AEC
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BNWL-458
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**APPLICATION OF SAFEGUARDS
TO NUCLEAR FUEL - FABRICATING PLANTS**

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ARHCO for	JUNE 1967	SEP 14 1967
GE BACKMAN	60013 2710	SEP 19 1967
L. F. Wierse	60109 222-T	DEC 29 1967
L. F. Wierse	61644 271-2	DEC 29 1967
L. F. Wierse	33666 Bldg	APR 1 1968

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RICHLAND, WASHINGTON

operated by

BATTELLE MEMORIAL INSTITUTE

for the

UNITED STATES ATOMIC ENERGY COMMISSION UNDER CONTRACT AT(45-1)-1830

PRINTED BY/ FOR THE U. S. ATOMIC ENERGY COMMISSION

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TO NUCLEAR FUEL-FABRICATING PLANTS

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June 1967

Prepared for the
Division of International Affairs
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FIRST UNCLASSIFIED
DISTANCE COPY JUL 18 '67

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RICHLAND, WASHINGTON

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INTRODUCTION

This report on the application of safeguards to nuclear fuel-fabricating plants complements two earlier reports prepared by Battelle-Northwest for the application of safeguards to reactor plants⁽¹⁾ and to chemical processing plants.⁽²⁾

During the fuel-fabricating phase of the nuclear cycle, there are many possibilities of diverting nuclear material to nonpeaceful uses because: (1) the fissionable material is in bulk form and readily accessible in large quantities, (2) it is highly purified and relatively nonradioactive, and (3) it is subject to many fabricating cycles that not only add diluents and incur possible material losses, but also generate heterogeneous scrap containing unknown amounts of fissile materials. A part of this scrap is recycled directly back to the original lot of material and causes no special safeguards problems. However, another part of the scrap is often difficult, uneconomical, or simply inconvenient to reprocess on a current basis and thus is allowed to accumulate with a final assay of this material sometimes not being completed for as long as 2 years after the initial storage date.

In order to design adequate safeguards procedures for the nuclear material received by, fabricated in, and shipped from a nuclear fuel-fabrication plant, one must use the material balance concept, an essential part of which is the ability to accurately sample and measure the inventory of all safeguarded material in such a facility. In commerce and business, it is normal practice to apply material balance accounting and/or other controls to materials of high intrinsic value. Furthermore, controls are frequently applied to materials because of legal requirements arising from health or revenue considerations. In fuel-fabricating plants, where such materials as enriched uranium, U-233, and plutonium are processed, controls are necessary both because these materials have high economic value and because they are subject to stringent legal requirements.

The U.S. Atomic Energy Commission implements the safeguards programs in some of the bilateral agreements entered into by the United States.

It also supports the safeguards applied by such international organizations as Euratom and the International Atomic Energy Agency. Within these areas of responsibility, and in this report, the term safeguards is defined as the systems of procedures or controls to detect the possible diversion of nuclear materials or equipment to nonpeaceful uses.

The ever-increasing use of nuclear processes to produce electricity requires additional production sources and involves the eventual production of large quantities of plutonium, which, it is estimated, may be 100 kg per day in 1980.⁽³⁾ Not surprisingly, this increasing number of facilities producing or using nuclear materials and the consequent greater availability of these materials will increase the possibility of nuclear materials being partly diverted to nonpeaceful uses.

The discussions and procedures developed in this study assume that safeguards start when the fuel materials are received at the fabricating plants and end when the materials are shipped as fuel assemblies. In this system, a prompt conversion of recoverable scrap and wastes into a form, such as a solution, which can be accurately sampled and measured is vital for proper safeguards control. This would normally mean a closely coupled scrap processing capability.

SUMMARY

A. Safeguards Problems in Fuel-Fabricating Plants

There are three main problems in applying safeguards to nuclear fuel-fabricating facilities:

- (1) There is the problem of measuring the fuel content of a finished fuel assembly. The measurement uncertainty associated with available nondestructive methods varies widely, depending primarily on the complexity of the fuel assembly. Although a relatively high precision has been achieved in specific instances, the precisions which might be attained under inspection conditions do not appear satisfactory from a safeguards standpoint. Furthermore, in most instances the performance of the assembly in the reactor cannot be used as a basis for estimating fuel content to the required degree of precision. Once the final assembly is fabricated, there is no generally satisfactory nondestructive method of determining its fuel content. Further research and development on the nondestructive assay of nuclear fuel assemblies is needed.
- (2) Another problem is the satisfactory evaluation of fuel material contained in scrap. Fuel-fabricating processes typically cause 3 to 20% of the original material to end up as recoverable scrap or disposable waste. The heterogeneous nature of this scrap material has made its measurement, prior to actual reprocessing, notoriously unreliable. Errors of 100% or more are not unknown. In many plants a significant fraction of the recoverable scrap material is accumulated over long periods before the actual material content of the scrap is established. A meaningful material balance cannot be made until good measurements are available for all recoverable scrap and process losses.
- (3) Reactor fuel fabrication is typified by specific contracts or campaigns which call for fabricating a definite number of fuel elements or assemblies built to a specific design under rigid specifications. The specified fuel design not only varies widely for different reactors but often varies for the location within the core of a specific reactor. Furthermore, subsequent core loadings for a

given reactor often have a completely redesigned fuel. Because of the many different processes and designs which are used in fuel fabrication, it is difficult, except in a general way, to characterize the process. Thus, a "typical" process yield (in terms of percent of the input fuel material contained in finished fuel elements, recoverable scrap, recycle streams, and losses) may be typical for only one process and fuel design. Therefore, personnel who inspect fuel-fabricating plants must be capable of applying general safeguards procedures and principles to many different fabrication processes and fuel designs.

B. Conclusions

Any system of safeguards acts as a deterrent to possible diversion attempts and, if a diversion is attempted, offers the possibility that the diversion will be detected. The amount of material diverted would, of course, affect the probability of detection. An effective safeguards system requires that the inspectors have the right to obtain plant designs, material flows, and suitable accounting records to the extent necessary to account for safeguarded materials. These data provide the starting point for an inspection, or audit, either by resident inspectors or visiting teams.

It is important to recognize that most fuel-fabricating plants are contract- or campaign-oriented. The scrap associated with a given contract or campaign must be processed to the point of obtaining reasonably precise measurements to establish material balances meaningful enough to decide whether or not a diversion has taken place.

Based on this study it is concluded that

- Depending upon the size of the plant, a resident inspection team of as few as two people, working in a carefully regulated plant, provided with calibrated test standards, and having access to independent, reliable, analytical services, could in most cases achieve a diversion detection capability of about 2% for a completed campaign.
- To consistently detect diversions of less than 1% would require continuous intensive inspection of the entire fuel-fabricating

process. The improvement from 2 to less than 1% in detection capability is almost entirely due to additional containment and surveillance efforts. This intensive inspection may be difficult to justify both economically and from the standpoint of plant interference.

In a few cases supplemental information may be available to an inspection agency through independent shipper and receiver measurements. Even if these "interface" measurements are assumed to be available, and if the diversion of less than 5% of the plant throughput is of safeguards significance, some degree of resident inspection would appear to be essential for most fabricating plants.

The detection capabilities set forth in this report could vary by a factor of about 2, depending on the nature of the plant and the complexity of the process.

CHARACTERIZATION OF FUEL-FABRICATING PLANTS

A. Background

During the nuclear fuel cycle, the materials flow is interrupted several times because of different locations of the reactors, processing plants, and fuel-fabricating plants (Figure 1). Fuel-fabricating plants are neither necessarily located near reactors nor often closely coupled with fuel conversion plants. Furthermore, reactors are not normally closely coupled with the processing plants. Present and future demands for nuclear power, however, may require more closely coupled systems for the nuclear fuel cycle.

Because of these demands, and because of the importance of a complete material balance for the application of safeguards, this report assumes that a fuel-fabricating plant includes both fuel conversion of the fissile materials and conversion of recoverable scrap into a form (such as a solution) which can be accurately sampled and measured. These conversions are required in order to have the material balance completed within the fuel-fabricating plants and thus make possible a meaningful system for safeguards.

B. Conversion

The fabrication of nuclear reactor fuels from uranium, thorium, and/or plutonium consists of several process steps involving conversion of feed materials to core materials, fabrication of fuel elements, and economic recovery of scrap. During the conversion step the purified and concentrated feed materials received from the refining or chemical separating plants are converted to fuel-core materials such as metal, alloys, or oxides for use in the fabricating process. A flow diagram is given in Figure 2.

1. Uranium Conversion

A principal fuel material is uranium containing up to 93% U-235. In a typical conversion plant, uranium hexafluoride (UF_6) or tetrafluoride (UF_4) is converted to metal or oxide. As the nuclear material moves through the several conversion processes, material accounting becomes increasingly difficult.

FIGURE 1. Nuclear Fuel Materials Cycle

FIGURE 2. Feed Material Flows

The UF_6 is received in large cylinders with known tare weights. Upon receipt, the cylinders are weighed accurately and the tare weights are subtracted from the gross weights, the net weights being then recorded. The cylinders are usually placed in a secured storage area. In the United States, material control and accountability balances are established between shipper and receiver. Since this practice may not be universal, additional emphasis may have to be placed on adequate receipt measurements.

At the start of the conversion process, the cylinders are withdrawn from the storage area and connected to the process system. Heating the cylinders changes the UF_6 to a gaseous state and forces it into the conversion system. After this gas displacement, the weight of each cylinder is checked to verify the amount of uranium that may be left as residue in the cylinder. When there is conversion to metal, the UF_6 is reacted with dry hydrogen gas to form uranium tetrafluoride (UF_4) or "green salt." The UF_4 is then reduced with a metal such as magnesium in a steel container (or chemical reactor) to form the uranium metal, commonly called a "derby." The uranium derbies are vacuum melted and poured into a graphite mold. The molded material, or ingot is cooled, removed from the mold, and cut. The top section ("skull") of the ingot is removed because during cooling the impurities concentrate in the top layer by directional solidification. The remainder of the ingot is now ready for transfer to the fuel-fabricating process for core shaping.

In one typical conversion of UF_6 to uranium metal, the process yield was 97.5%. Of interest from a safeguards standpoint is the fact that the scrap generation was about 2.5%, and of this 2.5%, about 2.4% was later accounted for in analytical samples (0.1%) and in process residues such as skulls, derby slag and sand, or in residues from liquid washes of UF_4 powder, pickling liquors, etc. (2.3%). The unrecoverable waste loss therefore was about 0.1%. However, the process losses mentioned above included a significant amount of the material in heterogeneous residues that were difficult to analyze for fuel content. (Such residues are often stored until a sufficient supply of each category is available for economical uranium recovery. Only at that time is it possible to close the material balance of the conversion.)

The procedures for converting UF_6 to UO_2 for reactor fuel fabrication are also well established. In one process, UF_6 is hydrolyzed in an ammonia solution to ammonium diuranate (ADU). This product is converted to U_3O_8 which is then reduced to UO_2 with hydrogen or cracked ammonia, the material balances being similar to those in the example just described for converting UF_6 to uranium metal.

2. Plutonium Conversion

Chemical processing plants normally use solvent extraction processes to separate fission products, uranium, and impurities from plutonium. The plutonium produced is in solution as plutonium nitrate. Conversion of plutonium nitrate solutions to feeds for fuel fabricating plants can follow several processing routes (Figure 2). The plutonium feed may be in the form of metal, oxide, or nitrate solutions. The nitrate solutions can be used with uranium nitrate solutions to prepare co-precipitated UO_2 - PuO_2 powders useful as fuel in both thermal and fast reactors. The plutonium nitrate solution can be converted to the metal by several processes. These processes normally contain two generalized steps; conversion of the plutonium nitrate to a halide, and reduction of the halide with an active metal. The conversion to the halide includes such alternatives as peroxide precipitation, calcination, and hydrofluorination or oxalate precipitation, calcination and hydrofluorination.⁽⁴⁾ Plutonium oxide can be obtained from metal by oxidation of the metal, by calcination of the oxalate, or by direct calcination of the plutonium nitrate solutions.⁽⁴⁾ This conversion of plutonium nitrate to feed materials for the fuel-fabricating plants generates many different types of plutonium scrap.⁽⁵⁾ Material balances are similar to those described for conversion of uranium feed stocks to fuel core materials.

3. General Observations

Based on several plant visits, literature surveys, and experience with the research and the development fabrication of fuels, several generalizations are possible. For a highly developed process such as the conversion of UF_6 or UF_4 to uranium metal or oxide, the process yield is about 97%, with about 2 to 3% being recoverable scrap. Nonrecoverable losses are

near or below the 1% level. Conversely, with a new or complex process that involves research and development studies, the scrap generation may be up to 10% of the total material input. By using a campaign-type operation and clean-outs between jobs or at definite time periods, the in-process inventory of scrap can be minimized and the processing of scrap can be expedited. The scrap recovery or processing must be closely coupled with the conversion facilities. The recovery of uranium or plutonium scrap is discussed later in this report.

C. Fabrication

1. Process Yields and Losses

The flow of nuclear materials in fuel-fabricating plants varies with the fuel requirements of each specific reactor for which fuel is being fabricated. A generalized flow chart for the fabrication of different types of fuels is shown in Figure 3. Rapid growth of reactor and fuel fabricating technology is continually changing fuel-fabricating processes.

As nuclear material moves through the several fabricating processes, material accounting becomes increasingly difficult. The reasons for this are (1) the nuclear materials are diluted with additives or metals, and, after being enclosed in metal plates or tubes, are fabricated into fuel assemblies for shipment to a reactor; (2) throughout the several fuel-fabricating steps, scrap and wastes are produced; (Some scrap materials, it is true, may be returned or recycled directly to the process, but other scrap materials are so impure that reprocessing is required for recovery.) and (3) there are losses of materials, such as fine dusts or wastes so dilute that recovery is uneconomical.

Material control starts at the material receipt and feed storage areas. As the material flows through the process, material accounting becomes increasingly less precise. As indicated in Figure 3, measurement precision can vary from 0.5 to 100%. The highest error is associated with recoverable heterogeneous scrap or wastes from the fabricating process.

NOTE: Scrap and waste measurement errors vary from ± 5 to 100%.

FIGURE 3. Comparison of Typical Process Steps and Material Balance Measurements in Fuel Fabrication

In general, process yields are better than 90%. * Thus, the potential uncertainty in the material balance is about 10% until the recycle and scrap fuel material can be completely evaluated.

Measured material balances for a number of different fuel-fabricating jobs in the United States have indicated unrecoverable fuel losses of from slightly less than 1% to about 2%. ** The range covered by these numbers reflects both the true variations between jobs and the measurement uncertainties. Since these are average values for an entire fuel-fabricating contract, individual batch material balances will show considerably greater variations.

A recent report⁽⁶⁾ describes fabricating the last 500 fuel rods of a total of 2200 rods for the Experimental Boiling Water Reactor (EBWR). Each rod contained 829 grams of depleted UO_2 -1.5 wt% PuO_2 fuel. The mixed oxide was densified by a pneumatic impaction process and the fuel was loaded into a tube by a vibrational compaction process (Figure 4). To obtain the variable costs of the fabrication of these rods, material balances as well as labor costs were compiled. The direct material requirements and losses for each process step were obtained. Data show that the uranium unaccounted for (MUF)*** was 1.3%, with the recoverable uranium from reject fuels and samples being 9.2%. The plutonium unaccounted for was 0.7%, with the recoverable plutonium from samples and reject fuels being 7.9%. Data on fabricating mixed PuO_2 - UO_2 fuels for the Plutonium Recycle Test Reactor (PRTR), the Plutonium Recycle Critical Facility (PRCF), and Saxton reactors indicated similar process yields.

* High Flux Isotopes Reactor and Materials Testing Reactor fuel started at 60% yield and increased to 85-90% after process development. Oak Ridge National Laboratory achieved 90-95% yield on these elements (fully enriched U-Al alloy or cermet dispersion). Mixed PuO_2 fuel for the Experimental Boiling Water Reactor had an ultimate yield of about 90%.

** Based on verbal information from fuels people at Argonne National Laboratory and Oak Ridge National Laboratory, and also on Hanford experience on Experimental Boiling Water Reactor, Saxton, and Plutonium Recycle Test Reactor fuels.

*** MUF (Material Unaccounted For) is the difference between physical inventory and book inventory after the latter has been adjusted for writeoffs, accidental losses, and normal operational losses.

FIGURE 4. Fabrication of EBWR Fuel by Pneumatic-Impaction and Vibrational Compaction (Ref. BNWL-131-C)

2. Measuring the Fuel Content of Fabricated Fuels

The best available method for measuring the fuel content of fabricated fuel plates, rods, etc., prior to assembly into the fuel cluster is by gamma spectrometer scanning. Westinghouse⁽⁷⁾ has achieved precisions as high as $\pm 0.5\%$ on MTR and Engineering Test Reactor (ETR) fuel testing. ORNL⁽⁸⁾ claims about $\pm 1\%$. ANL⁽⁹⁾ achieved about $\pm 1\%$ on CP-5 fuel rods. Under typical process conditions $\pm 3\%$ may be more realistic, particularly on irregular rod type fuel designs.⁽¹⁰⁾

Fuel content of finished fuel assemblies can be determined with high precision only through individual testing of each assembly in a critical facility or test reactor, and with carefully calibrated test standards. Under these conditions a precision of about $\pm 2\%$ is readily achievable.⁽¹¹⁾ This method is, however, slow and expensive, and such a facility and the necessary test standards may not be readily available. Gamma scans on finished fuel assemblies are limited in precision, due to assembly geometry, absorption, and isotopic content. Results varying from $\pm 5\%$ to $\pm 40\%$ are achievable,⁽¹⁰⁾ depending on fuel design and availability of good standards.

Assessment of fuel content by changes in reactivity after charging the fuel into the reactor might, under the best conditions, have a precision of $\pm 5\%$; under the worst conditions, greater than $\pm 20\%$.⁽¹²⁾ Under repetitive circumstances and with nearly identical reactor conditions, experienced plant personnel could probably detect a change in fuel content with a precision of better than $\pm 5\%$. However, it is unrealistic to assume that such precision could be obtained by an inspector unfamiliar with the complete operating history of the reactor to be inspected.

3. Measuring Scrap Produced by the Fabricating Process

For heterogeneous recoverable scrap, the following are specific examples of measurement methods and problems:

- H. D. Moss and others⁽¹³⁾ describe an enriched-uranium-scrap assay gauge for estimating enriched uranium content of combustible waste and air filters. They obtained results having a precision of

about $\pm 25\%$. However, their gauge did not distinguish between different enrichments, and the results were completely invalidated if any other radioactive material was present.

- W. A. Wayles⁽¹⁴⁾ describes a 184 KeV gamma counter for measuring the fully enriched uranium contained in recoverable scrap from a fuel-fabricating process. The precision he obtained ranged from ± 5 to $\pm 25\%$, depending on the scrap type and its geometry. However, obtaining results at this level of precision depended on careful calibration against specially developed standards and full knowledge of scrap form.
- L. E. Bruns⁽¹⁵⁾ describes four different methods for measuring several types of plutonium-bearing scrap. The best precision he obtained was about $\pm 10\%$ and the poorest was $+200-50\%$.

In summary, measurements on heterogeneous scrap are rarely better than $\pm 10\%$, and are often much worse. Experience typical of scrap recovery sites in this country, indicates that dissolution of scrap followed by careful sampling normally improves the measurement to about $\pm 1\%$ or better.

D. Scrap Recovery

1. Classification of Scrap

As previously mentioned, fabricating reactor fuel also produces scrap fuel material. In highly developed processes having a minimum of complexity this may amount to as little as 3% of the total fuel throughput. At the other extreme, with a new and complex process under development, scrap may initially amount to greater than 30% of the input fuel.

Scrap fuel may be classified into one of the four following categories:

- (a) Recycle fuel material which, with minor treatment (such as remelting, rescreening, or reblending), may be returned back into the process.
- (b) High-grade fuel scrap, consisting of such material as uranium or plutonium oxide mixed with other process materials

(casting slag and dross, machine cuttings and turnings, and the like) which cannot be returned to the process without chemical recovery.

- (c) Low-grade fuel scrap, such as contaminated air filters, etching and pickling solutions, coolant oil contaminated with fines of fuel material, glove box "sweeps," and the like.
- (d) Contaminated waste, such as rags, tools, miscellaneous equipment, wash solutions, etc.

Type (d) waste is generally not economically feasible to recover. A typical approach to Type (d) waste is to make a rough estimate of fuel content of the waste by the use of gamma spectrometer or neutron count measurement prior to discard. This measurement is to make certain that the fuel contained in the waste material is negligible. Fuel material lost in this manner is normally 1.0% or less of the total fuel throughput. As with the other types of scrap, care in the process design and processing procedures will minimize this type of loss.

2. Scrap Recovery Cycle

The input to the scrap recovery cycle consists of all the high-grade scrap generated from each processing lot, together with the low-grade scrap that has been determined to be practical to recover.

a. High-Grade Scrap

Fuel content measurement of high-grade scrap material, although often very difficult to obtain precisely because of its heterogeneous form, is of critical importance from a safeguards standpoint. The reason is that this type of scrap often contains from 3 to 20% of the total input fuel material. Consequently, it is very important that this type of scrap from each processing lot be rapidly converted to a form in which the fuel content can be measured accurately and with good precision. This measurement information, fully witnessed and independently verified by a member of the safeguards team, is necessary for the material balance of the fuel material lot from which the scrap came. This information is also needed to

establish a "beginning inventory" or "head-end" measurement for the scrap recovery process.

Generally, to obtain such measurements it is necessary to proceed with the recovery process to the point of chemical leaching or dissolution of the scrap, and then to sample the solution. Insoluble residues must also be sampled, due to the possibility of there being significant quantities of undissolved fuel material.

b. Low-Grade Scrap

It is particularly difficult to sample and to analyze low-grade scrap for fuel content. Processing methods and procedures should be designed in the fuel-fabricating plants to minimize the generation of this type of scrap. As mentioned earlier, several evaluating methods have been developed for estimating the fuel content of such materials, and these should be selected on a case-by-case basis, depending on which is most suitable to the problem at hand. Generally, these techniques are based on radiation counting methods that use multiple detectors in a fixed array around the scrap container. Radiation counting may be based on total gamma count, gamma spectrometer for specified energies, or neutron counting. Scrap contained in liquids or slurries is typically handled by radiochemical analysis. Fairly homogeneous types of dry scrap may be successfully evaluated by direct sampling followed by dissolution and chemical analysis. Once an evaluation of the fuel content has been made, a decision whether or not to recover will be based on the economics of recovery. If a decision is made to discard rather than recover, the estimated fuel content of the scrap should be identified as an operational loss. Losses of this type generally are less than 1% of the total fuel material throughput.

Once scrap fuel material has been successfully dissolved, chemical recovery can be accomplished by one of several different processes. A typical uranium recovery process is shown in Figure 5, and a plutonium recovery process⁽⁵⁾ is shown in Figure 6. These chemical recovery

FIGURE 5. Uranium Scrap Recovery Process

FIGURE 6. Plutonium Scrap Recovery Process

processes are very efficient. For example, a plutonium-scrap recovery plant has operated regularly with efficiencies of better than 99.5% of the input.⁽⁵⁾

The safeguards inspection team should witness and independently verify the input or "head-end" scrap measurements, the scrap dissolution, and the measurements on the recovered fuel material. Process yields appreciably less than the average obtained from past performance should be separately investigated.

When scrap production from fuel-element processing lots is small, economics dictates that several of these small amounts having similar uranium enrichments or plutonium compositions should be batched into a single scrap lot for recovery. Measurements of such combined batches will have to be pro-rated back to the original parent lots for purposes of satisfying the material balance for these lots.

3. Summary and Observation

To summarize, in nearly all fuel fabricating processes a significant percentage of the input fuel material ends up as some form of scrap. Therefore safeguards inspection of the scrap cycle is essential. Furthermore, evaluation of the fuel content of all scrap materials must be made promptly and, in the case of recycle material and high grade scrap, with the highest precision possible. Only in this way can fuel-lot material balances provide timely warning of possible diversions. As for recycle scrap, the inspection team must witness its weighings and/or volume measurements and take independent samples to verify a fuel removal from the material balance of one process lot and to verify a reported input into the material balance for a subsequent lot. They must also observe weight and/or volume measurements on all recoverable fuel scrap after dissolution and make independent analyses to verify the quantity of fuel that the fabricator shows as a scrap removal from the lot material balance. This information also becomes the "head-end" measurement for safeguarding the scrap recovery process. Verifying the fuel material ultimately recovered from the scrap recovery cycle is necessary to safeguard the entire fuel-fabricating process.

SAFEGUARDS PROCEDURES AND EFFECTIVENESS

A. Basic Considerations

Procedures designed to verify that safeguarded material is not used to further any military purpose have two effects: (1) they act as a deterrent by reducing the probability of an attempt being made to divert material, (2) they establish a finite probability that if there is such an attempt, it will be detected. In theory, therefore, a given inspection system in a given facility cannot be completely evaluated unless these two effects are considered. In the second effect, the probability of detection will be greater or less, depending on the amount of diversion attempted.

In previous reports^(2, 16) safeguards procedures were grouped into three basic types of activity: (1) containment, i. e., the use of locks, tags, and seals; (2) surveillance, i. e., the actual observation of facility operations and concomitant activities, and (3) material accounting. Each of these activities can be considered in the light of the two measures of effectiveness, i. e., its deterrent effect and its ability to detect an attempted diversion.

Containment, probably the most effective way of deterring diversion, represents the most clear-cut case for evaluation; for if a diversion were attempted, broken locks or seals would clearly indicate the fact. However, there is an obvious difficulty here in that effective containment limits the mobility of material or restricts access of plant personnel, and this may be incompatible with the operation of the process. The fact that the neatly packaged fuel elements in reactors are almost immobile is the main reason why containment procedures provide effective reactor safeguards.

The second type of inspection activity, namely, surveillance, can both detect and deter diversion. The effectiveness of surveillance, however is very difficult to quantify. Surveillance will be more effective if conducted continuously during plant operation. Anyone planning a diversion that might be detected by surveillance will obviously make his attempt

when surveillance is minimal or absent. Hence any nonrandom or announced periodic surveillance effort would be completely ineffective against a planned diversion attempt.

Although it is very difficult to determine how a given level of surveillance affects the probability of a diversion attempt and/or the probability of detecting a given amount of diversion, it is possible to establish the relative effectiveness of different levels of surveillance. For example, if one inspector has a certain probability of observing a diversion, it is possible to compute the probability with which at least one of three inspectors acting independently would observe a diversion. Using a subjective evaluation of a base level, computations of this type have been employed to obtain the relative levels of effectiveness in given types of facilities. ⁽¹⁶⁾

Containment and surveillance procedures detect a diversion now or one recently attempted. By contrast, the use of material accounting procedures determines indirectly whether or not diversion has taken place over some period of time, i. e., it is possible through effective material accounting procedures to "catch up" with a diversion that has taken place at some time in the past. In this sense, the material balance portion of the inspection system provides an upper limit to the amount which can be diverted. On the other hand, the evidence provided by this type of inspection activity is always circumstantial unless after-the-fact investigation can provide direct evidence of diversion. There is also a lower bound to what can be detected, in the sense that some small (or perhaps not so small) amount of material can always be diverted without being detected by material accounting. Both the deterrent effect and the detection capability of material accounting are highly dependent on the amount and type of material involved.

B. Inspection Procedures

1. Preliminary Considerations

Much of the material contained in the following sections is taken directly from Reference (2). For, not surprisingly, many of the inspection principles and procedures that apply to chemical processing plants also apply directly to fuel-fabricating and conversion facilities.

It is again emphasized that planning should begin long before operation. For if independent laboratory facilities are required there may be lead-time or logistic problems which must be solved before material control at a satisfactory level can begin. Furthermore, assigned personnel must receive instructions and training before-hand so that they may go prepared. The assumption of hypothetical conditions cannot form a firm basis for operations. Because of the highly technical nature of the work involved, it is not believed that the usual stereotyped security guard force can be very effective.

The inspection team should be self-sufficient as much as possible. Plant personnel will encounter a greater difficulty in determining weak points in the safeguards program if they have only limited access to information about specific details and schedules. With careful preparation, it should be possible to carry on a significant safeguards program that would not unduly interfere with plant operation.

2. Application to Fuel-Fabricating Facilities

a. General Description of Inspection Team Duties

The inspection team should review all available design and process information before starting a formal on-site inspection. In addition to reviewing the proposed design to ensure that good accountability can be obtained, the inspection should review the proposed operating procedures, calibration procedures, sampling and material homogenization methods, accounting methods, and analytical methods. If necessary, design changes and procedures modifications could be requested to ensure better measurements and/or more effective surveillance or containment.

At an early stage in the inspection, the team should observe and verify the calibration and operation of process measuring devices, sampling tests, and other plant activities pertaining to the measurement of nuclear materials. Analytical procedures, sample handling routines, and analytical data handling and reporting routines should be reviewed and learned by the inspection team. Analytical work involving synthetic samples and pure standards should also be in progress. It is important that the inspection team verify not only the precision and accuracy of the standards but also

the general quality of the plant laboratory work. The inspection team should also review and learn the plant accounting procedures, methods of measuring volume, weights and flow; data handling procedures; and calculational routines for nuclear material balances.

The main mission of the accountability group begins with the receipt of the first batch of fuel material at the processing plant. Safeguards personnel should follow the nuclear materials from their initial receipt to their shipment as product materials. Activities should include observing all key measurements; maintaining a running material balance; and reviewing MUF's with the plant operator. An unsatisfactory material balance may call for further plant clean-out, resamples, or the recalibration of certain equipment.

Finally, after the plant has completed a campaign, it will be necessary that the team complete its material balance for the safeguarded material. A study of this material balance with due regard for its authenticity and precision will permit a decision on the likelihood of a diversion.

b. Measuring Incoming Fuel Material and Assigning Fuel Material to Processing Lots

The key to safeguards control in a fuel-fabricating plant is the processing lot balance and how the material in it is measured and controlled. (17, 18, 19) When the inspection-team accurately measures the fuel-material receipts and assigns the received fuel to process lots, then the "receipts" for the lot material balance have been established. (It should be noted that the term lot is here used to mean a definite amount of nuclear material for which the inspectors can form a material balance. Thus under appropriate conditions a lot may describe a set of completed fuel assemblies, a certain inventory of uranium dioxide, or perhaps all of the material in a given campaign.)

If there are no valid shipper's measurements on incoming fuel material, the fuel is vulnerable to diversion from the time it is received at the plant until verified receiving measurements are made. This means that the receipt of incoming fuel shipments should be witnessed by the

inspection team and locked in a secured location until sampling and lot assignment. The inspection team must witness scale calibration with controlled calibrated weights immediately prior to fuel-weight measurements. They must also witness the weight and/or volume determinations of all incoming fuel shipments, take independent samples of the fuel material, and have these samples analyzed (by an independent laboratory) for fuel content and isotopic analysis if appropriate. ^(20, 21, 22) These independent analyses must be checked against the plant receiving measurements to ensure that any differences are within the combined analytical error. Not until this is done, and the receiving values have been agreed upon between the plant and the safeguards team, and the fuel material has been divided into identifiable process lots, is there inspection-team control over the incoming fuel shipment. At this point the key head-end fuel material measurement for the lot material balance will have been verified.

The inspection team must also obtain the best possible measurement data on all "removals" from the lot material balance. This includes measurement of the fuel content of fabricated fuel components, and the maintenance of physical security on the fuel components through assembly into fuel elements and until ultimate shipment from the plant, measurements of fuel recycle material transferred to subsequent process lots, and fuel scrap measurements. Each of these key points will be discussed separately.

c. Measuring Fuel Content in Fuel Components and Safeguarding Fuel Components Through Final Assembly and Shipment

Ideally, it would be desirable to measure the fuel content of finished fuel assemblies after all fabrication work is completed and immediately prior to shipment. However, many fuel designs are very complex, and measurement of the fuel content of such assemblies by conventional nondestructive methods is unacceptably imprecise. Quite precise measurements can, however, be made on nearly all clad fuel components, prior to assembly, by utilizing gamma spectrometer testing. But a final "removal" measurement (for lot material balance purposes) at this point in the process presents three main problems to the inspection team. First, the team

must have under its control at all times a complete set of calibrated fuel test standards. These standards must have precisely known fuel content; the fuel in the test standards must be of the same composition as that being used in the process (i. e., same plutonium isotopic distribution in the case of plutonium fuels or the same U-235 isotopic content in the case of uranium fuels); the test standards must be of the identical design and fabricated by the same process as the clad fuel components to be measured; and they must be calibrated against the same gamma spectrometer test equipment that will be used in the plant. Second, the inspection team must witness the actual testing of all fuel-containing components which have passed previous plant inspections and tests and are ready for final fuel assembly. The inspection team should periodically, during testing, use its own calibration standards to recheck the test equipment. It must also keep its own record of fuel component test results (as they relate to fuel content) for the lot material-balance record. Third, the inspection team must institute some form of physical security on all tested fuel components from the moment testing is completed until the moment the fuel components are shipped from the plant as finished assemblies. Simple "piece count" records are not satisfactory because they do not guard against the possibility of substituting other fuel components similar in appearance but different in fuel content. The safeguard alternatives appear to consist of either (1) true physical security through full-time surveillance during subsequent processing and use of a safeguarded locked storage vault when not in process, or (2) use by the inspection team of some form of tamper-proof and duplication-proof marking of each fuel component immediately after testing. While the latter is far more desirable both from the plant's standpoint as well as from that of the inspection team, it may be difficult to develop a satisfactory system to accomplish it.

d. Measuring Recycle Fuel Material

Nearly all fuel fabricating processes generate a type of scrap which, with very little rework, can be put directly back into the fabricating process. Sometimes this reworked material remains in the original process lot, but more often it is transferred to a subsequent process lot because of time

delay or other considerations. When recycle material remains with the parent lot, there is no need for the safeguards team to evaluate it because the lot material balance is not affected. However, when recycle material is transferred to another lot, it becomes a "removal" from the original lot and an input or "receipt" to the new process lot. Since the lot material balance will be affected, the safeguards inspection team must witness and independently verify the fuel content of the material being transferred. The verification methods used by the inspection team will depend on the chemical and physical form of the material involved in the transfer.

e. Measuring Scrap Fuel Material

The problems associated with scrap measurements and safeguarding the scrap recovery cycle have previously been discussed in some detail in this report (see pages 16 through 21). However, fuel material scrap is considered only from the standpoint of being a key "removal" from the fuel lot material balance (and therefore requiring safeguards attention), it should, as soon as possible after generation, be processed to the point where reasonably precise measurements can be made on its fuel content. Normally this will require processing to the point of chemical dissolution. At this point the safeguards team must obtain independent, representative samples of both the solution and insoluble residues and must verify solution volume and/or solution weight and residue weight.⁽²⁰⁾ Independent analysis of these samples, together with the verified weights and/or volume measurements, should be used by the inspection team as a basis for establishing the amount of fuel material removed as scrap from the process lot material balance, and as an input or "receipt" for a material balance to be established for a scrap recovery process lot.

f. Establishing the Final Fuel Lot Material Balance

Only when the safeguards inspection team has carried out all the four previously indicated functions will it have the basis for completing a material balance for each fuel processing lot. While it is believed that these are the primary considerations in establishing the fuel lot material balances, other factors may have to be considered in some circumstances. For example, a significant accidental loss of fuel material will require the close

attention of the inspection team and full cooperation from the plant to estimate as closely as possible, through process records, effluent analyses, etc., the extent of the loss.

C. Inspection Requisites

The previous sections have described in general the how and why of fuel-fabricating plants. The paragraphs just completed have dealt with the procedures to be followed in making an inspection. It is now time to examine the inspection-team capabilities, analytical support, and rights necessary for an adequate inspection.

1. Inspection Team Capabilities

The team should be selected so that the following essential competences are collectively available:

a. Operating-Process Engineering Competence

It is important that the team competence include experience in operating plant-scale equipment in the fuel-fabricating industry. First-hand knowledge of plant operation is necessary to ensure that the operating procedures are indeed the procedures on which accountability numbers are based. The team competence should include the ability to understand logical explanations of process upsets or flowsheet changes.

b. Accounting Competence

It is important that the team skills include competence in accounting. Establishing the procedures to be used in making material balance calculations and in keeping the many records pertinent to the safeguards activity will be an important function.

c. Analytical Chemistry Competence

The inspection team should thoroughly understand the analytical requirements for sampling and measurement throughout the process. They should also have an intimate knowledge of the analytical technology used by the plant laboratory and should be able to effectively observe the work of the laboratory. Closely allied skills are

required in converting gamma scan measurements into amounts of fissionable material. Many such measurements are taken of fuel plates, rods, and assemblies as well as of assorted wastes and scrap material.

d. Health-Physics Competence

Some experience with health-physics procedures is desirable, when processing uranium, to avoid undue contamination and/or exposure of the team members. A greater competence is required when plutonium or U-233 is processed.

2. Inspection-Team Analytical Support

When conducting a safeguards inspection at a fuel-fabricating facility, the inspection team must obtain accurate analyses of its samples. In order to obtain the desired degree of independence, it is recommended that the inspection team have access to an independent "safeguards" laboratory either on-site or off-site. The relatively low radioactivity of the samples taken from a fuel-fabricating plant does make it feasible to ship them to a "home" laboratory. In some cases, it may be possible and desirable to design and operate a semi-portable laboratory located near the safeguarded facility. A safeguards laboratory located near a plant would permit the examination of a particular problem much more quickly than if the laboratory were at a distant location.

The procedures for analyzing nuclear materials have been the subject of several reviews,^(20, 23, 24, 25) and an evaluation of the precision in standard methods is now available.⁽²⁶⁾ Moreover, the American Standards Association has published a volume entitled, "American Standard Reference Methods for the Chemical Analysis of Nuclear Fuels."⁽²¹⁾

Table I lists the procedures which are either being used or expected to be used. The listed methods are specific, unbiased, and reasonably

precise. The standard deviation listed for each method is based on the average experience of the USAEC sites under the best of analytical conditions. Considerably greater standard deviations would be obtained under such adverse conditions as the unavoidable use of two-phase samples, the existence of gross impurities in the samples, and periodic outages of analytical instruments.

The methods listed in Table I are unbiased when applied to samples of known composition, namely, when the concentration of interfering constituents are known and handled accordingly. However, the presence of "unsuspected interferences" can cause method bias. Laboratory practices in sample handling and identification, prevention of "cross-contamination," and use of reagents play a key role in analytical reliability. The random use of several of the independent methods listed in Table I is especially valuable in the detection of analytical biases, particularly those which might be used to mask diversion. It is important to know the conditions that could inadvertently cause a consistent inaccuracy in the analytical results reported by a plant laboratory. Occasionally it may be desirable to analyze certain samples by a method that is the same as the plant laboratory's.

The safeguards laboratory would require some general analytical capabilities (other than those required for nuclear materials). These would include the means for (1) determining general chemical constituents and physical properties, such as impurities, acidity, specific gravity, and moisture content; (2) measuring radionuclide concentrations; and (3) preparing reagents and standards.

Finally, the importance of obtaining representative samples should be emphasized. There will be occasions where obtaining a representative sample of nonhomogeneous scrap or waste materials is very difficult. The inspection team at the plant site should decide the best way to verify the sampling. Some verification of sampling is automatically included in most analytical control programs. Further checks could include sampling the same material in several locations and sampling after various mixing times.

TABLE I

ANALYTICAL METHODS FOR NUCLEAR MATERIALS CONTROL

Sample Material	Desired Constituent	Method Description	References	Standard ^(a) Deviation Rel. , %
Uranium Metal Oxides, Nitrates, or Fluorides	Uranium	Volumetric-Dichromate	26	0.04
		Volumetric-Ceric Sulfate	26	0.2
		Controlled Potential Coulometry	26, 27, 28	0.2
		X-Ray Fluorescence	24	0.2
		Potentiometric-Ferric Sulfate	26, 28	0.1
		Isotopic Dilution-Mass Spectrometric	26, 27	0.8
Plutonium Metal, Oxides, or Nitrates	Plutonium	Volumetric-Ceric Sulfate	26	0.1
		Photometric End Point	26	0.1
		Controlled Potential Coulometry	26, 28	0.1
		Spectrophotometric	24, 29	0.2
		X-Ray Fluorescence	24	0.2
Uranium	Uranium (Isotopic Composition)	Mass Spectrometric (Surface Ionization)	26, 27, 28	0.5 ^(b)
Plutonium	Plutonium (Isotopic Composition)	Mass Spectrometric	26	0.5 ^(b)

(a) Precision estimates are based on the capability of the method under the best of conditions, e. g. , optimum concentration, freedom of interference, and routine use by typical plant laboratory. The precision of an analysis for small amounts of uranium or plutonium in a waste sample is more likely to be about 10%.

(b) Precision for a single run (10 scans) for major peaks: 235/238, 240/239.

It is necessary that the on-site inspection team have equipment for performing gamma spectrometer scans of both the fuel material and the final-assembled fuel clusters. The calibration of such instruments and the preparation of standards for them will necessitate a continuing program between the safeguards laboratory and the on-site inspectors. A brief description of the expected precisions of such measurement methods was given on page 15.

3. Inspection Team Rights

In order to carry-out the procedures for inspection (see Paragraph B-2 above), it is necessary that the inspection team have certain well-defined rights. The justification for conferring such rights on the inspection team resides in its need to establish an independent decision on the likelihood of diversion. Naturally such rights must be well defined and negotiated in advance of an actual inspection.

Generally speaking, the inspection team must have the right (1) to lock and tag such storage areas as those used for incoming fuel materials or fabricated-fuel assemblies, (2) to enter the plant in order to observe operations involving safeguarded material, and (3) to form and verify an independent material balance. (Such a right necessarily allows access to operating instruments, process logs and data sheets, and nuclear material control records.)

In the following paragraphs on inspection effectiveness there is a brief description of the specific tasks that an inspection team must perform in order to achieve a detection capability of about 2%. This detection capability assumes that the inspection team is not denied the rights necessary to perform these tasks.

D. Effectiveness

The effectiveness of a given inspection effort depends on (1) the level of the inspection effort and the manner in which it is utilized, and (2) the time period involved, both in the sense of elapsed time and the frequency of periodic inventories. The latter is particularly important to the effectiveness of material balance control at fuel-fabricating plants. The amount of inspection required for a given facility is in turn a function of the size of the facility, its mode of operation, and the complexity of the process.

The primary quantitative measure of the effectiveness of a given inspection effort is the estimated capability of an independently established material balance to detect diversion of a given magnitude. Containment procedures where applicable are presumably 100% effective in the material balance sense. Surveillance is also 100% effective insofar as direct observation of diversion is possible. Surveillance also contributes importantly to the independence of the material balance established by the inspectors.

The capability of a material accounting system can be characterized by the precision with which the material balance can be established. And, in fact, if the safeguards requirements are defined as the probability P that the diversion of an amount D should be detected, it is possible to independently establish the precision σ_s^* of the material balance required to accomplish this. We can also define σ_a , the "attainable" or "achievable" precision of a material balance for the facility in question. The precision σ_a is a function of the process, the facility,

* In this report, we use the term precision to indicate the degree of uncertainty in the measurements. It is also assumed that this uncertainty can be measured or expressed in terms of an equivalent standard deviation, designated by the Greek letter σ with an appropriate subscript. In the sense that this uncertainty includes both long and short term variability, it includes the usual concept of periodic bias. All quantitative estimates of precision are expressed at the one sigma level. Multiplying these numbers by two would give approximately the "95% limits of recognized uncertainty" as used in nuclear materials management practice.

Note that a numerically low precision is better than a high one (i.e., a MUF with a precision of $\pm 1\%$ is to be preferred to a MUF with a precision of $\pm 2\%$).

and the measurement capabilities. It should not be equated with the precision which is actually "obtained" in a plant. In some situations it may be unnecessary, and therefore probably uneconomical, to achieve a precision as good as σ_a .

We can also consider the precision σ_i of the material balance which can be independently established by the inspectors. Unfortunately, in most cases, not all of the numbers which are used to form σ_i are independently secured. Because of shortages in manpower, laboratory facilities, equipment, etc., it is generally necessary that the inspector accept some data from the plant as well as that which he can independently secure. In such cases, the calculated precision σ_i of the material balance has a finite probability of being wrong, assuming that diversion is being attempted. Therefore it is appropriate to remember that there may be a distinction between the precision σ_i as defined and the precision σ_i as calculated in actual practice. The degree to which σ_i will differ from σ_a is a function of the level of inspection, i.e., the degree to which measurements can be made independently or be certified as correct by the inspection team.

With the foregoing definitions it is possible to consider two distinct cases:

- 1) $\sigma_s \geq \sigma_a$, i.e., the precision required for effective safeguards is achievable in the facility in question. In this case we must examine the amount of effort necessary so that σ_i will be equal to σ_s ;
- 2) $\sigma_s < \sigma_a$, i.e., the precision required for effective safeguards is not achievable. In this case the only possible way of increasing the probability of detection to an adequate level is through surveillance and/or containment.

It should be noted that both σ_i and σ_a will be functions of the throughput. Their absolute values would be expected to increase with throughput. Percentage-wise they will normally decrease with increasing throughput. As previously discussed, the precision (especially σ_i) is also sensitive to the process. A process with large scrap or recycle flows and a small throughput may easily show a larger (poorer)

precision than a large throughput plant having small scrap and recycle flows.

It is also necessary to determine the required precision σ_s as a function of throughput, i.e., it will be necessary to either state the amount of admissible diversion D as a percentage of throughput, or to limit the evaluation to a fixed amount of throughput or to a fixed time period. For the type of activity involved in fuel-fabricating plants, it is probably best to think of σ_i , σ_s , and σ_a as being defined over a fixed campaign, although it should be recognized that the probability of detection may be increased by lengthening the time periods involved.

It is important to recognize the nature of the relationship between D and σ_s or σ_i . Presumably, we will suspect diversion only if the observed independent material balance shows a significant loss, say greater than $2\sigma_i$. In order that the chances of observing a loss of this magnitude be 50-50, D must be about $2\sigma_i$. To consistently observe a loss $>2\sigma_i$, say with probability $P = 0.95$, requires that D be about $4\sigma_i$. While the above argument is probably an oversimplified version of the actual decision procedure, the important conclusion is that the consistent detection of a diversion D requires that its magnitude be two to four times the precision of the material balance which can be established by the inspectors.

Studies of actual experience at domestic fuel-fabricating plants indicate that material balance precisions on the order of 0.3% (plus or minus a factor of two) are attainable by plant personnel for a given campaign under the best of conditions. Without precise scrap and waste loss measurements, this figure would be increased by at least a factor of 2 or 3, depending on the nature of the process. An inspection team which carried out the program discussed in Section B could probably establish an independent material balance over the course of a campaign with a precision of from 0.5% to 1.0% depending on the completeness of scrap recovery and the degree of verification of unrecoverable losses. The essential activities of this team are:

- (1) Independent sampling and analysis of incoming fuel materials, and verification of quantities assigned to each processing batch or lot.

- (2) Controlled preparation and calibration of fuel test standards for non-destructive testing of clad fuel components, and nondestructive testing of randomly selected components prior to assembly.
- (3) Witnessing fabrication of the fuel assemblies and regulating access to or otherwise "securing" these assemblies thereafter.
- (4) Independent sampling, analysis and volume determination of dissolved recoverable scrap, and subsequently regulating access to this solution. A key factor in the establishment of an independent material balance is the prompt conversion of recoverable scrap into a form in which it can be sampled and assayed accurately. Normally this conversion process will require dissolution.
- (5) Independent sampling, analysis, and weight verification of recycle fuel material assigned to other process batches and/or campaigns.
- (6) Establishing material balances based on fuel material input, fuel content of output fuel elements, fuel content of recoverable scrap, and recycle fuel material assigned to other batches.

To carry out these functions it is obvious that resident inspectors would be required, and that for most facilities a minimum of two inspectors will need to be available while the plant is operating. For most processes observed in this study achieving an independent material balance with less than 0.5% standard error seems very difficult even with unlimited measurement capability. Further improvement in detection capability would depend entirely on containment and surveillance. This more intensive inspection may be difficult to justify both economically and from the standpoint of plant interference.

Without resident inspection it is impossible for the inspectors to establish an independent material balance based on their own efforts. Periodic inspections can verify inventories, but they provide no control over receipts and removals. In the typical case of international safeguards, independent shipper and/or receiver measurements are not usually available. Hence periodic inspection can be effective only to the degree that it acts as a deterrent and establishes the amount of material actually present in the facility.

A somewhat different situation arises when it is assumed that independent input and output measurements from shippers and receivers are available. If these interfaces are accessible and independent measurement of shipments to and from the plant being inspected is possible, and if it is assumed that inventory can be (ultimately, at least) verified through periodic visits and prompt conversion of recoverable scrap, then the two main problems facing the inspection team are (1) the uncertainty in the independent verification of the content of finished elements received by the reactor operator and (2) the verification of stated unrecoverable losses. Of these, the former is the more serious problem in view of the present state of nondestructive measurement. Systematic retention by the fabricator of as much as 5% of the fuel material from the center of a finished assembly would probably not bias a nondestructive measurement by more than 1-2%, especially if appropriate nonfuel material were substituted. A bias of this magnitude would not be detected over the length of a typical campaign with the present precision of nondestructive scanning, particularly if the fuel assembly were of a new and unique variety with little possibility of adequate calibration. In the absence of resident inspectors such substitutions could be easily accomplished. The most probable means of detection would be the ultimate performance of the fuel-assemblies in-reactor.

In view of the above considerations, it is concluded that periodic inspection, even with the possibility of verifying shipment and receipts, could not detect with high probability, and consequently would not effectively deter, the diversion of as much as 5% of the throughput during a campaign, even though prompt scrap recovery were required. Material-balances with less than 2% standard error could be achieved, but they could not be verified in the sense discussed above. Prior to the completion of the campaign and the processing of recoverable scrap, the material balance precision would be appreciably less, and even larger diversions could go undetected.

In summary, if independent shipper and receiver measurements are not available to the inspection agency, than resident inspection is necessary to establish an independent material balance. Even if these

"interface" measurements are assumed to be available, some degree of resident inspection would appear to be essential for most fabricating plants and processes if the diversion of less than 5% of the plant throughput is of safeguards importance. If amounts less than 1% of the plant throughput are of safeguards importance, the necessary protection can only be attained through continuous observation and/or containment. These numbers could vary by a factor of 2, depending on the nature of the plant and the complexity of the process.

The application of these technical conclusions to the problem of defining appropriate safeguards effort depends on considerations such as the amounts which are of safeguards importance, the operational and administrative condition under which the inspection is to take place, and the degree to which the inspection agency has access to other portions of the nuclear cycle. If the material involved is plutonium or highly enriched uranium, and assuming that diversions of greater than 1 kg of this material should be detected with reasonably high probability to satisfy safeguards requirements, then it would appear that the "break-point" at which resident inspection becomes necessary is a campaign or contract involving more than 50 kg. If on the other hand, the inspection agency is willing to tolerate diversions of 1 kg, but want a high probability of detecting diversions of 5 or more kilograms, they could probably tolerate periodic inspection for contracts or campaigns involving less than 100 kg if reactor follow-up were possible and initial shipments were well documented, but would require resident inspection for campaigns or contracts involving more than 250 kg. For uranium of lower enrichment, the inspection requirements could be lowered or the campaign totals could be raised, depending on the relative safeguards importance of the material. Extending these comments to the safeguarding of facilities (rather than material) which are involved in continuous campaigns or concurrent contracts involves defining safeguards importance not only in terms of amounts but in terms of time, i.e., amount per unit time. Only in this way can the conclusions as to detection capability be tied to plant throughput rather than a discrete amount of material subject to safeguards.

REFERENCES

1. D. P. Granquist. Formulation and Evaluation of Inspection Procedures for the Application of Safeguards to the Yankee Nuclear Power Station, BNWL-119. July 1965.
2. D. P. Granquist and R. A. Schneider. Application of Safeguards to Nuclear Fuel Processing Plants, BNWL-301. September 1966.
3. Remarks by Glenn T. Seaborg quoted in "The Nuclear Industry-1966," USAEC Division of Industrial Participation.
4. R. E. Felt. Equipment for the Direct Calcination of Plutonium Nitrate, RL-SEP-674, General Electric Co., Richland, Washington. December 1965.
5. L. E. Bruns. Geometrically Favorable Plutonium Scrap Recovery Plant, RL-SEP-147, General Electric Company, Richland, Washington, January 1965.
6. C. H. Bloomster. Fabrication Costs for Plutonium Fuel Elements, Part B, BNWL-131B. September 1965.
7. F. J. Arsenault. Nuclear Materials Control System, (NMCS) Phase II-Field Testing of the Fuel Assay Scanner, WCAP-6042, Westinghouse Electric Corporation, Atomic Power Department, Pittsburgh. June 22, 1960.
8. Verbal, from R. W. McClung and R. G. Cardwell, Oak Ridge National Laboratory.
9. N. S. Beyer. Quality Evaluation of CP-5 Reactor Fuel, ANL, INMM, 6th Annual Meeting. May 1965.
10. Verbal, from W. G. Spear, Instrumentation, Battelle-Northwest.
11. Verbal, H. L. Henry and L. D. Williams, PRCF, Battelle-Northwest.
12. Verbal, from Reactor Physics personnel, Battelle-Northwest.
13. H. D. Moss, W. G. McNamara, D. E. Zontek. An Enriched Uranium Scrap Assay Gage, WAPD-T-1905, Westinghouse Atomic Products. June 1966.
14. W. A. Wayles, paper presented at the 1966 AEC/Contractor Meeting at Berkeley, California on Nuclear Materials Management. October 1966.
15. L. E. Bruns, paper presented at the 1966 AEC/Contractor Meeting at Berkeley, California on Nuclear Materials Management. October 1966.

16. C. A. Bennett, J. W. Healy, W. R. Lewis, J. B. Work. Control and Inspection Systems for Plutonium Production, HW-62119, General Electric Company, Richland, Washington. October 1959.
17. R. F. Lumb (ed.). Management of Nuclear Materials, D. Van Nostrand Co., Inc. Princeton, N.J. 1960.
18. R. G. Cardwell, Jr. "Materials Control in the Fabrication of Enriched Uranium Fuels," SM-67/26, Nuclear Materials Management, Proceedings of the Symposium on Nuclear Materials Management, IAEA, Vienna. 1966.
19. Nuclear Materials Control in Reactor Fuel Fabrication, Staff Members, Hanford Atomic Products Operation, General Electric Co., Richland, Washington, TID-12101. April 1961.
20. R. J. Jones (ed.). Selected Measurement Methods for Plutonium and Uranium in the Nuclear Fuel Cycle, USAEC TID-7029. 1963.
21. American Standard Reference Methods for the Chemical Analysis of Nuclear Fuels, American Standards Association, Inc., Sponsored by the American Institute of Chemical Engineers, New York. 1967.
22. American Standard A.S.A. N5.4, 5, 6, 1965. Nuclear Grade: Uranium Metal Melt Stock; Uranium Dioxide, Sinterable; and Uranium Dioxide, Compactible. American Standards Association, Inc., Sponsored by the American Institute of Chemical Engineers, UDC 621-039.543.3, New York. 1965.
23. Nuclear Materials Control in Irradiated Fuel Reprocessing, USAEC TID-12100. January 1961.
24. H. Hicks, H. Bildstein, et al. A Comparative Study of Published Methods for Qualitative and Quantitative Analysis of Irradiated and Unirradiated Fuel Samples, SGAE-PHCH-1 (IAEA Report). 1964.
25. C. C. Thomas, Jr. Analytical Procedures and Facilities for a Nuclear Materials Control System, WCAP-6032, Westinghouse Atomic Power Department. December 1959.
26. M. W. Lerner. Evaluation of the Methods in TID-7029. Selected Measurement Methods for Plutonium and Uranium in the Nuclear Fuel Cycle, NBL-231, New Brunswick Laboratory. February 15, 1966.
27. M. J. Shepard, Jr. and J. E. Rein (eds.) Manual of the Analytical Method Used by the Control Laboratory at the Chemical Processing Plants, Parts I and II, IDO-14316 (1955), Supplement 1 (1956), Supplement 2 (1957), Supplement 3 (1957).

28. Oak Ridge National Laboratory Master Analytical Manual, USAEC
TID-7015.
29. C. F. Metz. Analytical Chemistry, vol. 29, p. 1958. 1957.

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