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FAIL-SAFE NEUTRON SHUTTER USED FOR THERMAL NEUTRON RADIOGRAPHY

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R. D. Sachs and R. A. Morris

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ABSTRACT

A fail-safe, reliable, easy-to-use neutron shutter was designed, built, and put into operation at the Omega West Reactor, Los Alamos Scientific Laboratory. The neutron shutter will be used primarily to perform thermal neutron radiography, but is also available for a highly collimated source of thermal neutrons [neutron flux = 3.876×10^6 (neutrons)/(cm²·s)]. Neutron collimator sizes of either 10.16 by 10.16 cm or 10.16 by 30.48 cm are available.

I. INTRODUCTION

Before the neutron shutter was put into operation at the Omega West Reactor (OWR), Los Alamos Scientific Laboratory (LASL), neutron radiography was accomplished only on an emergency basis. The operation was inconvenient because for each exposure the OWR power level had to be changed from approximately 0 to 4 MW and then back to as low a power level as possible. Therefore, a fail-safe, reliable, easy-to-use neutron shutter was designed, built, and put into operation. The hydraulic, electrical, pneumatic, mechanical, shielding, and radiation detection subsystems also were designed to be fail safe. The neutron shutter is used primarily to radiograph weapon detonators, but is also available to anyone needing a highly collimated source of thermal neutrons. Neutron collimator sizes of either 10.16 by 10.16 cm or 10.16 by 30.48 cm are available. The average thermal neutron flux is 3.88×10^6 n/cm²·s.

This report describes the original and present methods for obtaining thermal neutron radiographs.

II. THERMAL NEUTRON RADIOGRAPHIC PROCEDURE

The original (old) method of obtaining thermal neutron radiographs was as follows. The neutron radiographer would set up for the radiography inside the cave (a shielded enclosure) after the nuclear reactor was shut down. After the radiographer left the cave, the cave door was locked and the OWR reactor level was raised to 4 MW. The reactor power level was left at 4 MW (thermal) for the desired exposure time. After exposure, the reactor power level was lowered as far as possible. The radiographer would then retrieve the radiographic equipment and the radiographed parts. The procedure was repeated for other parts to be radiographed.

This procedure caused wide power fluctuations, which in turn caused the neutron flux, (neutrons)/cm²·s, and gamma-ray flux, (photons)/cm²·s, to vary over wide ranges. Therefore, the experimental portholes, which go toward the nuclear reactor core, would not have constant photon or neutron flux. This could cause errors

in experiments that assumed constant photon or neutron flux.

III. NEUTRON SHUTTER STANDARD OPERATING PROCEDURE

The new neutron shutter procedure was put into operation to alleviate the problem of power level changes. The cave can be entered when the shutter is in the DOWN position (Fig. 1) with the reactor at any power level within its limits.

To use the shutter for neutron radiography, or other experiments requiring a highly collimated or uncollimated source of thermal neutrons, the shutter operator activates a clock inside the cave for an arbitrary time, closes and locks the cave door (Fig. 2), and checks the cave mirror system (Fig. 3) to ensure that no one is accidentally trapped inside the cave. The radiographer then removes the Kirk Transfer Key from Kirk Lock No. 2 (Sec. IV) on the cave door, takes the Kirk Transfer Key to the neutron shutter control console (Fig. 4), inserts it into Kirk Key Lock No. 1 on the shutter control console, and asks the OWR operator to turn on the shutter master key. The operator then activates Kirk Lock No. 1 by turning both keys counterclockwise. As soon as the proper lights on the shutter control console are lit and the hydraulic pump slows down, the operator turns the digital solid-state electronic timer to the desired time exposure for the radiographic inspection and activates the start switch which causes the shutter tray to go to the UP position (Fig. 5). When the electronic timer stops, the shutter shield tray falls to the closed position and the operator removes the Kirk Transfer Key, unlocks and opens the cave door, and enters the cave. The exact operating procedures for the neutron shutter are given in Ref. 1.

IV. NEUTRON SHUTTER ELECTRICAL SYSTEM

The alternating current, 1.75-A, 110-V power for most of the shutter system was obtained from a previously unused power outlet having a major "Hinemann" circuit breaker in series with some

minor circuit breakers. The neutron shutter alternating current power was obtained from one of the minor circuit breakers.

Because voltage fluctuations occur on most power outlets at the OWR site, a constant voltage transformer, obtained from LASL salvage, was installed to provide all shutter power. The transformer is rated at 1 kVA with a nominal output voltage of 110-V ac. The output from the 1-kVA constant voltage transformer is carried by power cable inside metal conduit to the neutron shutter control console (Fig. 4) and to the hydraulic pumping system (Fig. 6).

The power and signal or power and control cables are never run in the same conduits in the system, which prevents a broken power cable from destroying the shutter control system or the gamma radiation signal system. The power cable conduit is grounded at the constant voltage transformer *and* at the mezzanine steel floor where the hydraulic system is attached.

The alternating current power is connected to a distribution terminal block, which has no signal or control cables attached to it, inside the neutron shutter control console. This was done to reduce the possibility of accidental connections of signal or control wires to the 110-V ac power. A large red neon indicating lamp is connected directly across the alternating current power where it enters the shutter control console. This red lamp indicates that power is available to the shutter console whether the shutter switch is off or on and warns maintenance personnel to turn off the circuit breaker leading to the shutter system.

The neutron shutter system circuit breaker is labeled conspicuously with large black lettering on a yellow field, making it easy to find for maintenance or emergency shutoff.

The neutron shutter control console front panel is hinged to the control cabinet for easier maintenance of the circuitry.

Neon indicating fuses are used in the power distribution points inside the shutter control console. This alternating current power goes to the (1) Model GA-2A NMC gamma-ray detection system, (2) direct current power supply (0-30 V, 1.5 A), (3) electric timer inside the cave, (4) alternating current microswitch (Microswitch-2) outside the cave, and (5) solid-state electronic timer. The neon indicating

Fig. 1.
Front view of neutron shutter shield tray in the
DCWN (closed) position.

Fig. 3.
Neutron shutter cave mirror system. The shut-
ter shield tray is shown in the DOWN position.

Fig. 2.
Front view of the "cave" located at the OWR.

Fig. 4.
Front view of the neutron shutter control con-
sole and the Nuclear Measurements Corpora-
tion GA-2A Gamma Console (lower box).

fuses are energized when the fuse interrupts a current overload, providing a good indication for fault location.

All electrical wiring, junction boxes, and conduits were installed with strict adherence to the most current (1975) National Electrical Codes.

V. ELECTRICAL CONTROL AND INTERLOCK SYSTEM

The electrical control and interlock system functional diagram is shown in Fig. 7. The system is basically a simple, logical AND (series) connection of switches and relay contacts. To force the shutter shield tray to the UP (open) position, all the electrical contacts in the series control path must be closed. This can be accomplished by the following sequence. The OWR Key Switch is closed by an OWR operator, the Kirk Transfer Key is removed from Kirk Lock LK1 (the cave door is now locked with MS1 and MS2 contacts closed), and the key is inserted into Kirk Lock LK2. Both Kirk Keys in LK2 are rotated together, thereby turning on the air-driven hydraulic pump. A direct current series path now exists up to the air pressure switch, assuming the cave clock is off and the cave safety switch is enabled. With the correct air and hydraulic pressures, the pressure switch contacts will be closed. Therefore, if the electronic timer is activated, the logical AND connections of switches are complete. The four-way solenoid valve is activated (with the digital clock enabled), with the hydraulic oil being pumped to the hydraulic ram raising the shutter shield tray.

Each closure of a switch contact is brightly displayed on the neutron shutter control console (Fig. 4) and by the shutter slaved status lights mounted on the OWR console (Fig. 8). The shutter console and the slave display panel also show the status of the shutter shield tray and the cave door (open or closed).

The shutter shield tray will fall any time the +26-V dc control path is opened, that is, when the cave door is opened or when the electronic timer is timed out. If at any time the four-way hydraulic valve is electrically disabled, a spring returns the valve to the de-energized position so that hydraulic oil can be

pumped back to the hydraulic reservoir by the shutter shield tray weight.

Two safety features of the control circuit are the cave safety SCRAM switch and the cave clock-alternating current relay combination. By hitting the cave SCRAM switch, the control system will be disabled and the SCRAM switch must be reset after each use. The cave clock-alternating current relay combination allows five minutes after the +26-V dc control path is broken before clock reset.

Danger could exist if the various electrical control contacts became stuck with the cave door open with the reactor at full power. This condition is detected and announced by the Radiation Detection and Annunciation System described in Sec. VI.

If the 110-V ac power or +26-V dc control power, or both, fail, the system will fail safe because the shutter shield tray will fall and remain in the DOWN (safe) position.

The Kirk Key System ensures that if the door or control panel is unsafe (door open or neutron shutter control panel energized), the other is locked so that the system is safe.

The control cables used throughout the shutter system are all Twisted Shielded Pair (TSP). The TSP shields are grounded at one end only for noise suppression.

A 0- to 30-V dc, 1.5-A adjustable power supply was used throughout the shutter control system with the direct current voltage adjusted to +26-V dc because the brightness of the cave door lights on the shutter display panel (Fig. 8) on the OWR console had to match the brightness of the other shutter and curtain status lights.

The "N.S. UP" and "N.S. DOWN" lights (Fig. 4) are actuated by microswitches located inside the cave.

The terminal blocks (TB's) inside the shutter control console used for +26-V dc control and lighting interconnections are distinct from the +26-V dc power distribution terminal block and the 110-V ac power distribution terminal block.

All wiring inside and outside the cave (Fig. 2) is encased in electrical conduit. The control wiring, power cables, and signal cables inside the cave had to be encased inside electrical conduit because explosives occasionally will have to be radiographed.

Fig. 5.
Front view of the neutron shutter shield tray in the UP (open) position.

Fig. 6.
Neutron shutter hydraulic pumping system with blast shield DOWN.

Fig. 7
Functional diagram of neutron shutter interlock electrical system.

VI. RADIATION DETECTION AND ANNUNCIATION SYSTEM

Figure 9 is the schematic diagram of the gamma-ray radiation detection and annunciation system. Figure 4 shows the Nuclear Measurements Corporation (NMC) GA-2A gamma console.³ This console contains the electronic circuitry necessary to process and annunciate gamma-ray conditions inside the cave. The GA-2A gamma console is a fail-safe instrument, so that if the critical electronic circuitry inside the NMC GA-2A fails, the radiation high level red light will glow.

The gamma-ray detector tube is located inside the cave above, and in line with, the thermal column gamma neutron beam. When the OWR is producing power, gamma rays will also be present with the thermal neutrons coming out of the thermal column porthole. The gamma-ray detector tube (which is omnidirectional) uses a NaI scintillator and a photomultiplier tube. The signal from the photomultiplier tube is transported through a shielded cable inside various electrical conduits to the NMC GA-2A console. The end of the gamma detector tube has a ²²⁶Ra source attached so that a small-scale deflection will always be present on the NMC GA-2A module meter as long as the GA-2A console has power applied. The small-scale deflection also indicates to the shutter operator that the NMC GA-2A electronic circuitry is working for small signals.

The analog gamma dose rate output from the NMC GA-2A module is displayed on a 10- to 10 000-mR/h (milliroentgen per hour) nonlinear scale (Fig. 4) and is also displayed on a large remote slaved gamma meter (10- to 10 000-mR/h) mounted on the wall inside the cave where it is visible to anyone entering the cave. The two gamma meters (connected electrically in series) were calibrated together with the NMC GA-2A electronic module by LASL Group P-6.

The NMC amber light information (left light, Fig. 4, on lower portion) is slaved to the gamma meter scale inside the cave and to the shutter status light panel on the OWR console (Fig. 8). The circuitry to accomplish this is shown in Fig. 9. The NMC GA-2A amber light circuitry was modified so that the amber light will glow when 110-V ac power is applied to the

GA-2A module and when the GA-2A meter pointer is above the lower meter setpoint. If the amber light is not glowing, the shutter operator and the OWR operator know that either the power to the NMC GA-2A module is off or the NMC GA-2A circuits are not functioning properly.

The red light on the NMC GA-2A gamma console (Fig. 4) lights any time the indicating needle in the meter reaches and touches the upper limit set point. Both the upper and lower set points in the NMC display meter are adjustable. The red light information (Fig. 9) is slaved to the red light mounted on the remote gamma indicating meter inside the cave, and is also transported to the neutron shutter status light panel mounted on the OWR control console (Fig. 8).

The neutron shutter control circuitry and the NMC GA-2A circuitry are interconnected so that the gamma alarm bell (Fig. 4) only rings when (1) the shutter 110-V ac power system is on, *and* (2) the cave door is open, *and* (3) the upper limit set point pointer is making contact with the indicating meter needle. Conditions (1), (2), and (3) could only occur if the reactor power level is high and the cave door microswitches (microswitches 1 and 2) probably have both been defeated, and if the shutter tray were raised or restrained to the UP position. This represents the worst possible radiation accident condition.

VII. HYDRAULIC AND PNEUMATIC SYSTEM

Figure 10 is a one-line schematic of the hydraulic and pneumatic system for the neutron shutter system.

The air hose (rated at 1.7237 MPag) connects the OWR supply line (0.620 MPag) to the air-hydraulic motor and is beneath the OWR steel mezzanine floor to prevent a rupture in the air hose from harming personnel working nearby. The air hose connects to the air solenoid valve actuated by the control system. The output from the air-solenoid valve goes to the air-hydraulic pump (Fig. 6).

Because of its reliability and speed, a hydraulic system was chosen to raise and lower the shutter shield tray. For high-quality neutron radiographs (Fig. 11), the opening and closing times of the shut-

ter must be small compared to the total radiographic exposure time. The time to raise the shutter tray (which weighs approximately 373.24 kg) is 2.5 s and the fall time of the shutter is 3.0 s. It would be difficult for an electric motor chain driven or worm gear driven system to raise the heavy shutter tray in 2.5 s or less. Even if a chain or worm gear raising mechanism were used, it is very doubtful that it would be as reliable as the air driven hydraulically operated system being used.

The hydraulic pumping system (Fig. 6) is a compact, reliable, easy-to-maintain system. The exhaust from the air driven hydraulic pump (Fig. 10) is vented through air hoses and pipes to the outside of the OWR building to keep the noise levels down. The hydraulic low-pressure input to the pump connects to a hydraulic reservoir. The hydraulic high-pressure outlet from the pump goes to an adjustable pressure relief valve, which adjusts to relieve from 3.447 to 13.789 MPag. The output line from the pressure relief valve goes to an accumulator (which acts as a hydraulic capacitor) connected in parallel to the high-pressure line, which then goes to a solenoid-controlled four-way valve. When the control system electrically actuates the four-way valve, the input high-pressure fluid is routed through the four-way valve to the tubing leading to the hydraulic ram attached to the shutter shield tray. When the four-way valve is de-energized electrically (removing the +26-V dc control voltage), a spring inside the four-way valve returns the valve mechanism to the un-energized position and in this position low-pressure hydraulic fluid can return from the ram to the hydraulic reservoir. The top of the hydraulic ram is always covered with hydraulic oil (factory recommended) using a low-pressure return line to the hydraulic reservoir.

All hydraulic tubing is 1.270-cm o.d., 0.0762-cm wall thickness, Type 316 stainless steel tubing. The burst pressure of this tubing is around 103.4 MPag. The working high pressure varies from 1.034 to 4.482 MPag, thus the connecting tubing has a safety factor of 24, which is the worst case. The tubing connections are all Swagelok-Crawford and are the type used in nuclear power plant control lines because they are highly reliable, leakproof, and very easy to install.

The hydraulic pumping system has two bleed

valves to bleed off pressure. If one bleed valve fails, then another bleed valve is available as a backup. This is another fail-safe feature of the shutter system. Two hydraulic pressure gauges monitor the high-pressure lines so that if one fails, a backup exists.

The hydraulic tubing from the pumping system to the inside of the cave (where the hydraulic ram is located) is underneath the OWR mezzanine floor to prevent a rupture in the tubing from injuring personnel working close to the neutron shutter. The tubing to the cave is 1.270-cm o.d., 0.0762-cm wall thickness, Type 316 stainless steel and is inside conduit tubing so that if a break should occur in the 316 stainless steel tubing, the conduit tubing would contain the rupture; another fail-safe feature. The rupture would be fail safe because the shutter tray would fall to the safe shielding position and because the flying hydraulic oil would be contained by the surrounding conduit tubing.

The hydraulic pumping system is grounded electrically to the OWR system ground and to the OWR mezzanine steel floor to which the pumping system is bolted.

A blast shield made of 1.27-cm-thick, clear Lexan is positioned over the hydraulic pumping system (Fig. 6). This allows continuous, safe monitoring of the various pressure gauges and other equipment in the hydraulic pumping system and allows detection of leaks or ruptures. Figure 6 shows the hydraulic pumping system with the blast shield in the DOWN position. One end of the blast shield is hinged so that it can be rotated about one end. The blast shield should contain the worst case hydraulic rupture that might occur if the hydraulic pump were accidentally set to put out its maximum hydraulic pressure of 32.06 MPag instead of its normal operating pressure of 4.3437 MPag.

The hydraulic oil used in the pumping system is combustible MIL-H5606 with a flash point in the range of 104.44 to 110°C. This oil was chosen because the seals and working parts of our equipment do not gum up under hydraulic pressure and this is the type of hydraulic oil used in many LASL machines.

Two fire extinguishers are close to the hydraulic pumping system; one is a CO₂ and the other is a dry chemical.

The air pressure switch is mounted in the air pres-

Fig. 3.

Neutron shutter and curtain slaved status lights and shutter master key on OWR control console.

NOTE: ARROWS INDICATE DIRECTION OF FLUID FLOW.
• INDICATES A PIPE CONNECTION.

Fig. 10.

Neutron shutter hydraulic and pneumatic system one-line schematic.

NOTE: • INDICATES AN ELECTRICAL CONNECTION.
N.C = NORMALLY CLOSED CONTACT,
N.O = NORMALLY OPEN CONTACT.

Fig. 9.

Radiation detection and annunciation system schematic.

Fig. 11.

Thermal neutron radiograph of an explosive timer. Side view of timer.

sure line that goes from the air solenoid valve to the reciprocating air motor. The high-pressure hydraulic switch is mounted in parallel with the high-pressure line leading to the electrically operated four-way valve.

The air pressure switch and the hydraulic pressure switch both have mechanical hysteresis built into them. This means, for example, that the switch might electrically close at 1.034 MPag, but it would not open until, say, 0.965 MPag. This mechanical hysteresis prevents chatter or switching uncertainly around the actuation (of contact close) point. Both pressure switches have actuation points that can be adjusted mechanically within ranges. The adjustment range for the air switch is 34.47 to 172.37 kPag. The adjustment range for the hydraulic switch is 0.689 to 1.72 MPag. The adjustability of the actuation points for both pressure switches allows a large range of operating points for the shutter control system.

The high-pressure hydraulic tubing inside the cave that connects to the hydraulic ram is made of 1.270-cm o.d., 0.16510-cm wall thickness, Type 347 stainless steel. Its burst pressure is 158.6 MPag, providing a safety factor of ~ 35.4 .

If the shutter tray becomes stuck in its UP position, then bleed valve 1 and/or bleed valve 2 (Fig. 6) can be turned to relieve the hydraulic pressure and lower the shutter tray.

VIII. SHUTTER SHIELD ASSEMBLY

The front view of the shutter shield assembly is shown in Fig. 1. The shutter shield tray, which goes up and down, can be seen attached to the hydraulic ram. A Lexan blast shield surrounds the hydraulic lines leading to the hydraulic ram.

The original shield design used a depleted uranium filled shutter shield tray with the depleted uranium peripheral shielding stacked along both sides. LASL Monte Carlo MCNG, Mode 1, calculations⁵ were made on the original shutter shield tray design, revealing that additional shielding for gamma rays and slow neutrons would be needed near the shutter tray-cave wall interface. This additional shielding was added after the original shielding design was tested with the reactor level at 8 MW.

The test not only verified the Monte Carlo calculations, but also showed that considerable, fast neutron, thermal neutron, and gamma streaming occurred along the small cracks between the peripheral stationary shielding and the shutter shield tray. Also, high radiation levels existed beneath the shutter shield tray.

Additional boral-lead-polyethylene sandwiches and borated polyethylene blocks were added to correct the above problems.

Gadolinium paint⁶ was applied to surfaces where thermal neutron levels were high. These surfaces included the sides of the shutter tray, the cave wall adjacent to the thermal neutron port, and the top surfaces of the shutter shield tray.

Neutron clay⁶ was used to shield against thermal neutrons in difficult geometry areas where the above-mentioned shield sandwich could not be installed easily.

When the shutter tray was raised and lowered during the shutter system preoperation tests, the tray sometimes wanted to rotate about the tray pivot point, knocking loose some peripheral depleted uranium shielding. This problem was corrected by adding antiroll bars close to the shutter pivot point.

Two, three-sided, clear-Lucite hand and body protectors were designed, built, and placed on top of the depleted uranium peripheral shielding to prevent contaminating personnel working nearby.

Two holding-bar assemblies, made of Type 347 stainless steel, are used to hold mechanically the shutter tray in the UP position for neutron thermal column maintenance. The strength of the original holding-bar assemblies was questioned by OWR operating personnel, so two new ones were built.

A LASL expert in stress analysis (J. W. Neudecker) did a stress analysis on the original assemblies to determine their breaking strength mechanically. The safety factor of each holding assembly was 5.8.

The new holding bar assemblies are far superior to the original ones, and radiographs were made of the two new assemblies as a quality assurance (QA) measure. The two new assemblies also underwent a complete ultrasonic and dye penetrant inspection as a further QA measure and no flaws were found by any of the nondestructive testing examinations.

IX. CONCLUSIONS

The above described fail-safe neutron shutter system performs very well with little or no maintenance, and the shutter system produces very good neutron radiographs.

The neutron flux impinging on the radiographic film, measured by LASL Group H-1 using the gold foil method, was 3.876×10^6 (neutrons)/cm² · s. This flux value closely agrees with Morris Battat's, Group T-1, calculated thermal neutron flux.

Microfilm copies of the as-built drawing were placed in a LASL fire-proof vault, as were wire lists, a Xerox copy of the shutter log book, and the quality assurance report.

The shutter system can be summarized as a foolproof, fail-safe neutron shutter system.

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the blast shield inside the cave. He assisted David Sachs in designing the antiroll bars, adjusting microswitches, and installing pressure switches.

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