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Optimal Allocation of International Atomic Energy Agency Inspection Resources

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OPTIMAL ALLOCATION OF INTERNATIONAL ATOMIC ENERGY AGENCY INSPECTION RESOURCES

by

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ABSTRACT

The Safeguards Department of the International Atomic Energy Agency (IAEA) conducts inspections to assure the peaceful use of a state's nuclear materials and facilities. Because of limited resources for conducting inspections, the careful disposition of inspection effort among these facilities is essential if the IAEA is to attain its safeguards goals. This report describes an optimization procedure for assigning an inspection effort to maximize attainment of IAEA goals. The procedure does not require quantitative estimates of safeguards effectiveness, material value, or facility importance. Instead, the optimization is based on qualitative, relative prioritizations of inspection activities and materials to be safeguarded. This allocation framework is applicable to an arbitrary group of facilities such as a state's fuel cycle, the facilities inspected by an operations division, or all of the facilities inspected by the IAEA.

I. INSPECTION RESOURCE ALLOCATION

Each year the International Atomic Energy Agency (IAEA) completes nearly 2000 inspections at over 400 facilities in 70 countries to confirm that nuclear materials and facilities are employed for peaceful purposes. The disposition of inspection resources among the various facilities and material categories is a complex and important function affecting the quality of the inspections and the safeguards conclusions derived from them. Because of limited inspection resources, however, the IAEA cannot fully attain its safeguards goals either quantitatively as measured by the inspection effort negotiated in facility attachments or qualitatively as measured by the Safeguards Implementation Report (SIR) Criteria. This shortfall in resources poses a difficult planning problem, requiring trade-offs in the level of safeguards for the materials and facilities under safeguards.

Under current IAEA procedures, the allocation of inspection resources assigns an essentially equal inspection effort to facilities of the same type. An alternative approach would incorporate consideration of all material categories and facilities to be assigned inspection resources when allocating effort to a particular facility. This report suggests such a method for allocating inspection resources, which is based on the safeguards criteria.

The safeguards criteria provide a framework for allocating an inspection effort that includes a ranking of material types according to their safeguards importance, an implicit definition of inspection activities for each material/facility type, and criteria for judging the attainment of safeguards goals in terms of the quality and frequency of these inspection activities. This framework is applicable to resource allocation for an arbitrary group of facilities such as a state's fuel cycle, the facilities inspected by an operations division, or all of the facilities inspected by the IAEA.

Application of the safeguards criteria for the purpose of resource allocation has several advantages. First, because the SIR Criteria are the IAEA basis for evaluating inspection effectiveness, a SIR-based allocation procedure should improve those evaluations. Second, the SIR-based allocations will improve the consistency between inspection effort and the materials with greatest safeguards importance to the IAEA. Third, because the safeguards criteria incorporate material valuations, priorities for inspection activities, and attainment levels that are qualitative, the SIR-based allocation procedures avoid the necessity to quantify subjective aspects of safeguards.

In subsequent sections, we describe the adaptation of the safeguards criteria to the inspection resource allocation problem. Conversion of the safeguards criteria to a tool for assigning inspection effort consists of

(a) interpreting the safeguards criteria as specific inspection activities for each material-category/-facility combination;

(b) calculating the annual inspection man-days required for each safeguards attainment level (the safeguards criteria recognize four levels: partial, attainment, almost timely, timely attainment); and

(c) developing allocation algorithms to maximize attainment of the safeguards criteria consistent with SIR priorities for material categories, inspection activities, and attainment levels.

II. SAFEGUARDS CRITERIA AS FRAMEWORK FOR INSPECTION RESOURCE ALLOCATION

A. Material Valuation

The safeguards criteria recognize the following material categories, which are listed in order of safeguards importance: direct-use material such as plutonium or highly enriched uranium, direct-use material in irradiated fuel, and indirect-use material such as low-enriched uranium (LEU). The relative safeguards importance is implied by the differences in the quality and timeliness of the inspection activities for each material category. For example, at bulk handling facilities for material not under containment and surveillance, the criteria for timely attainment require that direct-use material be verified monthly with at least a 0.9 probability of detecting a significant quantity defect, that spent fuel be verified every 3 months with at least a 0.5 probability of detection, and that indirect-use material be verified every 12 months with at least a 0.5 probability of detection. In general, the more attractive materials have a smaller significant quantity, a shorter interval between inventory verifications, and a higher required detection probability for defects.

B. Inspection Activities and Attainment Levels

For each material category in a reactor or bulk-handling facility, the safeguards criteria state, in general terms, inspection activities for examination and comparison of records and reports, for verification of material inventories, for verification of material flows, and for application of containment and surveillance. These activities are graded into four attainment levels according to the quality and timeliness of the inspection effort. Quality of the activity depends on factors such as the loss detection sensitivity of a verification method or the sample size of the items verified. Timeliness depends on factors such as the interval between receipt of a shipment and its verification or the frequency of inventory verifications.

The four attainment levels in order of increasing safeguards effectiveness are partial attainment of the quantity component, attainment of the quantity component, almost timely attainment, and timely attainment. Attainment of the timeliness criteria is not possible unless the conditions for the quantity component are attained, and almost timely attainment occurs when the timeliness criteria are met within 70%.

As an example, the safeguards criteria for verification of spent fuel not under containment and surveillance at a reactor are item counting for partial attainment of the quantity component, item counting and serial number verification [or attributes nondestructive assay (NDA)] for attainment of the quantity component, and fulfillment of the quantity component at 3-month intervals for timely attainment.

Using the safeguards criteria for 1986, we have converted the general criteria for the quality and timeliness of inspections into specific inspection activities. These inspection activities are summarized according to material category and facility type in the appendix. This interpretation of the Criteria reflects the author's judgment about what is necessary to satisfy the criteria and may not correspond exactly with current IAEA practice.

For those elements of the safeguards criteria requiring inspection activities at facilities, we have estimated the annual man-days for each material category, facility type, and attainment level (Figs. 1-4). Total man-days for each facility type and attainment level are summarized in Fig. 5. These estimates of inspection effort are derived from Standing Advisory Group on Safeguards Implementation (SAGSI) working group studies of the inspection effort required for each inspection activity. The reference facilities are a 1000 MWe reactor, an LEU conversion/fabrication plant with 400 tons UF_6 throughput/year, a reprocessing plant with 240 tons heavy metal throughput/year, and a mixed-oxide (MOX) fabrication plant with 500 kg PuO_2 throughput/year.

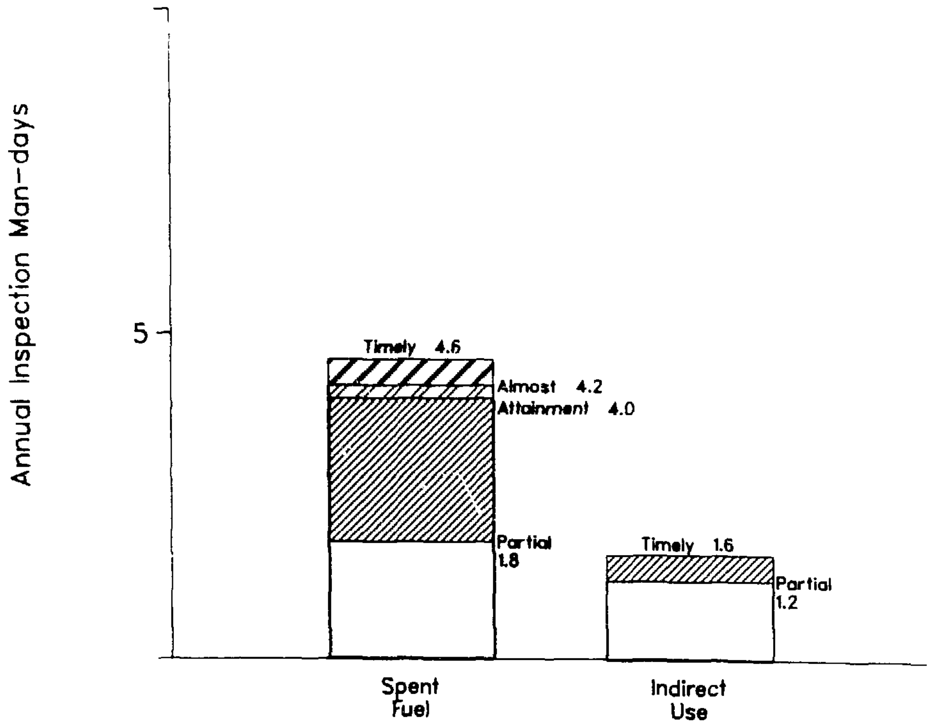

Fig. 1. Inspection man-days for SIR attainment at a light-water reactor.

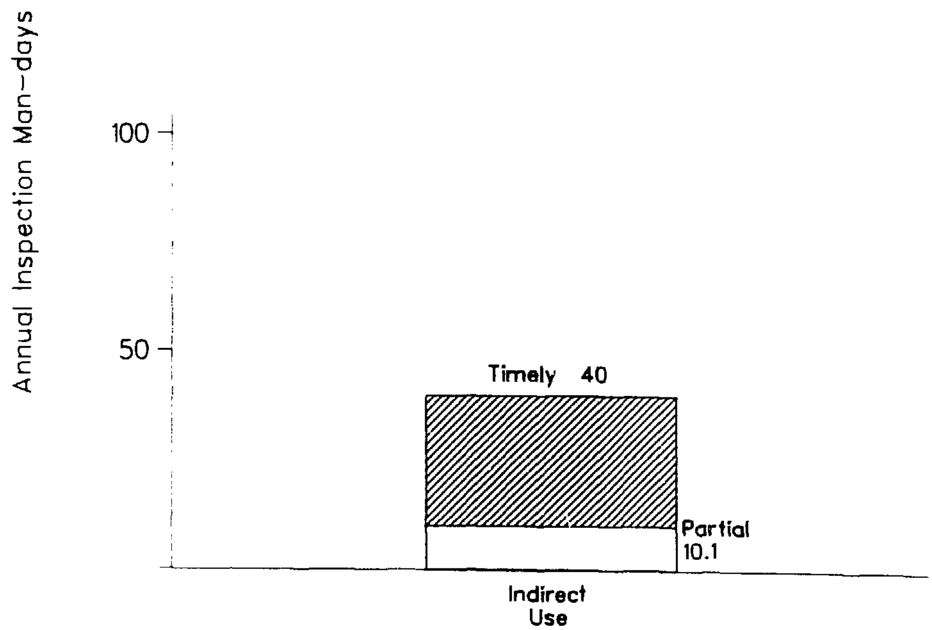

Fig. 2. Inspection man-days for SIR attainment at a conversion/fabrication plant.

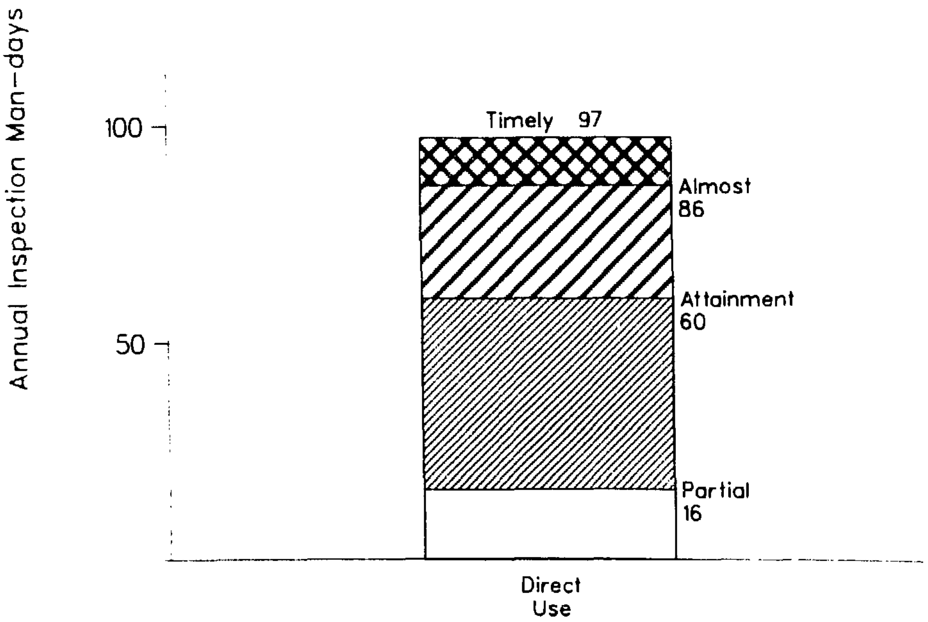

Fig. 3. Inspection man-days for SIR attainment at a mixed-oxide facility.

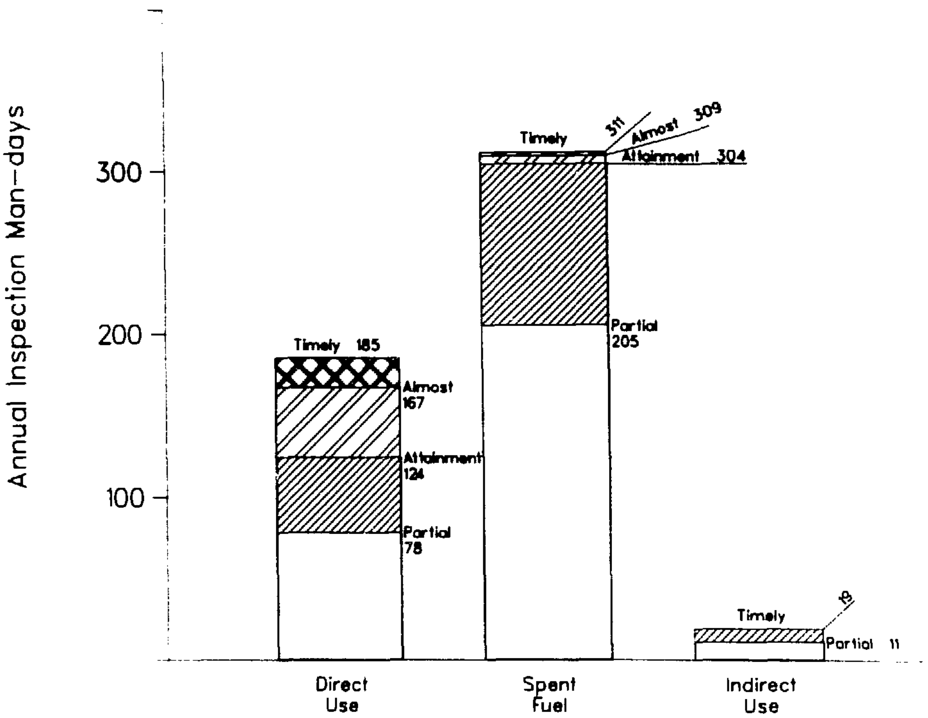

Fig. 4. Inspection man-days for SIR attainment at a reprocessing plant.

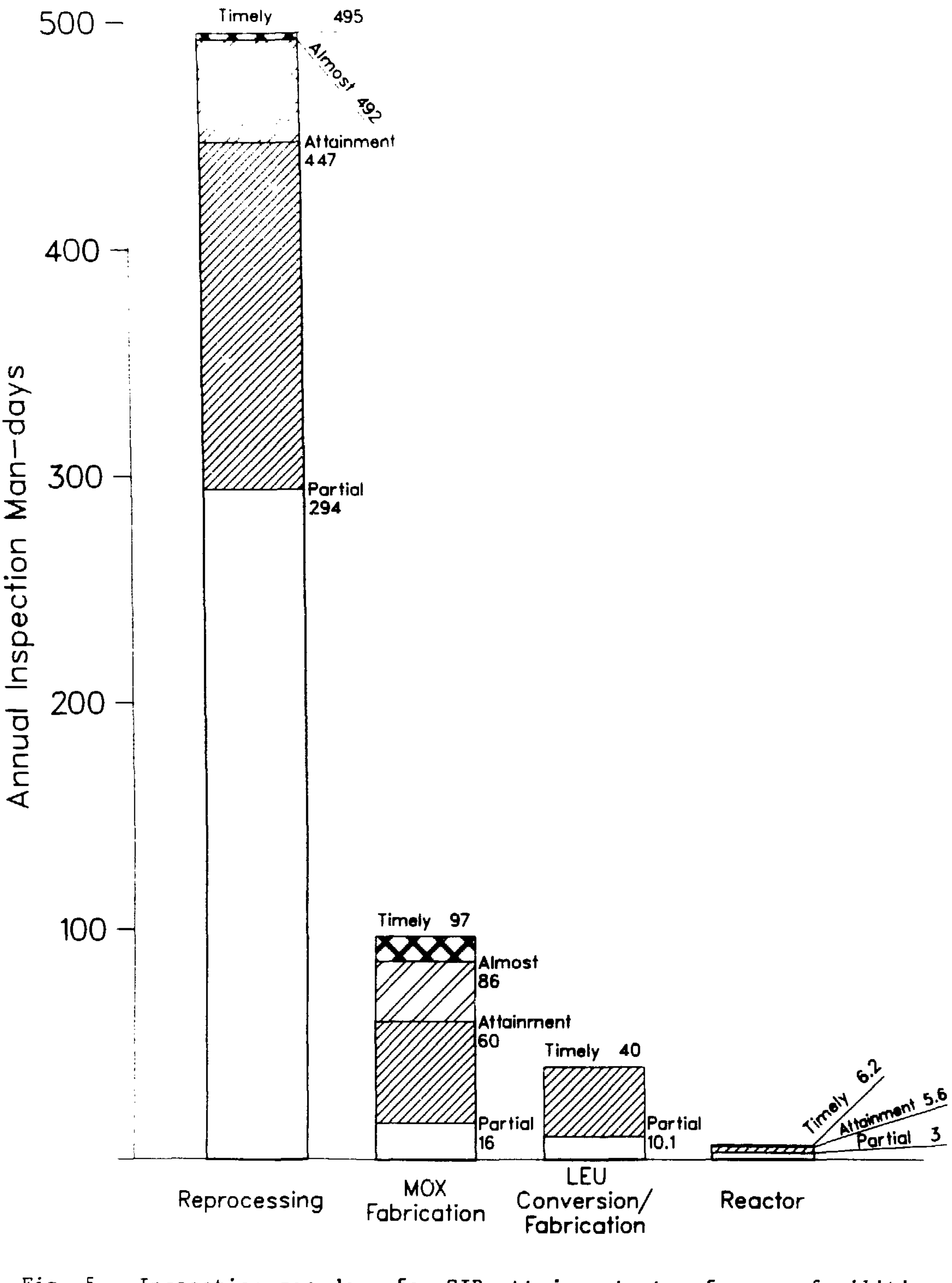

Fig. 5. Inspection man-days for SIR attainment at reference facilities.

III. RESOURCE ALLOCATION ALGORITHMS

This section describes the use of the safeguards criteria in establishing a rationale for allocating inspection effort among facilities. Our objective is to develop methods for allocation decisions that are consistent with current IAEA safeguards goals, that do not require quantification of subjective aspects, and that can be applied in a consistent way to an arbitrary group of facilities.

Previous studies formulated the resource allocation problem as an optimization problem in which a measure of effectiveness for an inspection allocation is maximized.[1,2] These studies required quantification of subjective factors, including the probability that an inspection activity (such as containment and surveillance) detects an anomaly, the relative safeguards importance of materials and facilities, and the safeguards utility of a level of inspection effort at a facility. To avoid the difficulty of determining a universally acceptable quantification of these subjective factors, the proposed allocation algorithm requires only relative, qualitative judgments. Indeed, the safeguards criteria are consistent with this approach because the material valuations, inspection activity priorities, and attainment levels are based on nonquantitative preference orders.

We formulate the problem of assigning inspection resources to a group of facilities as a constrained optimization problem in which resources are allocated to maximize attainment of the safeguards criteria subject to limitations on available inspection resources. Because our approach to assigning inspection resources emphasizes material categories rather than facilities, we do not distinguish between material of the same category at different facilities. Thus, we require resource allocations achieving uniform attainment across a material category. For example, spent fuel at a reactor or at a reprocessing plant is assigned inspection effort to achieve the same attainment level.

We denote the attainment levels for the material categories by the variables A_{DU} for direct use, A_{SF} for spent fuel, and A_{IU} for indirect-use material. These variables take one of the four values--partial attainment, attainment, almost timely, and timely attainment. To each allocation of inspection effort, we associate an attainment triplet (A_{DU}, A_{SF}, A_{IU}) that is a nonquantitative measure of the effectiveness of the allocation.

Consistent with the SIR priority for safeguarding material categories, we introduce the additional constraint that any inspection allocation should result in attainment levels satisfying

$$A_{DU} \geq A_{SF} \geq A_{IU} \quad . \tag{1}$$

In addition, the limitation on available inspection man-days that can be fielded by the operations divisions suggests a constraint

$$\text{cost}(A_{DU}) + \text{cost}(A_{SF}) + \text{cost}(A_{IU}) \leq \text{total man-days} \quad , \tag{2}$$

where, for example, cost(A_{DU}) indicates the inspection effort in man-days required to achieve a given attainment level A_{DU} for all direct-use material in the reference facilities.

Because we cannot simultaneously maximize the attainment levels for the three material categories, we construct preference orders on the attainment triplets (A_{DU}, A_{SF}, A_{IU}) that are consistent with the priorities expressed in the safeguards criteria and that allow us to identify a most preferred allocation of inspection resources.

Among the many possible preference orders for judging the relative worth of the attainment triplets (A_{DU}, A_{SF}, A_{IU}), there are two orders representing the extremes in allocation rationales. Preference order I prefers the triplet of attainment levels (A_{DU}, A_{SF}, A_{IU}) to (A_{DU}, A_{SF}, A_{IU}) when

$$A^1_{DU} > A^2_{DU} \tag{3}$$

or

$$A^1_{DU} = A^2_{DU} \qquad \text{and} \qquad A^1_{SF} > A^2_{SF} \tag{4}$$

or

$$A^{1}_{DU} = A^{2}_{DU} \quad , \quad A^{1}_{SF} = A^{2}_{SF} \quad , \quad \text{and} \quad A^{1}_{IU} > A^{2}_{IU} \quad . \qquad (5)$$

This preference ordering leads to allocations of inspection effort that favor attainment levels for the more attractive material categories at the expense of reduced attainment for other categories.

Preference order II prefers triplet (A_{DU}, A_{SF}, A_{IU}) to triplet (A_{DU}, A_{SF}, A_{IU}) when the minimum among the three attainment levels A_{DU}, A_{SF}, A_{IU} is strictly greater than the minimum among the three attainment levels A_{DU}, A_{SF}, A_{IU}. To avoid ties when these two minima are equal, we prefer the first triplet to the second triplet if either Eq. (3), Eq. (4), or Eq. (5) is satisfied. This preference ordering leads to allocations producing nearly uniform attainment levels across the material categories with preference given to the more attractive materials when complete uniformity cannot be achieved.

The optimization problem becomes: Find the most preferred triplet (A_{DU}, A_{SF}, A_{IU}) that is attainable within the constraints of inequalities 1 and 2 when the attainment triplets are prioritized using either preference order I or II.

IV. EXAMPLE FUEL CYCLES

We illustrate the application of these resource allocation procedures with three reference fuel cycles. Fuel cycle I consists of twenty 1000 MWe light-water reactors (LWRs) with fresh fuel imported and spent fuel exported. Fuel cycle II consists of 20 LWRs; 3 LEU conversion/fabrication plants each with 400 ton UF_6 throughput/year; import of UF_6 material; and export of all spent fuel. Fuel cycle III consists of 20 LWRs; 3 LEU conversion/fabrication plants; a reprocessing facility with 240 ton heavy metal throughput/year; a MOX fuel fabrication plant with 500 kg PuO_2 throughput/year; import of UF_6 material; and export of a portion of the spent fuel. These fuel cycles are based on data from SAGSI working group studies.

V. APPLICATION OF THE ALLOCATION PROCEDURE

The SIR-based allocation procedure discussed in this report was motivated by a perceived need for allocation methods that are fully consistent with IAEA safeguards objectives and avoid subjective or extraneous considerations when assigning inspection effort. A significant feature of the resulting method is its adaptive aspect, which allows a consistent allocation of resources even though the material categories and facilities of interest may vary widely. This section illustrates the advantages of using an adaptive allocation procedure.

The resource allocation examples presented in this section require estimates of the total inspection man-days theoretically available for inspecting each fuel cycle. We base these estimates on the Actual Routine Inspection Effort (ARIE) man-days as defined, for example, in Refs. 1, 3, and 4. Assumed ARIE values for the example facilities in this report are 10 man-days/year for an LWR; 80 man-days/year for an LEU conversion/fabrication plant; 180 man-days/year for a MOX fuel fabrication plant; and 600 man-days/year for a reprocessing plant.

Resource limitations on inspector man-days are reflected in the examples by reducing to 50-65% of ARIE the number of available inspection man-days implemented. These values are reasonably close to the inspection effort actually assigned by the IAEA under current practice.[1]

A. Dependence of Allocation on the Algorithm

The allocation algorithms I and II represent reasonable extremes among rationales for assigning inspection resources. Assuming a resource of 65% ARIE applied to fuel cycle III, Fig. 6 shows the differences in attainment levels for material categories under the two algorithms. Clearly, algorithm I favors the more attractive materials at the expense of the less attractive materials, whereas algorithm II seeks a more uniform attainment across all material categories. By calculating these two extreme allocations, an analyst can obtain a bound on the achievable attainment levels for any assumed level of inspection effort.

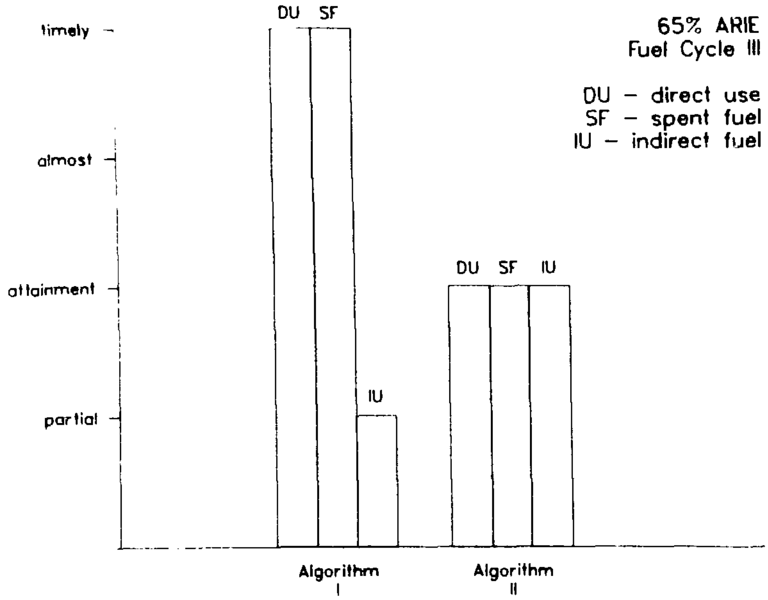

Fig. 6. Dependence of attainment level for material categories on allocation algorithm.

B. Dependence of Allocation on Fuel Cycle Context

The dependence of SIR attainment for a material category on the fuel cycle context is illustrated in Fig 7, which is based on a total inspection man-day resource of 50% ARIE and on algorithm II. As the size of the fuel cycle, and, therefore, of the available resources increases, the additional resources are employed to improve attainment for the more attractive materials. Thus, in fuel cycle II, spent fuel attainment improves at the expense of indirect-use material, and similarly in fuel cycle III, direct-use attainment is increased over the other materials. An alternative view of this same effect is represented in Fig. 8, which shows the percentage of the available man-days allocated to each facility type.

C. Facility Versus SIR-Based Allocation

The SIR-based allocation procedure described in this report assigns effort to a particular facility while considering the other facilities to be inspected under the available resources. This contrasts with the facility-based conceptual alternative of assigning essentially the same effort to facilities of the same type irregardless of the other facilities competing for resources. The difference in attainment of safeguards goals is illustrated by comparing Figs. 7 and 9.

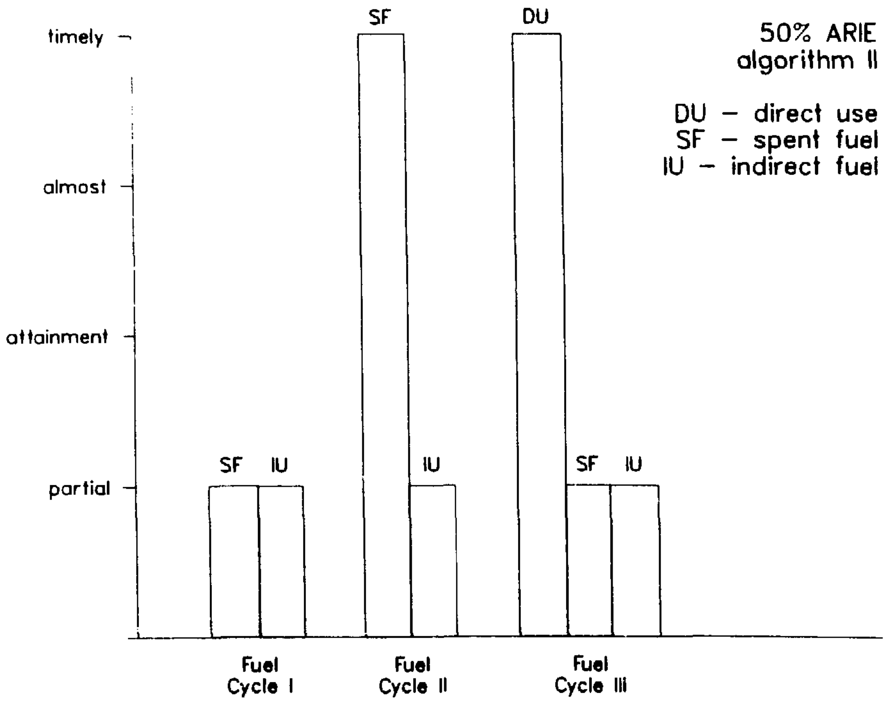

Fig. 7. Dependence of allocation effort to material categories on fuel cycle context.

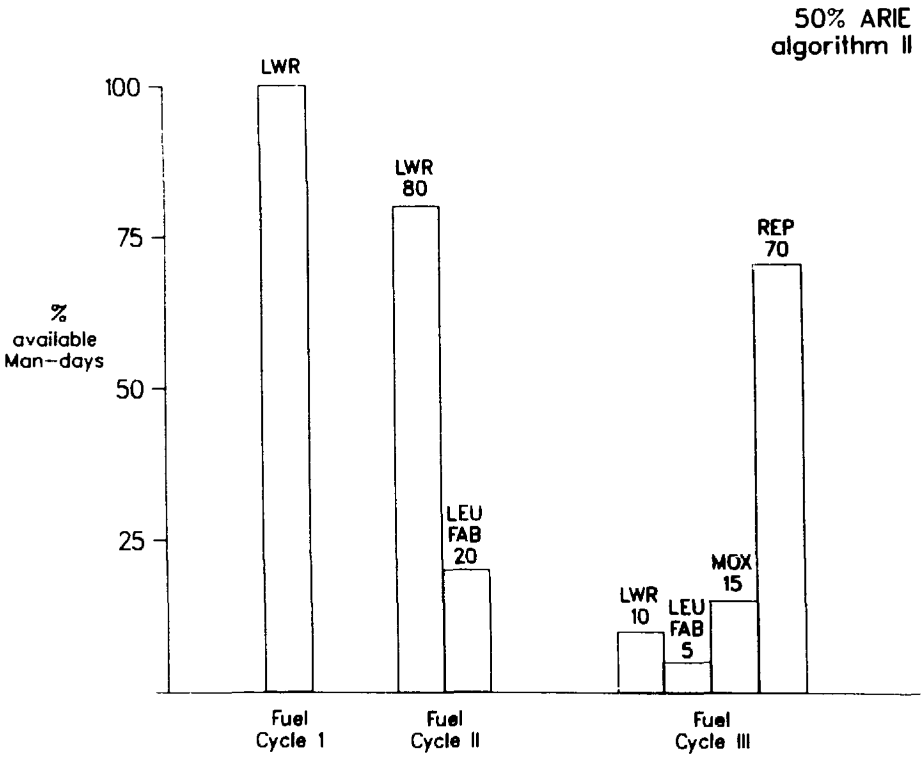

Fig. 8. Dependence of inspection effort allocation to facility types on fuel cycle context.

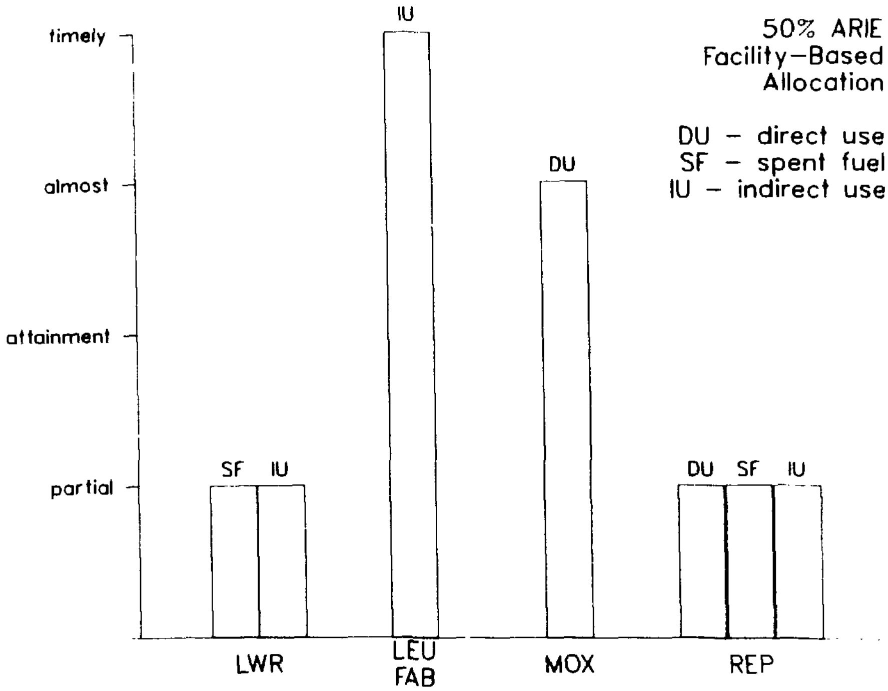

Fig. 9. Inspection effort allocation using facility-based distribution.

In Fig. 9, attainment levels for material categories at each facility are shown, assuming the effort at each facility is 50% of the ARIE for that facility type.

These results illustrate two important differences between these allocation procedures. First, the SIR-based procedure improves the attainment for direct-use material compared with the facility-based procedure. Second, the attainment for a material category is uniform with the SIR procedure, whereas the facility-based procedure results in a wide variation in attainment level within a material category.

VI. SYSTEMS ANALYSIS APPLICATIONS

Although the allocation procedure described in this report is consistent with the principles of the IAEA inspection regime, in practice, it represents a significant departure from the current procedures for allocation of inspection effort by the operations divisions. Thus, realistically one cannot expect in the near term that this SIR-based allocation procedure could be adopted by the IAEA. There are, however, some applications of proposed method that could be made within the current framework of inspection planning.

First, the algorithms for maximizing SIR attainment could be applied by operations divisions to determine how their current allocation departs from an optimal one. This comparison could suggest modifications to current allocation practice having a high return in improved SIR attainment.

Second, studies to determine inspection resources necessary to satisfy fully the current safeguards criteria would be aided by the procedures described in this document. Such studies would have relevance to near-term planning for staffing the operations divisions.

Third, the development of the long-term safeguards criteria might benefit from analyses to determine the inspection resource requirements implied by these new Criteria and to determine how the level of safeguards for material categories and facility types is likely to evolve when inspection resources are not adequate to fully satisfy the new Criteria.

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APPENDIX A

SUMMARY OF INSPECTION ACTIVITIES IMPLIED BY SAFEGUARDS CRITERIA FOR 1986

TABLE A-I

SUMMARY OF SAFEGUARDS CRITERIA FOR ATTAINMENT OF INSPECTION GOALS AT REACTORS

A. Examine Records and Reports

Examination should be sufficient to detect discrepancy exceeding 1 significant quantity (SQ) during period between last physical inventory verification (PIV) in successive years.

B. Physical Inventory Verification

Fuel Type*	No C/S**	Successful C/S
FH	2 PIV item count, verify ID variables NDA coverage ≥ RH†	1 PIV item count attributes NDA coverage ≥ RH
FL	1 PIV item count verify ID or attributes NDA coverage ≥ RM	1PIV item count
SF	2 PIV item count verify ID or attributes NDA coverage ≥ RM	1 PIV item count
CF	(refueling) 1 PIV item count	(no refueling) successful C/S

C. Detection of Fuel Borrowing

C/S measures, simultaneous inspections, or inspections without advance notice were used to detect borrowing of fuel items.

*FH - fresh fuel containing direct-use material, FL - fresh LEU, natural U, or depleted U fuel, SF - spent fuel, CF - core fuel.

**C/S - containment and surveillance.

†Verification coverage: C - complete verification, RH - sample size with detection probability ≥0.9, RM - sample size with detection probability <0.9 and ≥0.5, and RL - sample size with detection probability <0.5 and ≥0.1.

TABLE A-II

SUMMARY OF SAFEGUARDS CRITERIA FOR PARTIAL ATTAINMENT OF INSPECTION GOALS AT REACTORS

A. Examine Records and Reports

Examination should be sufficient to detect discrepancy exceeding 1 SQ during period between PIVs.

B. Physical Inventory Verification

Material Type	No C/S	C/S
FH	1 PIV item count attributes NDA coverage $\geq$ RL	2 PIV C/S only
CF	1 PIV item count	1 PIV C/S only
FL/SF	1 PIV item count	1 PIV C/S only

TABLE A-III

SUMMARY OF SAFEGUARDS CRITERIA FOR TIMELINESS OF INSPECTION GOALS AT REACTORS

Timeliness goals

Unirradiated direct use	1 month
Core or spent fuel	3 months
Unirradiated indirect use	12 months

Following intervals not to exceed timeliness goal.

Direct use

Time between shipment and confirmation of receipt in reports or by inspection

Time between PIVs

Time between surveillance restart and film review

Time between seal application and examination

TABLE A-IV

SUMMARY OF SAFEGUARDS CRITERIA FOR ATTAINMENT OF INSPECTION GOALS AT BULK HANDLING FACILITIES

A. Comparison of Records and Reports

Examination should be sufficient to detect discrepancy exceeding 1 SQ during periods between PIVs.

B. Verification of Receipts

1) Simultaneous inventory of facilities with same material

<u>or</u>

Bulk Material

quantitative method for receipts coverage RH for direct use coverage RM for other	or	quantitative method at shipment coverage RH for direct use coverage RM for other C/S since verification

<u>and</u>

Spent Fuel

2)	item count receipts verify identity coverage RM	or	item count at shipment verify identity coverage RM C/S since verification

C. Physical Inventory Verification

Material Type	No C/S	C/S
Direct use (bulk)	2 PIV quantitative method coverage $\geq$ RM	2 PIV item count attributes NDA coverage $\geq$ RM
Indirect use (bulk)	1 PIV quantitative method coverage $\geq$ RM	1 PIV item count attributes NDA coverage $\geq$ RM

TABLE A-IV (cont)

Material Type	No C/S	C/S
Fuel items		
Direct use (unirradiated)	2 PIV quantitative method coverage $\geq$ RM	2 PIV item count attributes NDA coverage $\geq$ RM
Direct use (irradiated)	2 PIV verify item identity attributes NDA coverage $\geq$ RM	2 PIV item count
Indirect use (irradiated)	1 PIV attributes NDA	1 PIV item count
Other (waste, discards)	quantitative method or attributes NDA	coverage $\geq$ RM

D. Material Borrowing

C/S, simultaneous, or inspections with no notice

E. Facility Specific Criteria

Enrichment Facilities

Inspection activities to detect unreported HEU production

Reprocessing Facilities

Verify fuel dissolution by quantitative method with coverage $\geq$ RH

Verify fuel transfers by C/S

Verify plutonium product shipments by quantitative method with coverage $\geq$ RH

TABLE A-V

SUMMARY OF SAFEGUARDS CRITERIA FOR PARTIAL ATTAINMENT OF INSPECTION GOALS AT BULK HANDLING FACILITIES

A. Comparison of Records and Reports

B. Physical Inventory Verification

Material Type	No C/S	C/S
Direct use (bulk)	1 PIV attributes NDA coverage $\geq$ RM	1 PIV C/S only
Indirect use (bulk)	1 PIV attributes NDA coverage $\geq$ RM	1 PIV C/S only
Fuel items		
Direct use (unirradiated)	1 PIV attributes NDA coverage $\geq$ RM	1 PIV C/S only
Direct use (irradiated)	1 PIV item count	1 PIV C/S only
Indirect use (irradiated)	1 PIV item count	1 PIV C/S only

C. Facility Specific Criteria

Enrichment Facilities

Inspection activities to detect unreported highly enriched uranium production

Reprocessing Facilities

Verify fuel dissolution by quantitative method with coverage $\geq$ RH

Verify fuel transfers by C/S

Verify plutonium product shipments by quantitative method with coverage $\geq$ RH

TABLE A-VI

SUMMARY OF SAFEGUARDS CRITERIA FOR TIMELINESS
OF INSPECTION GOALS AT BULK HANDLING FACILITIES

Timeliness goals (for quantities $\geq$ 1 SQ)

Unirradiated direct use	1 month
Direct use in irradiated fuel	3 months
Indirect use	12 months

Following intervals not to exceed timeliness goal.

Direct use

Time between shipment and confirmation of receipt in reports or by inspection

Time between PIVs

Time between C/S restart and film review

Indirect Use

Time between PIVs