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**AEC
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**FORMULATION AND EVALUATION
OF INSPECTION PROCEDURES
FOR THE APPLICATION OF SAFEGUARDS
TO THE YANKEE NUCLEAR POWER STATION**

July, 1965

RELEASED FOR ANNOUNCEMENT
IN NUCLEAR SCIENCE ABSTRACTS

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FOR THE APPLICATION OF SAFEGUARDS
TO THE YANKEE NUCLEAR POWER STATION

By

D. P. Granquist

July 9, 1965

RELEASED FOR ANNOUNCEMENT
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APPLIED MATHEMATICS DEPARTMENT
PACIFIC NORTHWEST LABORATORY
Richland, Washington

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FORMULATION AND EVALUATION OF INSPECTION PROCEDURES
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INTRODUCTION

Article II of the Statute of the International Atomic Energy Agency provides that the Agency "shall ensure, so far as it is able, that assistance provided by it or at its request or under its supervision or control is not used in such a way as to further any military purpose." To implement this responsibility, Safeguard agreements are entered into between the Agency and one or more Member States in which the Member State(s) agrees not to use certain items in such a way as to further any military purpose, and also agrees to allow the Agency the right to observe compliance with such undertaking. An agreement placing the Yankee Nuclear Power Station at Rowe, Massachusetts, under international Safeguards was entered into force on August 1, 1964. The Agency has started work under this agreement, and inspectors from the Agency have officially visited the Yankee Reactor site on several occasions.

Discussions with Mr. W. A. Strauser of the Division of International Affairs at Germantown on February 3, 1965, provided a basis for initiating an independent evaluation of appropriate procedures for Safeguarding the Yankee facility. A letter from C. A. Bennett to J. M. Musser dated February 18, 1965, set forth the following frame of reference for this report:

- a. The Safeguards Procedures as presently defined by the Agency will be followed.
- b. Provision will be made in the study to treat the Yankee Reactor as a facility to be inspected independent of its environment.
- c. The procedures to be developed will assume that Safeguards start with the receipt of fissionable material at the reactor and end when the material is shipped from the site. It should be noted that in a complete Safeguards system the fabrication and eventual dissolution of fuel will also be subject to appropriate inspection under Safeguard Procedures.

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SUMMARY

A careful evaluation of the Safeguards problem in a nuclear reactor area shows that it is primarily a function of exact fuel inventory. Any inspection procedure involving less than full time resident inspection depends almost entirely upon

- a. a positive identification of fuel pieces through the total system, and
- b. the absolute containment of neutrons to their intended use within the reactor.

Fuel contained within the Yankee reactor is tamper-proof during reactor operation. The positive identification of fuel outside of the reactor requires some additional development effort. Available information shows that it is almost impossible to obtain any appreciable number of neutrons external to the Yankee reactor.

DISCUSSION

In general, any inspection and control system designed to prevent the loss or misuse of special materials may be divided into two parts: (a) Direct Observation, and (b) Material Balance Accounting. The subject is treated below with respect to the present problem.

DIRECT OBSERVATION

Direct observation at a reactor site is treated in two subdivisions which are distinguishable chiefly as a function of time.

Initial Inspection

In a general case, the IAEA Inspectorate would conduct inspections during reactor construction. These preliminary inspections would insure that the as-built drawings are accurate and that at least one or two of the inspectors have accurate, detailed, and first-hand knowledge of the mechanical features of the plant. In the case of an operating reactor, such as Yankee, this "pre-inspection" phase is obviously impossible. This particular study has

been largely based, therefore, on verbal discussions and written material which has been assumed to be correct. Such an assumption may or may not be true for other situations. In particular, a Safeguards organization should have the right to verify such information to the extent necessary. The IAEA has this right per paragraphs 51 and 52 of GC(LX)/294.

The time, effort, and degree of emphasis needed to acquire a detailed knowledge of a particular site will vary depending upon the site under consideration. Primarily, an inspector must know what is normal before he can sense what is abnormal.

The main objective of an initial inspection is to personally verify that the available information as recorded on paper, such as that available in drawings, operating procedures, and log books, agrees with what is actually there and how it is operated. The number, size and location of all major equipment pieces should be verified. Items affording access near or to the reactor, including piping, electric cable, access ports or doorways, elevators, etc., need verification. A few simple measurements with portable instruments are relatively easy to do and would provide checks on the system. Unirradiated fuel elements might be checked for physical size, weight, and identifying marks. Process piping and vessels could be checked for size, and in some cases, the contained material could be sampled. Portable clamp-on volt-ammeters can be used to establish the input to a variety of electrically-driven (AC) prime movers. Simple thermometers or portable potentiometers with thermocouples could furnish temperature measurements. Some of the electrical and temperature readings will be duplicated on plant instruments, thus furnishing an additional check point. Finally, it is recommended that detailed inspection be made of all available gauges and recorders. Readings should be consistent with past experience as recorded on plant operating logs. The plant operator should be capable of explaining apparent discrepancies noted during inspection.

It is estimated that for maximum effectiveness an inspector should devote on the order of a month's time in residence during this initial inspection phase for the Yankee Reactor. About two weeks of this allotted time would have to be timed to coincide with a reactor shutdown so that at least semi-direct observations could be made of the reactor, heat exchangers, pumps, etc.,

located within the containment shell. A part of the specifics of Safeguard procedures will evolve from the initial inspection.

Observation of Reactor Operation

Safeguards control by observation of operation at the Yankee Reactor should be relatively easy provided that means can be found of positively identifying fuel elements. The present schedule at Yankee calls for reactor operation for about eleven months followed by a month of down time for refueling and maintenance. During the scheduled shutdown about one-half of the 76 fuel bundles in the core are removed to the Spent Fuel Pit and new unirradiated fuel bundles are added to the fuel core. The removal or charging of fuel to the reactor core requires that the reactor be shut down and that the reactor lid be removed. It is impossible to remove fuel from within the reactor while it is operating.

A. Control of Fuel Elements within the Reactor

It should be possible to employ safing wire techniques on the missile shield located above the reactor lid without too much interference with normal reactor operation. In addition, the blank inserted in the fuel discharge chute during reactor operation should be amenable to safing wire techniques. Removal of highly radioactive material other than through the regular fuel discharge chute might be possible, but it would certainly be difficult to accomplish. Rather complete descriptions of one system of safing wire techniques are contained in RL-REA-2228, Tamper-Indicating Safing System, July 6, 1965. (Official Use Only) A potential drawback exists where safing wire(s) are used by non-resident inspectors. There are occasions where a reactor operator would have a legitimate reason to break a safing wire. Normally, an action of this sort would be reported to the IAEA "without delay." No research has been directed towards developing methods which will positively determine whether the safing wire was broken on the date specified or at an earlier time. There are methods of alleviating the difficulty. If the possible discrepancy occurs only once, there may be little to worry about because the magnitude of the possible diversion tends to be small. Repeated discrepancies are cause for alarm and could be treated by increasing the inspection frequency.

The potential effectiveness of safing wires in this application can be enhanced by using them in a series or multiple fashion. At Yankee, for example, we propose attaching safing wires to both the missile shield and to the blank in the fuel discharge chute. Under normal conditions the reactor operator may have to remove the missile shield for some reason, such as repairing a control rod drive. There should be few, if any, legitimate reasons for removing both safing wires at once except, of course, during a normal charge-discharge of the reactor. Thus, if it is possible to place two or more safing wires at different locations along a possible diversion route, it would appear difficult to invent a logical excuse for breaking all of the devices between inspections.

The alternative to a safing wire technique to control removal of fuel elements from the reactor core is to have random inspection of the reactor with a mean time interval of about three weeks. Presumably such an inspection procedure would be regarded as inferior, by the IAEA because of manpower cost, and by the operator of the Yankee Reactor as a nuisance.

It appears virtually impossible to obtain a significant number of neutrons at the Yankee Reactor except in the reactor itself. We would suppose, however, that the IAEA Inspectorate would personally wish to verify this conclusion. It might be possible in the general case to somehow line the inner wall of the neutron shield tank (i.e., adjacent to the reactor pressure vessel wall) with a uranium blanket. At Yankee, the thermal neutron flux level at the neutron detectors located in the neutron shield tank is only about 1×10^9 nvt. The production of appreciable quantities of plutonium requires a thermal flux of at least 10^{12} nvt.

B. Control of Fuel Elements Outside the Reactor

The single most important Safeguards question is whether or not the fuel bundle(s) which arrives at the site is the same one(s) placed in the reactor; and that the fuel bundle(s) removed from the reactor is the same bundle(s) eventually shipped to the chemical processing plant. At Yankee, the fuel material which arrives (3-5% U-235 in U-238) is probably not as important in a Safeguards problem as the plutonium-bearing fuel which is shipped.

Ideally, the fuel manufacturer would incorporate a permanent "fingerprint" into the fuel bundle which could be positively identified when the fuel was received, when it was loaded into and then out of the reactor, and finally when it was shipped. It is of course much preferred to validate entire tube bundles (76 in reactor core) rather than the 23,142 individual fuel rods which form the fuel bundles. This preference leads to the conclusion that the end fittings and the method of fastening individual tubes into the end fittings are of primary importance in this Safeguards problem. In the Yankee case, there appears to be a possibility of removing the end fixture (nozzle assembly, spacer, and end plate), on which the identifying markings are stamped, from the fuel tube bundle. On the fuel bundle displayed at the site, the eight cap screws holding the nozzle assembly to the fuel end plate were restrained from shaking loose by three detents in a metal sleeve(s). Unless these cap screws were permanently fastened, such as by welding, it is probably possible to remove the end fixture with its identifying marks and attach it to a substitute fuel bundle.

Hopefully, the method(s) of identifying a fuel bundle (or its "fingerprint") is nondestructive, inexpensive, and requires a minimum amount of time. Two or perhaps three methods offer possibilities.

(1) Photography

If the tube bundle can be regarded as a single integral unit, photographs of random markings such as a weld bead provide nearly conclusive evidence of identity. Non-random markings, such as stamped serial numbers, can probably be closely duplicated. A sufficient number of jigs must be used to position the camera and fuel bundle in identical relative positions for successive photographs. The Stanford Research Institute has studied this problem under SRI Contract 244/RB, Development of a Photographic Identification System for Fuel Elements. A description of an operating unit is provided in DP-931, "A Periscope for Viewing and Photographing Radioactive Objects under Water," November 1964 by F. J. Locke. Before complete reliance is placed on a photographic identification system, it is recommended that some experimental effort be directed towards determining the permanency of the markings to be photographed.

Small changes will be expected to occur in the appearance of a fuel element or its markings due to corrosion, erosion, or deposition of various materials, especially during irradiation in a reactor core. The degree of permanence of a specific marking will be a function of the marking itself, the material on which the marking was made, and on the environment to which the marking was exposed.

(2) Gamma Ray Spectrometry

Theoretically, it would seem that gamma ray spectrometry should provide an accurate method of analyzing fuel elements. Uranium-235 in unirradiated fuel may be determined by application of this method to within about 2 to 3 per cent under suitable conditions. When measuring a Yankee tube bundle, however, the outer rods would seriously attenuate any gamma or X-rays emitted from the more central rods. Thus, it would seem possible to interchange central rods without having much effect on a gamma-ray dosage detectable at the surface of the tube bundle. The close rod spacing (0.082 inches) does not permit the insertion of any (at least of conventional) probes to the interior. A further discussion on the probable limitations of gamma ray spectrometry is contained in Appendix (I).

The Research and Development Section, Physics and Instrument Department of Battelle-Northwest, has developed a gamma-ray spectrometer which takes advantage of known relationships for the formation and decay of radioisotopes. This instrument is to be used at Hanford to check the "age" of irradiated fuel elements. This particular instrument can be used on HAPO fuel slugs that have up to about 150 days of "cooling" time out of the reactor. This instrument is largely solid-state, occupies a volume comparable to a filing cabinet, and was informally estimated to cost \$8,000 on a replacement basis. The possibility of patent application prevents the disclosure of further details at this time.

Such an instrument should be of value to both the IAEA inspectors and also to the reactor operator. After some minor laboratory testing for a particular case, it should be possible to

- a. provide an estimate of the U-235 content of an unirradiated fuel bundle subject to the limitations previously mentioned;
- b. check the radioactive decay of fuel element bundles in the cooling basin. If sufficient fuel bundle supports, collimators, and shielding are available to allow measurements of the same area of fuel at different times, there is a possibility of identifying a particular fuel bundle. This possibility would be expected only for irradiated fuel where the variation in gamma emission along the length of the bundle is unique to that fuel bundle.
- c. detect the presence of any appreciable amounts of U-238 or thorium that might secretly be incorporated into control or shim rods.

(3) X-ray and Radiographic Techniques

The use of X-ray or radiographic techniques would be new in this application and would require some development effort. There may be methods of incorporating randomly-spaced material of different density (to x or γ rays) into the end fixture(s), or less likely, into the fuel rods themselves which could be used to produce a characteristic "fingerprint." The development of such techniques should take into consideration that the fuel bundle before irradiation is nearly non-radioactive, and that the fuel after irradiation emits a high gamma flux. Related work is described in RL-REA-2228.

A few words in summary on Observations are in order. There are two main areas of interest provided that the initial inspection has provided an accurate set of "as-built" drawings and has enabled one or two inspectors to gain a thorough first-hand knowledge of the physical plant. These are:

- I - a positive identification of fuel elements through the entire system, and
- II - the absolute containment of neutrons to their intended use within the reactor.

Item I has been discussed at length. Fuel bundles seem safe when they are contained within the reactor. The use of safing wire techniques or frequent inspections should provide assurance that the reactor lid had not been removed. Methods of identifying fuel bundles external to the reactor are not quite as

well developed. Three methods for performing such identification were suggested which should, however, provide positive identification with a small amount of development effort.

Item II has been but briefly mentioned for the specific case of the Yankee Reactor. Photographs and visual inspection of the reactor core, of the underside of the reactor lid, and of the neutron shield tank when the reactor is shut down, combined with periodic inspection of the reactor perimeter should reveal material foreign to stated standard conditions.

MATERIAL BALANCE ACCOUNTING

Calculations of fuel burn-up and of plutonium formation require a knowledge of applicable power levels during the irradiation period. Unless it is possible for the IAEA Inspectorate to independently verify these measurements, the calculation procedure in itself provides little assurance from a Safeguards viewpoint. Therefore, lacking a resident inspector or a tamper-proof instrument, one is forced to rely on fuel piece counting. The major reason for performing burn-up calculations, based on the host nations data, might be one of establishing a "normal" burn-up. An abnormal result in future time would be indicative of operations that should be intensively checked.

It should also be pointed out that the IAEA or any other single group is bound to have some difficulty in establishing a general physics calculation code. Reactors are individual pieces of equipment, and each and every site will have established their own methods of calculation. Trying to establish one code as "the" method for calculating burn-up is bound to engender some opposition. At least part of this opposition will be sound in that codes will require modification to take care of unusual variables. This would not preclude an attempt at running a particular case through a general code, but one might occasionally expect answers which are rather inaccurate. The calculated and analytically determined answers would be expected to get better with time as cross-checks are applied. They probably will never entirely agree, however, because conditions (i.e., improved performance) at the reactor site will be expected to change with succeeding reactor fuel loadings. It should also be

noted that some of the individuals engaged in the calculations will require a complete first-hand knowledge of the reactor and its operating characteristics. This initial learning period is predicted to take in the vicinity of three to four months of work at the reactor site.

Early planning with respect to later cross-checks between reactor and dissolver measurements is highly desirable. Irradiated fuel leaves the Yankee Reactor in approximately half-core batches (say, 30 to 40 fuel bundles). A total core loading is given as 52,334 pounds (for 76 fuel bundles) of uranium dioxide. Thus, depending on dissolver equipment, it might be necessary to consider loadings ranging from 685 pounds (one fuel bundle) up to as much as about 27,400 pounds of UO_2 when processing a half-core discharge. Reactor calculations should be apportioned in a manner consistent with the data to be secured from the dissolver loadings.

Despite this somewhat pessimistic appraisal of burn-up calculations, it is recommended that the IAEA inspectors do conduct a material balance calculation on uranium-238. Only a small fraction of the U-238 is consumed within the reactor, and even large errors in a burn-up calculation will have little effect upon the estimated total throughput. The amount of U-238 found at the dissolver should check closely with the amount originally received at the reactor site minus the calculated loss due to burn-up. Thus any major (certainly five and perhaps three per cent) deletion of fuel rods should be noticeable unless fuel rods with equivalent U-238 are put back in to the system.

We note that there should be some check on the wastes presently shipped in 55-gallon drums from the plant.

RECOMMENDATIONS

The following recommendations should be regarded as tentative and subject to change. The exact definition of a Safeguards Procedure must follow the initial inspection discussed previously, as conducted by the IAEA Inspectorate. The recommendations are broadly divided into two classes: resident and non-resident inspection. The division is not distinct in the sense that there is a considerable overlap in procedure and evaluation.

It is important to understand that the chief value of resident inspection lies with an increased probability of detecting some action which differs from standard operating procedure. In a reactor area there is only a limited possibility that the securing of more accurate operating data by resident inspection will lead to burn-up calculations which are significant from a Safeguards viewpoint. On the other hand, an observation that a fuel bundle is missing would be a direct indication that a Safeguard violation is probable.

Non-resident inspectors will be more dependent upon various applications of safing wire techniques. Safing wires or any other device installed by the IAEA will have to be attached in a manner which minimizes interference with normal reactor operation. It must be possible for the reactor operator to quickly remove such devices if reactor safety or even quasi-regular maintenance is threatened. Normal operating procedure should call for notification of the IAEA within a short period of time if reactor operations require the breaking of such a seal.

Non-Resident Inspection

Assuming that the IAEA Inspectorate has acquired the basic familiarity discussed previously under the initial inspection phase, the figures which follow represent a minimum non-resident inspection effort:

- (1) Two inspectors would be required continuously when the reactor lid is off--a period of perhaps two weeks.
- *(2) At least one inspector should be present for a week preceding and a week following the time when the reactor lid is off the reactor. These people would test and inspect the fuel bundles to go in and also those removed from the reactor. Some portion of the time would also be required in inspecting safing wires before removal and in replacing them after the reactor components are back in place.

* Note that the use of a single inspector provides a means for the reactor operator to effectively deceive the IAEA Inspectorate by means of bribes and/or coercion. Presumably, the use of two or three inspectors would nearly eliminate this problem. If individual inspectors are used, it is advised that a system of rotating assignments be employed.

Discussions should be held with plant personnel to obtain information on the past performance of the reactor and on past and proposed changes in operating procedures.

- *(3) An inspector is required whenever fuel is delivered to or removed from the reactor site.
- *(4) We would recommend a visit by two inspectors every three months for time periods not covered in parts (1), (2) and (3) above, and provided that safing wire techniques are employed.

Resident Inspection

- *(1) A single individual with authority to visit any place within the plant at any time (subject to safety rules, etc.) should be able to monitor the operation sufficiently.
- (2) A supplemental inspector should be available during plant shutdown.
- (3) Special tests could be run in conjunction with a visiting inspector when required (perhaps at 2-4 month intervals). As an example, at Yankee, successive reactor cores have used increased concentrations of uranium-235 along with increased boron concentrations in the water moderator. Such changes would generally call for experiments by the reactor operator at start-up to measure such quantities as reactivity and effectiveness of control rods, both hot and cold. Such experiments could profitably be run in conjunction with IAEA assistance. Other tests might include the independent calibration of certain plant instruments or perhaps a recording of the gamma decay curve for a fuel bundle.

Safing Wires

Unless inspections take place on less than a three-week period, it is recommended that safing wires be attached to the missile shield and to the blank in the fuel discharge chute. The three-week time period was chosen in

* Refer to note on bottom of previous page 11.

this case as it was estimated by personnel at Yankee to be the minimum time required to remove and replace a fuel bundle within their reactor. For more frequent inspections (essentially resident) they are not required because of the time required to change the reactor core. A few tests might be conducted even in this case, however, in order to test the applicability of such a procedure.

Safing wires should be attached to the access lid on the roof of the Spent Fuel Pit. Depending upon operating schedules, it may be possible to use safing wire techniques on the large crane located outside of the pit, the small crane inside of the pit, or the access door used for the new fuel bundles. From a study of the drawings, it would be possible to apply a safing wire to the new fuel bundles.

Unfortunately, it appears much more difficult to use such a technique directly on the irradiated fuel bundles since they are individually stored under water in special racks. Very little of the fuel bundle except for the nozzle assembly is visible from the top of the pool.

Other Devices

Several methods and devices are available for measuring the rating of a power reactor. We have largely ignored them in this study for two reasons:

- (1) They do not give a direct measurement of plutonium production and are therefore subject to the errors associated with translating a power reading to a plutonium production figure.
- (2) Unless they are under the direct observation of a resident inspector, they are subject to tampering. Instruments having moving parts may be subject to immobilization by magnetic or electrical fields, or perhaps by chilling. Signals, especially electronic, intended to confirm instrument operability can be recorded and fed back from a "black box" at a later time with the original source disconnected.

It would be worthwhile to conduct a limited amount of research in this field. Portable accurate instruments such as those mentioned in the section on "Initial Inspection" would be of value to the IAEA Inspectorate in resolving ambiguous results.

Flux measuring instruments introduced into the reactor core would be tamper proof during operation. There may be some technical problems on the installation method used in placing such an instrument in the core, and also one might expect some reactor operators to complain about undue interference with normal reactor operation.

Records

It is recommended that the IAEA attempt to obtain and to file duplicates of most of the reports, logs, operating records, etc., of an operating plant. Their primary value is associated with cross-checks which become available and not their inherent accuracy. They should be easy to obtain and to file, and their very presence would act as a deterrent to evasive action.

It is also recommended that calculations be made and recorded of the anticipated formation and loss due to irradiation of both the fissile and fertile materials at a reactor site. Material balance accounting of the uranium-238 may be of direct value in determining reactor throughput.

EVALUATION

The Agency under the provisions of Safeguards Agreements should ideally be able to account for all nuclear material, both fissile and fertile, placed within its jurisdiction. Practically a limit of one kilogram of plutonium and/or contained U^{235} in uranium enriched above 20% has been proposed as an amount which can be exempted from safeguards control. Uranium with an enrichment below 0.2 (20%) is taken account of by multiplying its weight by five times the square of the enrichment (paragraph 22 of GOV/COM. 14/19).

It is assumed that these limits would also define diversion which should be detected with a reasonably high probability by safeguards inspections.

For the Yankee Reactor these limits translate to one kilogram of plutonium or 207.5 pounds of 4.61 per cent enriched fuel as metallic uranium. One fuel bundle at the Yankee Reactor contains 685 pounds of uranium dioxide, equivalent

to 603.8 pounds of uranium as the metal. The reactor core will consume about 200 kilograms of uranium-235 and will produce nearly 100 kilograms of plutonium in a year of operation. Therefore, an effective Safeguards procedure at Yankee cannot permit the diversion of more than about one hundred (1/3 of a complete bundle) individual fuel rods over a year's time. Certainly the diversion of a single fuel bundle could not be permitted within these limits.

This degree of control should be possible following the procedures outlined in this report provided that it is possible to positively identify individual fuel bundles. If positive identification is not possible and resident inspection is not employed, diversion to this degree by a determined operator seems possible. This is true because uranium accountability is no better than about three to five per cent for uranium-238 as estimated in a previous section, and safing techniques alone cannot absolutely prevent the diversion of fuel bundles, in whole or in part, from the storage area. It also appears difficult on a technical basis alone to estimate plutonium production at Yankee to within about five kilograms per year, which is well outside the proposed limits. It should be pointed out that continuous diversions of this order over longer periods could probably be detected by accounting techniques.

ACKNOWLEDGMENT

In conclusion, the author wishes to express his thanks to the personnel at the Yankee Reactor who generously gave of their time and knowledge in furnishing background material for this report.

APPENDIX I

A DISCUSSION ON THE NECESSITY OF
POSITIVE IDENTIFICATION OF REACTOR FUEL

For purposes of this discussion we will divide material accounting into two classes. In one class, material is grouped or summed and a material balance is made where the total input minus the total output must equal the total accumulated within the system. In the second class, each individual piece is identified and accounted for.

Group Accounting

Most business establishments are able to use group rather than individual piece accounting. As an example, a cash register will show a given total at the end of a day. Accounting is regarded as being accomplished when the value of the various monies equals the total displayed by the register. No one cares whether or not a particular coin counted at the end of a day is the identical coin tallied at the register. In fact, it is likely that it is not the original-- money is received and change is handed out all day long. The reasons that such a group accounting system works are (1) all monies of a particular denomination are regarded by everyone as identical in value; and (2) a total sum or value of money can be formed from any combination of lesser denominations which will arithmetically sum to the desired total.

Individual Piece Accounting

The reasons stated above do not generally apply where individual piece accounting is used. A typical example might be the diamond industry (gems not industrial). For this case, one carat is not necessarily equal in value to an adjacent carat and the value of the sum of two individual carats as two diamonds probably differs from two carats as a single gem.

In an analogous fashion, the amount and grade (i.e., isotopic content) of the contained plutonium in an irradiated fuel element will be expected to vary from element to element. As the discussion which follows will point out, it is almost impossible to determine precisely the amount and grade of plutonium contained within an irradiated fuel element either by calculation or by nondestructive testing. Thus the only sure way to maintain identical value in the sense of amount and grade of the contained plutonium is to actually account for the specific fuel element.

Discussion of Probable Errors in Group Accounting at the Yankee ReactorCalculations

It is understood that preliminary indications are that the Yankee Reactor core calculations agree to within about ten per cent with some early analytical data from the first core. This is considered good agreement between theory and analytical results. The calculations would not have shown such good agreement, however, without the use of considerable data derived from careful experiments. Here is a point of significant difference between what might be expected of calculations performed by people associated with Yankee and by people of the IAEA Inspectorate. Unless the IAEA Inspectorate has experimental data taken essentially by their own group(s), comparable in amount and in quality to that taken on behalf of the Yankee reactor, they cannot expect the results of calculations to be as good as those done by Yankee. It would not be surprising to find an occasional calculation which differed by fifty per cent from the true analytical value, where the calculations are based on sketchy, assumed, and/or inaccurate data. We note also that some data must be taken for as long as the reactor operates, since changes in operating conditions made to improve operating efficiency will modify the data used for calculations.

It is also true that most reactors as well as most manufacturing plants are deliberately over-designed so as to accommodate slight errors that may have occurred during design calculations. After a period of operation and the introduction of a few relatively minor engineering improvements, it is quite common to obtain a plant which operates at twenty to fifty per cent greater capacity than the nominal nameplate design rate.

A short discussion on obtaining a material balance across a reactor based on uranium-238 was given in the main body of the report.

Nondestructive Testing

If the calculations for determining the amount and quantity of fissionable material are at least difficult, if not impossible, within the limits imposed by Safeguards, what, if any, nondestructive methods are available for this purpose? Unfortunately, there are no known nondestructive tests which will give accurate measurements of fissionable isotopes for a general case with irradiated fuels. There are a few changes of a visual nature, such as stains and corrosion products, but these are more a function of the physical atmosphere (i.e., boiling

liquid coolant) rather than any indication of prior neutron density. Irradiated fuel elements emit a characteristic glow when placed in water, but it would seem likely that the direct readout of gamma would be easier to interpret than the Cerenkov glow.

Gamma ray spectrometry probably offers the best method of nondestructively examining a fuel element for Safeguards work, but it is unlikely that the method is accurate enough to serve as a total basis for this task. The concentration of U-235 can be determined within about two to three per cent on a good sample. By good we imply a flat plate (such as MTR-type fuel elements) known jacket thickness (for shielding), and a relatively nonradioactive sample. The accurate determination of U-235 or plutonium appears to be much more difficult in radioactive samples by any of the nondestructive tests that are now known. It might be worthwhile to attempt some laboratory research with this objective in mind.

Under certain conditions, it is possible to obtain some knowledge of the past irradiation history of a fuel element by gamma ray spectrometry. The total gamma count rate is an indication of the exposure level (MWD) as modified by "cooling" time, as would be the total gamma at a particular energy.

There are some difficulties in the application of gamma ray spectrometry to power reactor fuels such as those from the Yankee Reactor. Zirconium-niobium, as an example, contributes more than 75 per cent of the total gamma emitted from irradiated fuels cooled less than about 200 days. Zirconium-95 has a half-life of 65 days. After 65 days of irradiation in a reactor, zirconium-95 will reach 50 per cent of its saturation level. After another 65 days, the value is 75 per cent of saturation (i.e., the Zr again reaches 50 per cent, or one-half of saturation, but the original Zr present as the 50 per cent attained during the first irradiation period has decayed during the second period to 25 per cent, or one-fourth). Therefore, the total amount present is $1/2 + 1/4 = 3/4$ or 75 per cent of saturation. After three half lives in the reactor, or about six months for zirconium-95, the amount of fission product present will be $1/2 + 1/4 + 1/8$ equals $7/8$ or 87.5 per cent of a saturated value. Thus, the incremental increase in concentration becomes smaller and smaller, and consequently it becomes increasingly difficult to determine irradiation exposure by analyzing for fission products of short half-lives.

Another difficulty, peculiar to the Yankee reactor, is associated with the power decrease near the end of the operating period. By gradually lowering the temperature of the reactor, it is possible to extend the core life of the Yankee reactor for about four months, effecting a considerable economic saving. By assuming a linear decrease in power from 185 to 125 megawatts over a four-month period following an eight-month period at 185 megawatts, one obtains a figure of 89% of saturation for zirconium -95 (we used a half-life of two months vice 65 days). This is barely different from operating for only six months at 185 megawatts where, as shown previously, we obtain 87.5 per cent of a saturated value. In short, from a zirconium -95 analysis alone, it is not possible in this instance to distinguish between about six months of full power operation or eight months of full power followed by four months of gradual decrease as explained above.

In order to obtain an accurate gamma reading of a fuel bundle, it would be necessary to take readings along the total active length, preferably on all four sides. At least a week (i.e., 40 hours, 38 fuel bundles in a half-core discharge) would probably be required for this task. This would involve lifting the bundle from the storage rack by crane, placing it in a special holder within the water-containing storage vault, moving the counting head or the bundle relative to each other, but with geometry held constant except for the lengthwise traverse; probably rotating the bundle and again taking readings, perhaps a total of four times; and finally, replacing the fuel bundle in the storage rack. At some time during the sequence it would be necessary to identify the particular element. The total exercise appears to be time-consuming and moderately expensive. Besides the gamma ray spectrometer, special racks for counting would have to be built and placed under water within the storage facility. Besides the IAEA inspectors, it is probable that the reactor operator would have to supply a crane operator and a person responsible for the monitoring of radioactivity. Minor amounts of radioactive debris would require disposal.

One suspects that the cost in time and money which results from an adequate inspection of this type will be regarded as an unnecessary burden by the reactor operator unless he can be reimbursed. Some reduction in the inspection

effort is possible because the complete lot of fuel bundles need be examined only once. A second inspection, i.e., when the fuel is to be shipped, might be conducted on a partial lot selected at random from the total set.

Perhaps a compromise where only the visible end of the individual fuel bundles are gamma counted without removing the elements from the fuel storage rack would be the most acceptable solution at Yankee. In this case a particular fuel bundle can be partially identified through a gamma decay curve, but the IAEA inspectors will obtain only limited knowledge about the total heat output (MWD) of the fuel.

Conclusions

From the discussion above, it is apparent that we think it extremely difficult to accurately determine the amount of fissionable material contained within an irradiated fuel element without a dissolution and chemical analyses procedure. For adequate Safeguards in a reactor area, it is necessary to individually account for specific fuel elements.

Therefore, it seems that the Safeguards Inspectors are left with a choice of (1) keeping the fuel element in view at all times, (2) placing the element within a sealed vault such that the inspector(s) is present whenever the vault is opened, or (3), somehow marking or "fingerprinting" each fuel element such that each individual fuel element can be uniquely identified. In practice, some trade-off among these three alternatives can be accomplished.

At the Yankee Reactor, fuel within the reactor core during operation would meet the conditions mentioned in (2) above.

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