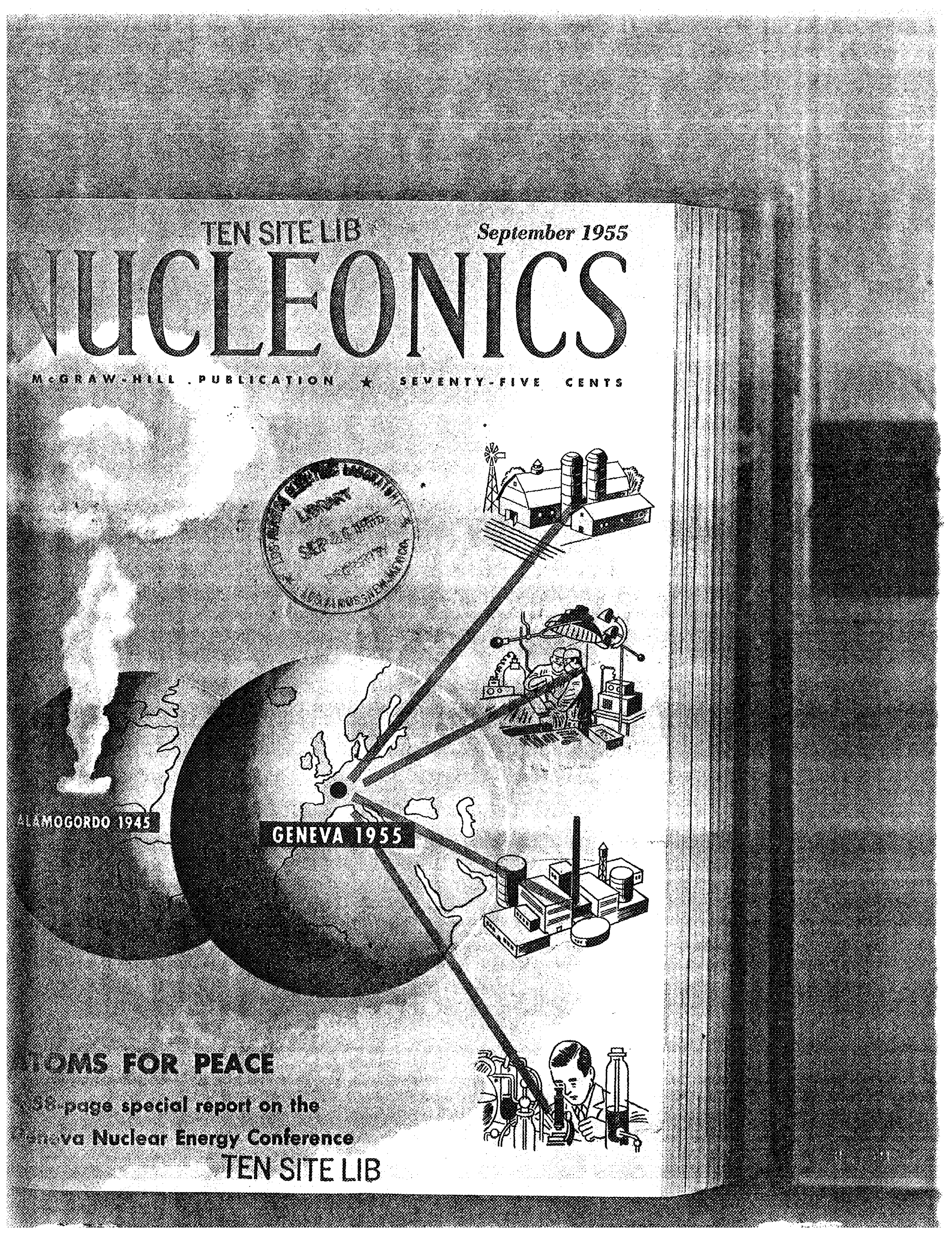
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GENEVA CONFERENCE—A Special Report

REPORT from GENEVA

reactors

Design features and experience with power reactors, including the Borax tests—Power reactors under construction—Research reactors

Operational Power Reactors

Design features and operating experience with power reactors are summarized below. Figure 1 shows the 30-Mw reactor used in Russia's 5-Mw power station (see also NU, March '55, p. 70). Figures 2–4 show Argonne National Laboratory's prototype boiling-water power reactor (Borax-3).

Figure 5 shows the Borax-1 reactor, which was built to test transient behavior of boiling-water reactors; Fig. 6 shows a fuel element. Figure 7 shows the reactor shutting itself down safely by water expulsion after being made supercritical by 2.1% k_{eff}. This nondestructive ejection of water occurred when the minimum period of the excursion was 0.005 sec. After this reactor had served its purpose in the experimental study of over 200 short-period operations, it was destroyed as shown in Figs. 8–10.

To make Borax-1 destroy itself, a 4%-k_{eff} control rod was completely ejected from the core while the reactor water was at room temperature. The rod, which was completely out in ~0.2 sec., was only 80% removed when reactor power reached its peak; minimum period was 0.0026 sec. The excursion melted most of the fuel plates, burst the reactor tank, and sent most of the contents of the shield tank into the air. Total energy release was 135 Mw-sec; peak power was ~19 Bw; peak pressure was probably over 10,000 psi. Nuclear power release terminated at an early stage (0.003-sec heat flash was over before debris appeared above top of shield). Although spectacular, the explosion was moderate in intensity; most of the equipment outside the shield was either undamaged or repairable. At the control station ½ mile away, it sounded like 1–2 lb. of 40% dynamite on the bare ground at the same distance.

Most of the heavy debris landed near the shield pit. The ~1-ton control drive mechanism went 30 ft into the air and fell on the earth shield. Recognizable fuel plate pieces were found up to 200 ft from the reactor site. Most of the fuel plates had almost completely melted; some of the peripheral elements had only partly melted and parts of their fuel plates remained fastened to their side plates as in Fig. 11. Some melted fragments were found as spongy metallic globules as in Fig. 12; others had melted only inside as in Fig. 13. Practically all of the reactor's fuel was accounted for within 350 ft of the reactor, thus no large portion of the core left the site as airborne material.

The experiments with the Borax reactors prove that these reactors are inherently highly safe and indicate that boiling-water reactors can be designed to be safe from any practical reactivity accident.

The world's first electricity to be generated from nuclear energy was derived from heat developed by the Experimental Breeder Reactor in Figs. 14 and 15. The design is quite flexible both as to loading and operating conditions. It was designed when enriched uranium was not available in large amounts—so it has a small critical mass (48.2 kg U^{235}). Practical fast power reactors could be of somewhat similar design, but more stainless steel and sodium will be present for structure and cooling. This will necessitate a much greater dilution of fuel—and a degraded median energy of neutrons.

ATOMIC POWER STATION (APS-1). **Russia, 30 Mw Heat, 5 Mw electricity, 5% enriched U fuel, graphite moderated, water cooled, $\phi_{avg} = 5 \times 10^{13}$, critical on 5/9/54, generated power on 6/27/54 (615).***

Description. Fuel alloy is contained in hollow SS-clad tubular elements in vertical SS-lined channels through stacked graphite bricks (whose T_{max} = 650–700° C). There are 128 channels; reactor is critical with fuel in 60; fuel charge is 550 kg U. Active core is 5.6 ft high × 4.9 ft diam. and is surrounded by graphite reflector. Reactor is hermetically encased in steel cylinder, which is filled with He or N_2 to prevent graphite oxidation; graphite has separate water cooling system. U burnout is 15%; enrichment decreases from 5 to 4.2% during operation. Pu production is only 0.32 because of low resonance capture. Shielding is provided on sides by 3.3 ft water and 9.8 ft concrete, and on top by extra graphite, steel cover, cast Fe plate, and extra concrete.

* References are to UN papers on p. 94.

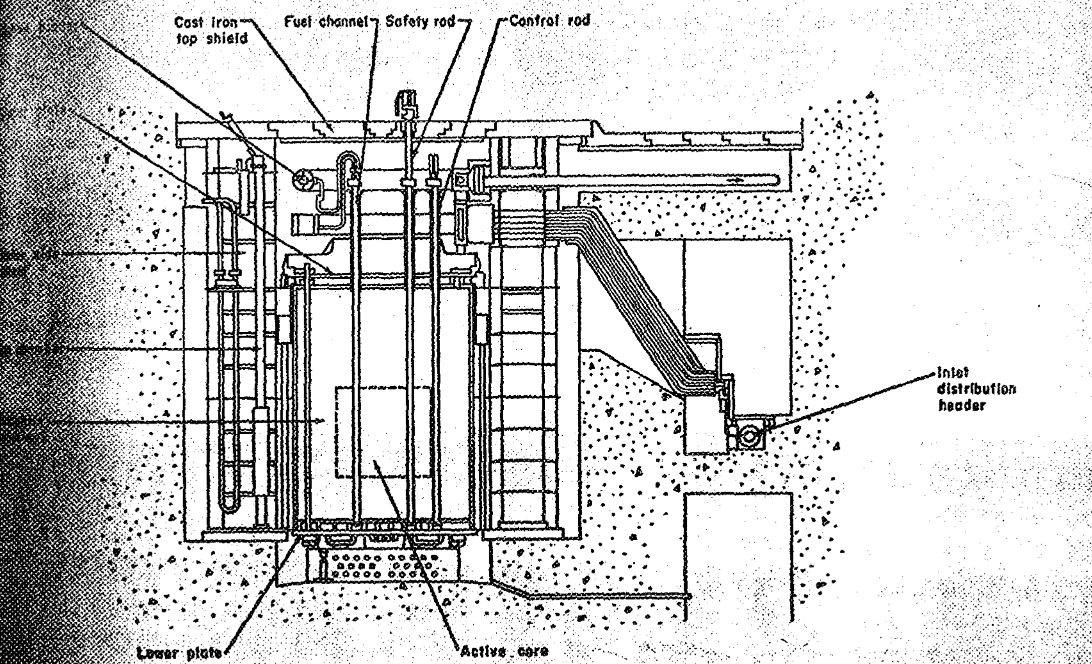


FIG. 1. Russia's pressurized-water graphite 30-Mw reactor used in 5-Mw power station

... $\times 10^6$ cal/m²/hr heat is removed from U surface ... recirculated 1,470-psi water (flow and temp. are ... each channel) that flows from top inlet header, ... fuel tubes, then returns up by flowing over outer ... fuel elements, at ~265° C it passes out to 3 of 4 pairs ... steam generators (each consists of water heater, ... evaporator, and superheater); water leaves steam gen... 190° C and goes to 3 of 4 main coolant pumps ... tons/hr. Condensate pumped from turbine to ... generators is turned into 185-psi ~260° C steam at ... tons/hr. To hydraulically seal shafts of main ... makeup pumps feed water to seals of main pumps ... above main system pressure. Storage batteries ... emergency power for afterheat cooling.

... 18 boron-carbide shim rods—6 are near center, 12 ... cavities of active core. They are moved vertically ... water-cooled channels (having separate cooling ... wire ropes and servomotors. 4 automatic regulat... work at a time) in the reflector maintain power ... Two safety rods have servomotors directly over ... There are 12 emergency shutdown signals. Most ... are: 20% over maximum power, too-rapid power ... cut-off of main-pump power, certain changes in flow ... temperature of water in fuel channels. At startup, suf... reactivity is present for 2½ months of full power ... Water flow is almost completely stopped to a ... if it ruptures.

... facilities. Include: 6 curved channels to core ... and reflector ($\phi = 2\text{–}8 \times 10^{12}$); 3 straight hori... , 1 of which goes to core center ($\phi = 10^7\text{–}10^9$ at ...); 1 thermal column ($\phi = 10^9$) with remotely ... plugs so objects can be charged without shutdown.

... Plant has produced $\sim 15 \times 10^6$ kwh. No ... failures; fuel channels easily removable. Cool... automatic control equipment functioned without ... fuel elements are replaced every 2 months, change ... days. Startup from zero to rated power takes ... automatic startup system is being developed. Moving peripheral elements to center extends U^{235} burnup to 20%. Have found only few pits and cracks in cooling system, although there are several thousand welds. Erosion of Cu gaskets and asbestos-graphite valve seals has caused some dry residue to build up. At temperature and pressure in cooling system, detonatable water-decomposition ions recombine at a rate such that recombiner could be shut down. Power from this station compares favorably in cost with that from small thermal plants, but considerably exceeds cost from large plants (10 kopeks/kwh = cost of electricity from Russian thermal power stations in 1953).

PROTOTYPE BOILING-WATER POWER REACTOR (BORAX-3). NRTS, Idaho (ANL project). *15 Mw heat, ~2 Mw electricity, ~90% enriched U, water moderated and cooled, 1955.* **Built for experience with operating power plant. Whole core assembly can be replaced easily (851).**

Description. U-Al alloy is in Al-clad plates with 24 vertical plates in each box-type element, whose total dimensions (including top and bottom extensions) are 56½ × 3.875 × 3.828 in. Active portion of plate is 25.8 in.; additional ½ in. of Al is on each end. Plate centers are 0.324 in. apart; volume ratio of metal to water in core = 0.36; reactivity loss from 27 to 182° C = 0.8% k_{eff}. Fully loaded, core contains 87 fuel elements; 11.8 kg are required to cover criticality, temperature, operating Xe losses, and 2 kg for burnup. Each element costs $425 to fabricate; 137 gm U^{235} are in each central element; each peripheral element has 233 gm U^{235} so as to flatten power distribution and adjust void coefficient. Average element delivers 138 kw at 12 Mw total power. With 6.26-liter active section of each element, avg. power density is 22 kw/liter. Core is on framework that is supported from top of vessel (just below flat-lid closure). Vessel is ¾-in. SS, 15 ft 11¼ in. high and 52½ in. i.d.

Heat. $\sim 1.1 \times 10^6$ cal/m²/hr heat is avg. heat flux (max. is 2½ × this) removed from 215° C surface of heated fuel plate by naturally circulating 300-psi water in core. Each cooling channel is 0.265 in. thick, 1.27 in. wide and 26.8 in. long. Water flows up through elements and steam formed collects above water surface 4 ft above core, leaves vessel through 6-in. pipe

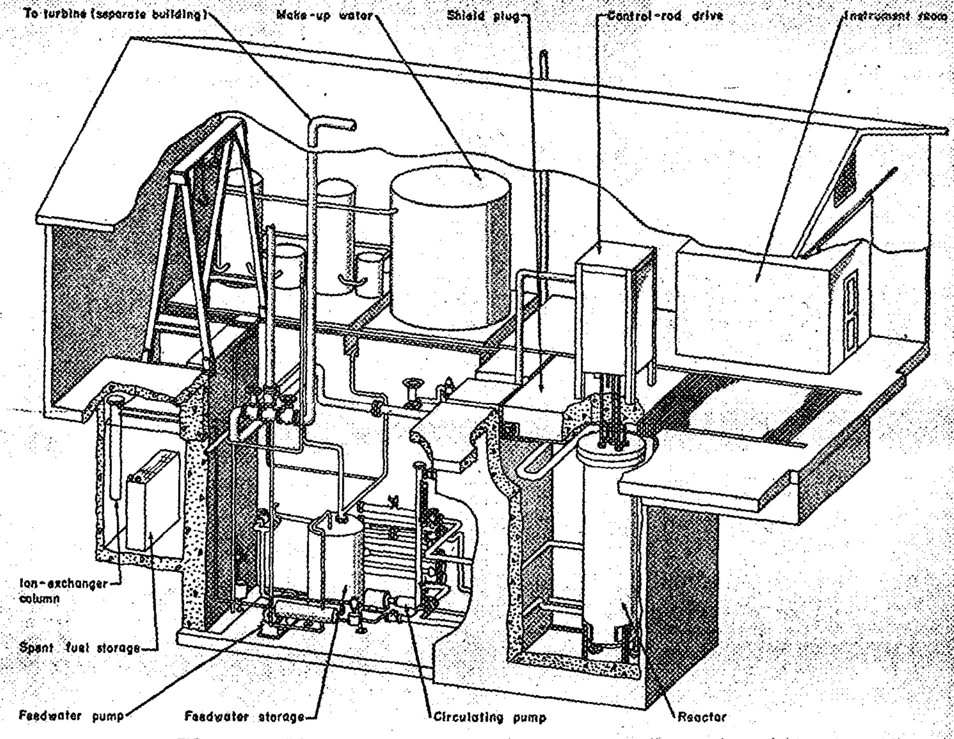


FIG. 2. US's 15-Mw prototype boiling-water power reactor (Borax-3) plant

and is vented to atmosphere or delivered directly to 3.5-Mw turbogenerator. Large steam volume in top of vessel is effective in raising steam quality. As water cools, it flows downward near vessel walls (where it serves as reflector); feedwater from condensate deionizer is pumped into the annular downcomer to promote natural circulation.

Control. 1 cross-shape and 4 blade-type control rods using Cd, B, and Hf as absorbers are driven vertically by drives mounted above concrete shield plug rolled over top of reactor. For each, steam cylinder and piston in which rod terminates balances lifting force due to steam pressure in core; steam for balancing cylinder comes from reactor vessel. Pneumatic piston exerting 800 lb drives rod. Rapid insertion is by switching air pressure to side of cylinder that moves rod down. Since facility also is used for transient testing of reactor cores, the control room is some distance from the reactor itself. Operating conditions are indicated by electrical means (including TV). For continuous operation, where burnup steadily reduces available reactivity, burnup plates incorporating boron are affixed to fuel elements.

Experience. Has operated under stable conditions at pressures from atmospheric to 300 psi. At 12 Mw and 300 psig (where power density = 22 kw/liter of core, which corresponds to 1.5% Δk in steam), short-period power fluctuations amount to 3.2%; these produced no detectable variations in reactor pressure or steam flow. $550,000 is total cost of facility; over 50% is in power conversion and cooling equipment. With 80% load factor and 20% efficiency, total electricity produced is 1.4×10^7 kwh/yr. With 15%/yr amortization, capital charges = 5.9 mills/kwh. If all 11.8 kg of U^{235} must be changed after 2 kg are burned, 1.8 fuel charges will be needed per year and consumption will be 3.6 kg/yr. To allow some radioactive decay of fuel, 1.5 loadings always will be committed to plant; with U^{235} assumed to cost $15/gm and 4% interest, inventory costs $10,600/yr, or 0.76 mill/kwh. The 3.6 kg burnup adds 3.85 mills/kwh. Fabrication of 1.8 fuel charges/yr at $425/element adds 4.7 mills/kwh. Processing at $5/gm (presently practical) adds 6.2 mills/kwh. A 12-man operating staff adds 8.6 mills/kwh, bringing total power cost to 30 mills/kwh. For this small a plant, capital and operation charges are fairly fixed, but considerable cuts are possible in cost of fabrication and processing.

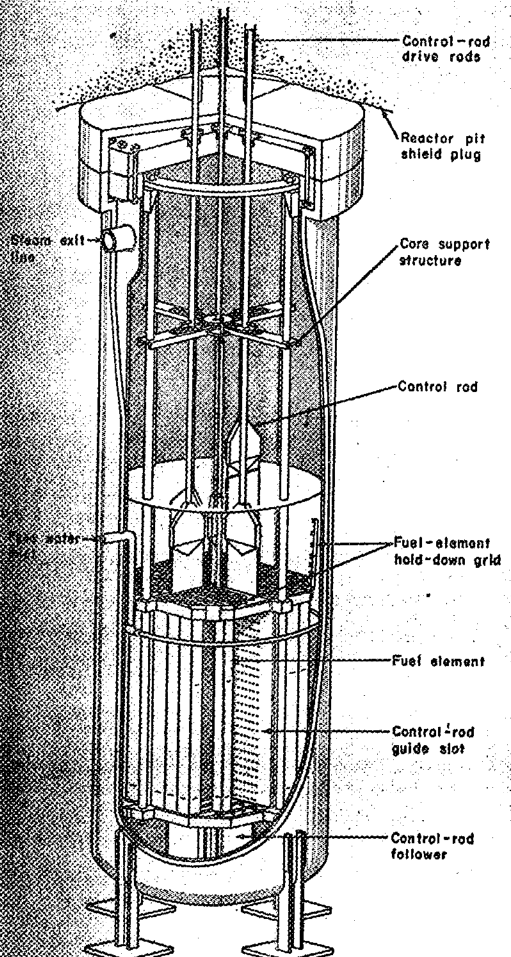
BORAX-2. NRTS, Idaho (ANL project), 13 Mw heat, ~90% enriched U, water-moderated and cooled, 1954. Built to test transient performance of boiling-water power reactors (*481, 851*).

Description. Similar to Borax-3 (used same vessel) except that: core was considerably smaller, no turbogenerator was used, and fuel elements were narrower and somewhat different—similar to elements of Borax-1 except that there were only 10 fuel plates/element; plate centers 0.324 in. apart, volume ratio = 0.422; 93.4 or 157.3 gm U^{235}/element, reactivity loss from 27 to 182° C = 1.16% k_{eff}.

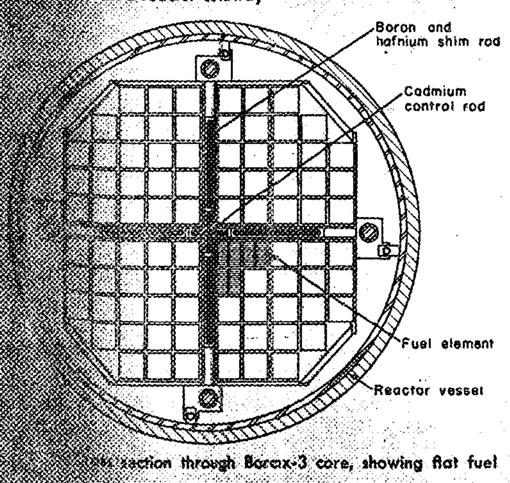
Experience. At 5.2 Mw and 300 psig (where power density = 22 kw/liter of core, which corresponds to 2.6% Δk in steam), short-period power fluctuations amount to ~15%; these produced no detectable variations in reactor pressure or steam flow.

BORAX-1. NRTS, Idaho (ANL project), ~90% enriched U, water moderated and cooled, 1953. Built to test transient performance of boiling-water power reactors (*481, 483, 851*).

Description. U-Al alloy in Al-clad plates 60-mils-thick with 18 vertical plates in each ~3-in.-square box-type element, which was not as wide as Borax-3's and was of different design; 138.6 gm U^{235}/element; plate centers 0.177 in. apart, volume ratio = 0.626; reactivity loss from 27 to 182° C =



Borax-3 reactor cutaway



...ss section through Borax-3 core, showing flat fuel

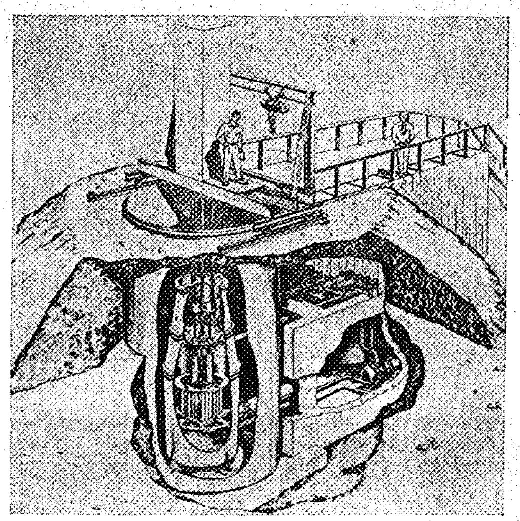


FIG. 5. Borax-1 reactor cutaway

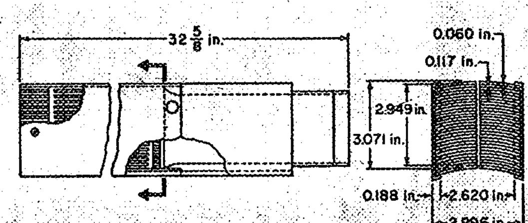


FIG. 6. Borax-1 fuel element used 18 plates each 60 mils thick; Borax-2 element had 10 plates of same thickness; both element types had external dimensions shown

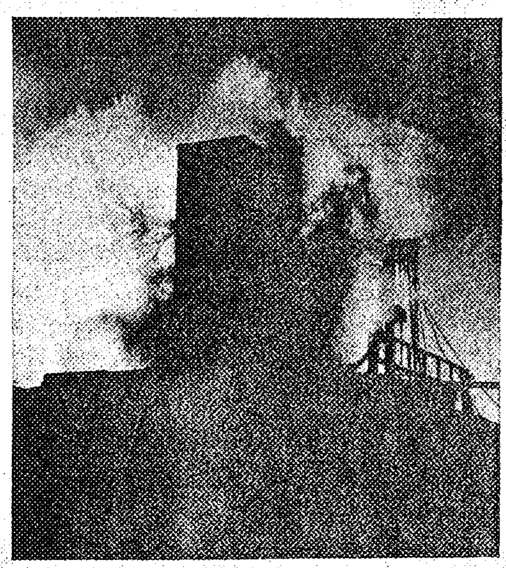


FIG. 7. Borax-1 shutting itself down safely by water expulsion after being made supercritical by 2.1% k_{eff}

FIG. 8. When a 4%-k_{eff} control rod was 80% ejected from Borax-1's core there was a light flash as reactor power peaked near 1.9 × 10^{10} watts, then a dark gray column appeared

FIG. 11. Peripheral-fuel-element side plate with attached cluster of fuel plate fragments

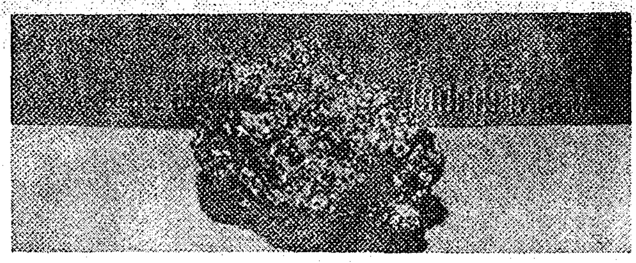


FIG. 12. Globule of spongy Al-U from fuel element that evidently had been molten

FIG. 13. Fuel-plate fragments that appeared to have been molten inside while outside remained solid

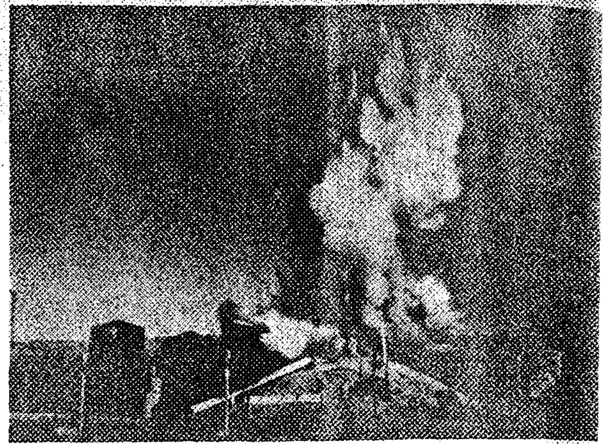


FIG. 9. Part of box housing control equipment can be s starting to go up. Light-colored objects probably are Al-U f fragments burning in air

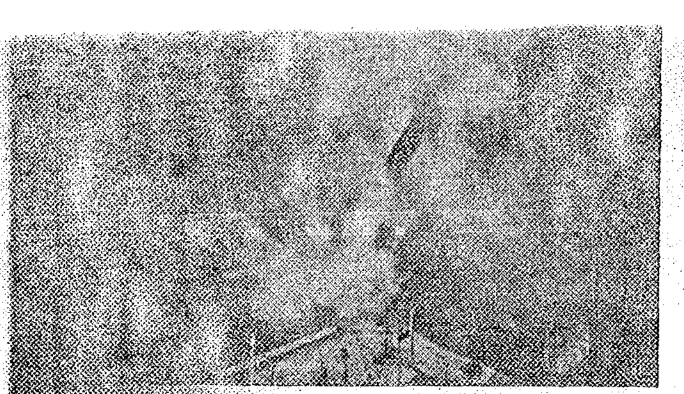
3.5% k_{eff}. Elements held in lower supporting grid and movable top cover grid. Reactor tank, of ½-in. steel, 4 ft in diam. and ~13 ft high; it was in 10 ft diam. sh tank sunk partly into ground and with earth piled around added shielding; shield tank filled with water only when actor was shut down. Adjacent to shield tank was a c crete-walled pit with equipment for filling and empty reactor and shield tanks and for preheating water in reac tank; water level in reactor tank was 3–4½ ft over c Facility located outdoors.

Control. 5 Cd elements operated by drives in rectang housing above shield tank. Spring-loaded magnetic co lings connected mechanisms to rods. When released, cer rod dropped out of core to apply excess reactivity used experiments. Other 4 rods were dropped into core to s experiments. Each rod took ~0.2 sec to traverse c Control station was ½ mile from reactor.

Experience. After steam pressure (built up in forcing w rapidly from reactor during short-period experiments atmospheric pressure) caused permanent deformation of plates (max. temp. still did not melt fuel elements), it decided that the reactor, which had fulfilled its experime purposes, should be sacrificed in an experiment viol enough to melt the fuel plates. This was done on July 1954. After explosive experiment, control-rod drive me nism and most other equipment outside shield tank v decontaminated, reconditioned, and used on Borax-2.

EXPERIMENTAL BREEDER REACTOR (EBR-1). NRTS, Idaho (project), 1.4 Mw heat, fast, ~90% enriched U, NaK cooled, ϕ_{max} = ~10^{14}. Built to gain purely experimental experi with fast breeder reactor system. Produced >100 kw electrical power in Dec. '51—this was world's first nuclear pc (*813, 814, 816*).

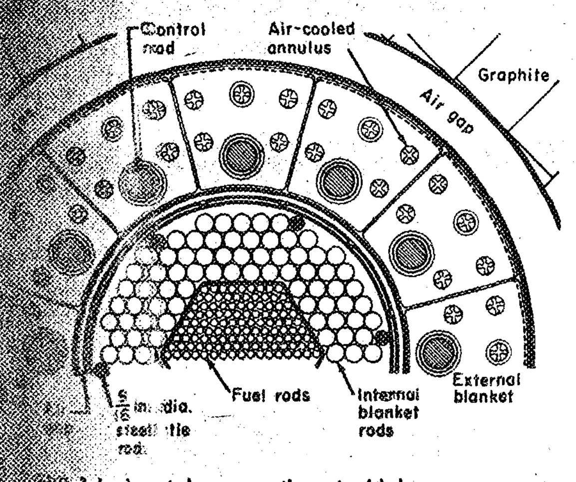
Description. U^{235} is in slugs 4¼ in. long and 0.384 in. di with 0.064-in.-thick SS jackets; 2 slugs are in each ver rod, which is included in a close-packed array on 0.49 centers. Over and under fuel in rods are 0.384-in.-di U^{238} slugs that make blanket at ends of core; each rod upper space for collecting fission gases and a top shiel section of SS that extends through part of reactor's top sh to serve as handle for removing rods; over-all length is 1 Plates over and under blanket sections position rods in c there are 217 spaces, but those not used for U^{235} rods con blanket slugs. Core contains 52 kg U^{235}; critical mas 48.2; reactivity loss from 38 to 200° C = 0.53% k_{eff}. side blanket is in 2 sections; first part is separated from cor ⅛-in.-thick SS hexagon 7½ in. across flats. It consist tight array of 138 U^{238} rods each 1⁵⁄₁₆ in. diam. and 20 long inserted in 0.020-in.-thick SS tubes; they also l upper shielding and handling portions. This blanket part deep-drawn 15.9-in.-i.d. SS-347 can ⁵⁄₁₆ in. thick and 2



[illegible] At height of explosion, large amount of debris in [illegible] of reactor tank, controls, and core went 80 ft up. [illegible] no dangerous fallout beyond a few hundred feet

[illegible] Above this small-diameter section, the diameter of the [illegible] tank increases, this portion is filled mostly with steel [illegible] as a shield; the entire vessel is supported on the [illegible] formed by the diameter change. Surrounding the [illegible] section is an outer tank of $\frac{1}{16}$-in. Inconel with ribs [illegible] $\frac{1}{8}$-in. space (for insulation and part of main-[illegible] leak-detection system). The second blanket section is [illegible] the reactor tank; it is of 84 keystone-shaped U^{238} [illegible] weighing ~100 lb each, jacketed in 0.020-in. SS and [illegible] position in 12 stacks by an inner shell of $17\frac{9}{16}$-in.-i.d. [illegible] 2S Al and an outer shell of 31-in.-i.d. $\frac{3}{16}$-in.-[illegible] Al. Outside the external blanket and a 2-in. gap is a [illegible] shell and an 18-in.-thick graphite reflector. Beyond [illegible] air-cooled 6-in. Fe thermal-neutron shield followed [illegible] concrete.

[illegible] $\times 10^6$ cal/m²/hr is avg. heat flux in core; [illegible] heat generated by reactor is in core, 14% in inner [illegible] and 14% in outer blanket, which is kept at 200° C [illegible] ft³/min air through 5 vertical holes in each of [illegible]. The air cooling of the blanket limits reactor [illegible]. NaK at ~228° C enters reactor tank above [illegible] section, is distributed in header, flows through [illegible] fluted section of rods and down between blanket [illegible] bottom of tank. From here it flows into the hex-[illegible] separator and up among the fuel rods, through top [illegible] in holding plates, and at 316° C exits sidewards [illegible]. Then it is cooled in heat exchanger by 215° C [illegible] NaK system and goes to a lower storage tank, [illegible] it is pumped to a high tank and returns to the



[illegible] EBR-1 horizontal cross section at midplane

for plant operation.

Control. 12 SS-jacketed U^{238} control rods (1 in each outer-reflector stack of 2 in. diam.) move vertically to change neutron leakage from core; 8 can be pulled out of the blanket rapidly and serve as safety rods of 0.20%-k effectiveness. Together with a bottom safety (cylindrical block that can be driven out bottom by pneumatic force), these 8 rods can remove 0.27% k in 100 msec. Other 4 rods are regulating rods controlling 0.10% k. Whole outer blanket rests on lower shield on a hydraulically driven elevator; its top $4\frac{1}{2}$ in. of travel is mechanically controlled with 0.001-in. accuracy; through top $4\frac{1}{2}$-in. travel, 0.89% k is affected; complete dropping of outer blanket affects 8.2% k. Control-rod drives are under elevator. Loss of coolant has an effect on reactivity equivalent to removing 2 kg U^{235}.

Experience. Has operated reliably for $3\frac{1}{2}$ yr while being used for a number of experiments and generating 4×10^6 kwh heat, much of which went for generating plant electricity. Plant is inherently quite stable and largely self-regulating—very little operator effort is needed to maintain operating conditions. Instead of controlling reactor by load requirements, it is held at constant power and a pressure-regulating valve unloads excess steam to condenser. Plant efficiency is only 17% because of small size of plant and part-load operation. One method of determining conversion ratio gave a value of 1.00 ± 0.04; another method gave 1.01 ± 0.05. Strong circumstantial evidence indicates considerable neutron leakage out of blanket, a more efficient blanket probably would give a ratio of ~1.3. To replace the outer-blanket bricks, elevator lowers blanket, handling dolly lifts blanket from shield plug and takes it to shielded room, where manipulators disassemble it.

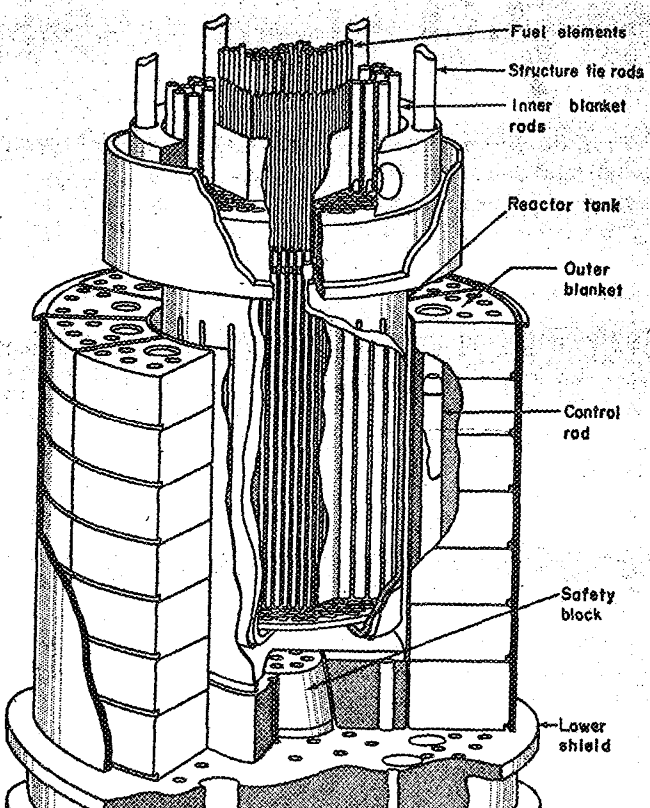


FIG. 15. EBR-1 cutaway