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CONCRETE FOR RADIATION SHIELDING--IN PERSPECTIVE

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A historical outline of the use of concrete for radiation shielding is presented with particular emphasis on the Hanford operations in the state of Washington.

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THE FIRST HANFORD REACTORS WERE BUILT ABOUT 25 YEARS AGO. REACTOR SHIELDING CONSISTED OF ALTERNATING LAYERS OF STEEL PLATE AND SHEETS OF MASONITE. THE STEEL PROVIDED DENSITY; WHEREAS, THE MASONITE (A COMPRESSED WOOD PRODUCT) SUPPLIED THE HYDROGEN REQUIRED FOR ATTENUATING HIGH-ENERGY NEUTRONS. THE REACTOR SHIELDS WEIGHED ABOUT 265 LB PER CU FT AND PERFORMED WELL. HOWEVER, THEY WERE EXPENSIVE TO CONSTRUCT AND COULD NOT BE OPERATED AT VERY HIGH TEMPERATURES. FOR THESE REASONS, CONCRETE WAS USED TO CONSTRUCT THE BIOLOGICAL SHIELDS FOR THE SECOND GENERATION OF HANFORD REACTORS. THE PROBLEMS THAT WE ENCOUNTERED WHILE DESIGNING AND CONSTRUCTING THESE SHIELDS ARE PROBABLY SIMILAR TO THOSE FACED BY MANY OF YOU; FOR EXAMPLE:

1) WHERE CAN HEAVY AGGREGATES BE OBTAINED AND HOW TO USE THEM, AND
2) WHAT ARE THE PHYSICAL AND SHIELDING PROPERTIES OF THE RESULTING CONCRETE?

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SOMETIME PRIOR TO 1950, ENGINEERS AT THE OAK RIDGE NATIONAL LABORATORY DEVELOPED TWO TYPES OF SHIELDING CONCRETE, ONE MADE WITH STEEL PUNCHINGS AND LIMONITE AGGREGATES AND THE OTHER WITH BARITE. THE LATTER MATERIAL WAS OBTAINED FROM SWEETWATER, TENN., AND HAD A SPECIFIC GRAVITY OF AROUND 4.2. THE LIMONITE CAME FROM THE JAMES MINE IN MICHIGAN. IN ORDER TO LOCATE SOURCES OF SHIELDING AGGREGATE CLOSER TO HANFORD, WE MADE A NUMBER OF SURVEYS. OVER 200 SAMPLES OF HEAVY AGGREGATE AND SERPENTINE WERE OBTAINED AND TESTED TO DETERMINE THEIR SUITABILITY FOR MAKING CONCRETE. THE SAMPLES INCLUDED VARIOUS TYPES OF IRON ORE, BARITE, GALENA AND FERROPHOSPHOROUS. THE INVESTIGATION INDICATED THAT THERE WERE A NUMBER OF WESTERN VENDORS WHO COULD SUPPLY SHIELDING AGGREGATES OF EXCELLENT QUALITY. HOWEVER, THE BARITE IN THE WESTERN PART OF THE UNITED STATES WAS NOT AS HEAVY, OR AS STRONG, AS THAT FROM SWEETWATER, TENN. WHEREAS, MAGNETITE WITH A SPECIFIC GRAVITY GREATER THAN 4.5 WAS QUITE PLENTIFUL AND LESS EXPENSIVE. FOR THESE REASONS WE BEGAN TO USE MAGNETITE AND OTHER IRON-BEARING AGGREGATES TO PRODUCE HIGH-DENSITY CONCRETE. OUR FIRST MAGNETITE CONCRETE SHIELD WAS BUILT IN 1951. THE MAGNETITE HAD A SPECIFIC GRAVITY OF AROUND 4.2, SO THAT THE CONCRETE WEIGHED ONLY 220 LB PER CU FT. HOWEVER, WE WERE PLEASED WITH THIS WALL, AS IT WEIGHED AS MUCH PER CU FT AS THE BARITE CONCRETE PRODUCED AT OAK RIDGE.

SHIELDING CONCRETE FOR THE INLET AND OUTLET SHIELD OF THE K-REACTORS HAD TO HAVE A CHEMICAL COMPOSITION SIMILAR TO THAT OF THE OLD STEEL AND MASONITE SHIELDS. THE REQUIRED DENSITY AND COMPOSITION COULD BE OBTAINED BY USING A MIXTURE OF STEEL PUNCHINGS AND LIMONITE, SIMILAR TO THAT USED IN THE CONSTRUCTION OF THE BROOKHAVEN REACTOR. IF USED TO CONSTRUCT THE K-REACTOR SHIELDS, IT WOULD HAVE TO BE PLACED BETWEEN AND AROUND NUMEROUS, CLOSELY SPACED TUBE SLEEVES, REINFORCING BARS, AND OTHER EMBEDMENTS. HOWEVER, IT WAS DOUBTFUL IF THIS TYPE OF CONCRETE, WHICH WEIGHED 265 LB PER CU FT, COULD BE PLACED SUCCESSFULLY UNDER SUCH DIFFICULT CONDITIONS BY MEANS OF THE CONVENTIONAL METHOD. FOR EXAMPLE, IF THE

CONCRETE WAS TOO STIFF WHEN PLACED IN THE FORMS, VOIDS MIGHT RESULT. IF TOO WET, THE STEEL SLUGS WOULD LIKELY SEGREGATE FROM THE LIMONITE MORTAR. THUS, WE DECIDED TO USE THE PRE-PLACED AGGREGATE METHOD FOR PLACING SHIELDING CONCRETE IN THE BIOLOGICAL SHIELDS OF THE NUCLEAR REACTORS BEING BUILT AT HANFORD IN THE 1950s. (THE PRE-PLACED AGGREGATE METHOD IS CURRENTLY REFERRED TO AS THE PA METHOD.) QUALITY CONTROL PROCEDURES WERE DEVELOPED TO ASSURE THAT THE PA CONCRETE, MADE WITH SPECIAL SHIELDING AGGREGATES, WOULD HAVE THE REQUIRED UNIFORMITY, DENSITY AND COMPOSITION, AND THAT IT COMPLETELY FILLED THE FORMS. THE DECISION TO USE CONCRETE TO CONSTRUCT REACTOR SHIELDS WAS JUSTIFIED BY 1) ITS SUPERIOR STRUCTURAL STRENGTH, 2) ITS SHIELDING EFFECTIVENESS, ESPECIALLY AT HIGH TEMPERATURES, AND 3) THE LOWER COST OF CONSTRUCTION. A SAVINGS OF OVER 11 MILLION DOLLARS WERE REALIZED BY USING HIGH-DENSITY CONCRETE TO CONSTRUCT THE BIOLOGICAL SHIELDS FOR THE TWO K-REACTORS INSTEAD OF STEEL AND MASONITE.

THE PRE-PLACED AGGREGATE (PA) METHOD PROVED VERY EFFECTIVE FOR PLACING HIGH-DENSITY CONCRETE IN SHIELDING STRUCTURES WHEN CONDITIONS WERE DIFFICULT AND THE FORMS RESTRICTED. THIS WAS ESPECIALLY TRUE WHEN THE PRE-PLACED AGGREGATES CONSISTED OF TWO OR MORE TYPES OF AGGREGATE, SUCH AS STEEL PUNCHINGS AND LIMONITE. THE LIMONITE, USED AS COARSE AGGREGATE, HAD TO BE STRONG AND RELATIVELY FREE OF FINE DUST. IN ADDITION, LIMONITE USED IN REACTOR SHIELDS HAD TO BE DENSE AND HIGH IN HYDRATED WATER. THIS REQUIRED A SPECIAL TYPE OF ORE. OUR INVESTIGATION OF AGGREGATE SOURCES LOCATED ONLY THREE VENDORS WHO COULD SUPPLY THIS QUALITY OF MATERIAL, ONE OF WHICH WAS IN PRODUCTION AT THE TIME. LIMONITE-GOETHITE ORE WAS EVENTUALLY PROCURED FROM A MINE LOCATED NEAR MONTELLO, NEVADA, AND WAS USED TO CONSTRUCT SHIELDS FOR THE TWO K-REACTORS. THIS MATERIAL WAS VERY TOUGH AND HAD A HIGH WATER CONTENT; HOWEVER, THE MINE WAS DEPLETED OF HIGH-DENSITY ORE BEFORE THE PURCHASE ORDER WAS COMPLETED. A SMALL AMOUNT OF LIMONITE WAS SUBSEQUENTLY OBTAINED FROM THE JAMES MINE TO COMPLETE THE JOB.

AT THE PRESENT TIME, I DON'T KNOW WHERE TO OBTAIN LIMONITE AGGREGATES HAVING THE PREMIUM SHIELDING QUALITIES OF THE TWO TYPES USED TO CONSTRUCT THE K-REACTOR SHIELDS. THE JAMES MINE, I AM TOLD, IS FILLED WITH SEEPAGE WATER; WHEREAS, THE THIRD SOURCE MENTIONED ABOVE IS NOT IN PRODUCTION. IF I HAD TO HAVE SOME LIMONITE AGGREGATES FOR SHIELD CONSTRUCTION IN THE NEAR FUTURE, I WOULD PROBABLY HAVE TO FACE THE SAME PROBLEMS TO OBTAIN THEM AS I DID EARLIER. THIS IS ONE PROBLEM AREA THAT HAS NOT CHANGED OVER THE YEARS. IF ANYTHING, IT IS WORSE, AS I DON'T HAVE THE JAMES MINE TO BACK ME UP.

ALTHOUGH THE PRE-PLACED AGGREGATE, OR PA, METHOD WAS USED TO CONSTRUCT A NUMBER OF REACTOR SHIELDS AT HANFORD, OTHER METHODS WERE INVESTIGATED AND USED WHEN FEASIBLE. AS A MATTER OF FACT, THE BULK OF THE CONCRETE USED TO CONSTRUCT RADIATION SHIELDING STRUCTURES HAD A NORMAL WEIGHT OF 150 LB PER CU FT AND WAS PLACED BY CONVENTIONAL METHODS. ON THE OTHER HAND, THERE WERE TIMES WHEN SPECIAL METHODS WERE UTILIZED FOR PLACING HIGH-DENSITY CONCRETE. FOR EXAMPLE, AFTER CONSTRUCTION WAS UNDER WAY FOR A FUEL-PROCESSING PLANT, CERTAIN EQUIPMENT WAS CHANGED. THIS MODIFICATION REQUIRED MORE GAMMA SHIELDING IN A PARTICULAR BARRIER WALL. IT WAS TOO LATE TO DOUBLE THE THICKNESS OF THE WALL, SO PLANS WERE MADE TO INCREASE ITS DENSITY. ALSO, THERE WAS NOT ENOUGH TIME TO PROCURE STEEL PUNCHINGS OR FERROPHOSPHOROUS. FORTUNATELY, THE AEC HAD ON HAND SEVERAL THOUSAND TONS OF STEEL SLUGS, TWO TO FOUR INCHES IN DIMENSION. THIS MATERIAL HAD BEEN EXCESSED OFFSITE AND OBTAINED FOR SHIPPING COSTS. BECAUSE OF SIZE RESTRICTIONS, IT COULD NOT BE USED IN REACTOR CONSTRUCTION. NECESSITY IS OFTEN THE MOTHER OF INVENTION: THUS, THE "PUDDLING" METHOD WAS CONCEIVED. THE LARGE CHUNKS OF STEEL WERE SUBSEQUENTLY USED TO CONSTRUCT THIS BARRIER WALL. THE "PUDDLED" CONCRETE WEIGHED OVER 310 LB PER CU FT.

ANOTHER INNOVATION IN SHIELD CONSTRUCTION WAS THE USE OF SHOTCRETE TO CONSTRUCT THE WALLS OF A LARGE HOT CELL IN 1959. TESTS INDICATED THAT HIGH-DENSITY

CONCRETE COULD BE PLACED EFFECTIVELY IN VERTICAL SHIELDING WALLS. UNIT WEIGHTS OF 235, 280, 287, AND 325 LB PER CU FT WERE OBTAINED WITH THE FOLLOWING SANDS: MAGNETITE, FERROPHOSPHOROUS, A MIXTURE OF STEEL SHOT AND MAGNETITE, AND FINE STEEL SHOT, RESPECTIVELY. WE WERE REALLY INTERESTED IN USING MAGNETITE SAND, AS THIS MATERIAL WAS AVAILABLE IN QUANTITY ON SEVERAL BEACHES OF THE LOWER COLUMBIA RIVER. EVEN WITH THIS RELATIVELY INEXPENSIVE SOURCE OF MAGNETITE, IT WAS NECESSARY TO RECLAIM AND WASH THE REBOUND SAND. OTHERWISE, THE SHOTCRETE METHOD WOULD NOT HAVE BEEN COMPETITIVE WITH MORE CONVENTIONAL METHODS FOR PLACING MAGNETITE CONCRETE.

TWENTY YEARS AGO, LITTLE WAS KNOWN ABOUT THE PROPERTIES OF HEAVY AGGREGATES AND VARIOUS TYPES OF SHIELDING CONCRETE. TO OBTAIN DATA REQUIRED FOR SHIELD DESIGN, AN EXTENSIVE TEST PROGRAM WAS INITIATED IN 1948 AND CONTINUED UNTIL ABOUT 1965. THIS PROGRAM WAS FUNCTIONAL IN NATURE RATHER THAN INVOLVING FUNDAMENTAL RESEARCH. TIME WAS LIMITED FOR A GIVEN SERIES OF TESTS. DESIGN AND CONSTRUCTION SCHEDULES HAD TO BE MET. THUS, ONLY THOSE TESTS REQUIRED TO DEMONSTRATE THE ADEQUACY OF A PARTICULAR TYPE, OR TYPES, OF SHIELDING CONCRETE WERE PERFORMED.

ALTHOUGH HANFORD HAS AN EXCELLENT CONCRETE CONTROL LABORATORY, IT DOES NOT HAVE FACILITIES FOR PERFORMING GENERAL RESEARCH ON CONCRETE PROPERTIES. FOR THIS REASON, CONTRACTS WERE ESTABLISHED WITH OTHER LABORATORIES. WE SUPPLIED THEM WITH SHIELDING AGGREGATES, DESIGN MIXES, AND TEST PROCEDURES. FOUR TYPES OF SHIELDING CONCRETE AND ONE STRUCTURAL CONCRETE WERE TESTED AT THE UNIVERSITY OF WASHINGTON DURING 1952. FROM 1953 TO 1965, OUR TESTS WERE PERFORMED BY THE CORPS OF ENGINEERS AT THE NORTH PACIFIC DIVISION LABORATORY LOCATED IN TROUTDALE, OREGON. DURING THE LATTER PROGRAM, 11 TYPES OF SHIELDING CONCRETE WERE INVESTIGATED, INCLUDING 5 KINDS OF PA CONCRETE. OVER 40 TYPES OF MORTAR WERE ALSO TESTED. THE FOLLOWING TYPES OF AGGREGATE WERE USED IN THE DEVELOP-

MENT PROGRAMS: STEEL SLUGS, IRON SHOT, FERROPHOSPHOROUS, LIMONITE, GOETHITE, HYDROUS-IRON ORE, MAGNETITE, ILMENITE, BARITE, SERPENTINE, AND CONVENTIONAL SAND AND GRAVEL. BESIDES THE USUAL CONCRETE TESTS, PHYSICAL PROPERTIES WERE DETERMINED ON AIR-COOLED SPECIMENS THAT HAD BEEN PREVIOUSLY HEATED AT ELEVATED TEMPERATURES UP TO 350 C.

RADIATION SHIELDING PROPERTIES OF SEVERAL TYPES OF CONCRETE WERE DETERMINED BY PLACING CONCRETE SLABS IN TEST WELLS LOCATED IN AN OPERATING HANFORD REACTOR. AN ARRAY OF NEUTRON DETECTORS AND EQUIPMENT FOR MEASURING GAMMA RADIATIONS WERE PLACED BETWEEN THE VARIOUS ATTENUATION SLABS. ATTENUATION MEASUREMENTS WERE MADE ON THE FOLLOWING TYPES OF CONCRETE: IRON-LIMONITE, IRON SERPENTINE, MAGNETITE-LIMONITE, MAGNETITE, FERROPHOSPHOROUS, BARITE, AND CONVENTIONAL. DATA DESCRIBING THE RESULTS OF THE HANFORD ATTENUATION TESTS ARE SUMMARIZED IN THE ENGINEERING COMPENDIUM ON RADIATION SHIELDING, BEING PUBLISHED BY SPRINGER-VERLAG.

WE WERE SUCCESSFUL IN DEVELOPING VARIOUS TYPES OF HIGH-DENSITY AND IN USING THEM TO CONSTRUCT BIOLOGICAL SHIELDS. HOWEVER, WE WERE NOT SO SUCCESSFUL IN OUR ATTEMPT TO DEVELOP A CONCRETE THERMAL SHIELD. (A THERMAL SHIELD, WHILE EXPOSED TO HIGH TEMPERATURES, ALSO RECEIVES INTENSE LEVELS OF GAMMA RADIATION AND NEUTRON FLUX.) PHYSICAL AND THERMAL PROPERTIES WERE DETERMINED FOR A NUMBER OF REFRACTORY MORTARS MADE WITH BORON ADDITIVES AND ONE OF THE FOLLOWING AGGREGATES: STEEL SHOT, FERROPHOSPHOROUS, FERROSILICON, TABULAR ALUMINA, ALUMINUM PELLETS, OR SILICON CARBIDE. THE AGGREGATES WERE SELECTED BECAUSE OF THEIR STABILITY AT HIGH TEMPERATURES AND THEIR HIGH THERMAL CONDUCTIVITY. MOST OF THE MORTARS HAD ADEQUATE STRENGTH AT ELEVATED TEMPERATURES; HOWEVER, THEIR THERMAL CONDUCTIVITY DROPPED APPRECIABLY WHEN HEATED. WORK WAS DISCONTINUED AFTER IT WAS DECIDED TO USE BORON STEEL PLATE, AND NOT CONCRETE MORTAR, FOR FABRICATING THERMAL SHIELDS AT THE N-REACTOR.

AT ONE TIME IT WAS NOT KNOWN IF SATISFACTORY SERPENTINE AGGREGATES COULD BE OBTAINED FOR USE IN PA CONCRETE. THEY WOULD HAVE TO BE STRONG, AS WELL AS FREE OF ASBESTOS FIBER. FOR THIS REASON, TESTS WERE PERFORMED TO DETERMINE IF HYDROUS AGGREGATES COULD BE MANUFACTURED BY CRUSHING HARDENED MORTAR MADE WITH PORTLAND CEMENT AND WATER. THE CONCEPT SHOWED PROMISE; HOWEVER, THE PROGRAM WAS STOPPED AFTER SUITABLE SERPENTINE AGGREGATES HAD BEEN LOCATED. ADDITIONAL RESEARCH MIGHT HAVE DEMONSTRATED THE FEASIBILITY OF THE TWO CONCEPTS DESCRIBED ABOVE. HOWEVER, THERE IS STILL AN ECONOMIC INCENTIVE TO DEVELOP A TYPE OF CONCRETE OR MORTAR WHICH COULD BE USED TO CONSTRUCT THERMAL SHIELDS, AS CAST IRON AND BORON STEEL SHIELDS ARE VERY EXPENSIVE.

MUCH HAS BEEN ACCOMPLISHED DURING THE PAST 25 YEARS AT HANFORD, AS WELL AS AT OTHER REACTOR SITES. WE KNOW BY EXPERIENCE THAT SPECIAL AND HIGH-DENSITY CONCRETES CAN BE FORMULTED AND PLACED SUCCESSFULLY BY A NUMBER OF METHODS. IN RETROSPECT, I BELIEVE THAT ANY SUCCESS THAT WE HAVE HAD AT HANFORD WITH RADIATION SHIELDING CONCRETE WAS DIRECTLY RELATED TO THE QUALITY OF AGGREGATES THAT WE WERE ABLE TO OBTAIN FOR SHIELD CONSTRUCTION. THE EFFORT EXPENDED IN LOCATING AND OBTAINING THESE PREMIUM AGGREGATES WAS JUSTIFIED IN MANY WAYS. IT ALSO HELPED US AVOID CERTAIN PROBLEMS THAT HAVE BEEN EXPERIENCED AT OTHER REACTOR SITES. FOR EXAMPLE, ALL OF OUR CONCRETE MIXES HARDENED NORMALLY, INCLUDING THOSE MADE WITH FERROPHOSPHOROUS. GAS GENERATION HAS NOT BEEN TROUBLESOME. AGGREGATES USED IN SHIELD CONSTRUCTION WERE NOT CHEMICALLY REACTIVE WITH PORTLAND CEMENT, INCLUDING SOME WHICH CONTAINED PYRITE. MINIMUM CONCRETE DENSITIES WERE OBTAINED WITHOUT DIFFICULTY. NO SIGNIFICANT VOIDS WERE LEFT IN THE CONCRETE SHIELDS. OUR QUALITY CONTROL MEASURES, SPECIFICATIONS AND THE EXPERTISE OF OUR CONSTRUCTION PERSONNEL ALSO CONTRIBUTED TO THE SUCCESSFUL COMPLETION OF THE WORK.

CONSIDERABLE INFORMATION IS PRESENTLY AVAILABLE ON THE PROPERTIES OF SHIELDING CONCRETE. IN ADDITION, STANDARDS FOR HEAVY AGGREGATES AND FOR CONSTRUCTING CONCRETE RADIATION SHIELDS ARE AVAILABLE. THUS, THE ENGINEER CAN PROCEED WITH MORE ASSURANCE THAT HIS SHIELD DESIGN WILL FUNCTION PROPERLY, THAN HE COULD A NUMBER OF YEARS AGO. HOWEVER, HE STILL NEEDS ADDITIONAL INFORMATION ON ITEMS SUCH AS: 1) THE EFFECT OF GAMMA RADIATION AND NEUTRON FLUX ON CONCRETE PROPERTIES, 2) THE EFFECT OF HIGH TEMPERATURES, 3) CREEP, 4) THERMAL PROPERTIES, 5) WATER MIGRATION, AND 6) THE BEST TYPE OF AGGREGATE FOR A PARTICULAR SHIELD DESIGN. TESTING IS COMPLICATED BECAUSE OF THE WIDE VARIETY OF AGGREGATES AND CONCRETE THAT ARE BEING USED TO CONSTRUCT RADIATION SHIELDS, AND BECAUSE EACH TYPE MAY BE EXPOSED TO ELEVATED TEMPERATURES AND DIFFERENT ENVIRONMENTS.

REFERENCE TO THE PRINTED PROGRAM FOR THIS SEMINAR, INDICATES THAT A NUMBER OF THE DELEGATES ARE CONCERNED WITH THE ABOVE PROBLEMS. I, FOR ONE, AM LOOKING FORWARD TO HEARING THEIR REPORTS AND OF LEARNING ABOUT RECENT ADVANCES IN THE USE OF CONCRETE FOR NUCLEAR REACTORS.

Discussion by Bryant Mather

Dr. Davis, in all three of his papers on shielding concrete, makes reference to ferrophosphorus-aggregate concrete. He stated[1] "All of our concrete mixes hardened normally, including those made with ferrophosphorus. Gas generation has not been troublesome." In the appendix to his second paper[2] it is reported that permeability tests could not be made on ferrophosphorus-aggregate concrete because gas was generated in the specimens and prevented movement of water through them. Ferrophosphorus is mentioned in the third paper[3] as a material that can be used with serpentine in shielding concrete. I should like to call attention to problems that have been encountered by others who have used ferrophosphorus as aggregate. ASTM Designation: C 638-69T[4] states that ferrophosphorus "may radically affect setting time of concrete, and will result in the generation of flammable and possibly toxic gases which can develop high pressures if confined." Clendenning, Kellam, and MacInnis[5] have described the experience of Ontario Hydro as related to evolution of hydrogen gas. They mention minor explosions of hot-cell windows traceable to the use of ferrophosphorus concrete. They abandoned the use of ferrophosphorus after

(1) "Concrete for Radiation Shielding - in Perspective" (Session 1)

(2) "N-Reactor Shielding" (Session 12).

(3) "Iron-Serpentine Concrete" (Session 13).

(4) 1969 Book of ASTM Standards, Part 10.

(5) Journal, American Concrete Institute, Proc., Vol.65, December 1968, pp 1021-1028.

the problem of gas evolution developed and completed the work using metallic iron. The U. S. Atomic Energy Commission reported[6] a high-pressure gas release in a 6-in. diameter shield plug in the wall of a radioactive materials laboratory hot cell. The plug, which was steel-encased, 3-ft long, and 200 lb in weight was found on the floor in the operations area into which it had jetted out of the cell wall after internal pressure had ripped open the circumferential weld on the inner end plate. Subsequent inspection revealed convex ends on most of the 1/4-in. steel plate ends of the other plugs. About 90 of the 100 plugs were found to have internal pressure. The plugs contained ferrophosphorus-aggregate concrete. Unpublished data from the Tennessee Valley Authority and from Mr. R. S. Barneyback, Jr., Director of Research, Kaiser Sand and Gravel, Oakland, California, report ferrophosphorus-aggregate concretes that evolved acetylene gas, that failed to develop set in 30-days time after mixing, that evolved hydrogen gas, and that manifested serious spontaneous spalling and cracking beginning several months after placement. Since the explanation for these various forms of undesirable behavior is as yet not adequately known, I conclude that it is prudent not to use ferrophosphorus as aggregate in shielding concrete since there is no procedure that I know of to insure that future experience will be satisfactory--as was that reported by Dr. Davis.

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(6) USAEC "Serious Accidents, No. 295," 9 December 1968.