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STUDIES ON CAPACITY MANAGEMENT FOR FACTORIES OF NUCLEAR FUEL FOR RESEARCH REACTORS

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ABSTRACT

The use and the power of nuclear reactors for research and materials testing is increasing worldwide. That implies the demand for nuclear fuel for this kind of reactors is rising. Thus, the production facilities of this kind of fuel need reliable guidance on how to augment their production in order to meet the increasing demand efficiently, safely and keeping good quality. Focus is given to factories that produce plate type fuel elements loaded with LEU U_3Si_2-Al fuel, which are typically used in nuclear research reactors. Of the various production routes for this kind of fuel, we chose the route which uses hydrolysis of uranium hexafluoride. Raising the capacity of this kind of plants faces several problems, especially regarding safety against nuclear criticality. Some of these problems are briefly addressed. The new issue of the paper is the application of knowledge from the area of production administration to the fabrication of nuclear fuel for research reactors. A specific method for the increase in production capacity is proposed. That method was tested by means of discrete event simulation. The data were collected from the nuclear fuel factory at IPEN. The results indicated the proposed method achieved its goal as well as ways of raising production capacity in up to 50%.

1. INTRODUCTION

Nuclear research reactors are responsible for a relevant portion of the generation of knowledge of nuclear technology as well as for a part of the benefits generated by the use of its techniques [1]. The spread of nuclear applications implies a growing utilization of nuclear research reactors [2]. That growth in turn causes an increase in the demand for nuclear fuels for research reactors [3]. Generally speaking, the production of nuclear fuels for research reactors happens in small scale, is exclusive for one reactor and the production facility is located near the corresponding user.

The fuel type chosen for this study is uranium silicide dispersed in aluminum, using Low Enriched Uranium (LEU) known as LEU U_3Si_2–Al fuel. We choose LEU U_3Si_2–Al fuel because of its wide use in research reactors, its good capacity of uranium loading, and its excellent performance [4–6].

The production of LEU U_3Si_2–Al fuel includes chemical processes, which may have considerable variability [7]. This fact imposes the selection of one specific chemical route in order to set the range of this work. We chose the chemical track that includes the hydrolysis of uranium hexafluoride (UF_6) for these reasons:

- this path stands out for its simplicity and relative safety,
- it is used to produce small quantities of the intermediate products, and
- the rising demand for nuclear fuels for research reactors will probably affect facilities operating this production scheme.

The reasons above underline the convenience of having a safe and reliable method of expanding production capacity of factories of FE loaded with LEU U_3Si_2–Al fuel, whose fabrication process includes UF_6 hydrolysis. The facts mentioned so far guided us in establishing the objectives of this paper, which are: to propose and test a procedure for expanding the production capacity of FE for nuclear research reactors using LEU U_3Si_2–Al fuel, whose manufacturing path includes UF_6 hydrolysis.

The source of actual data for this paper is the nuclear fuel plant at IPEN, Nuclear and Energy Research Institute, which is part of CNEN, Brazilian National Commission on Nuclear Energy, located in São Paulo, Brazil. That factory produces FE for the nuclear research reactor IEA-R1, which belongs to IPEN itself. The mentioned FE are loaded with LEU U_3Si_2-Al fuel, which is produced on the route of UF_6 hydrolysis.

2. LITERATURE REVIEW

2.1. Plant

We reviewed the literature that deals with capacity enlargement of general manufacturing plants [8–15]. That literature presents several methods for the generic case of designing manufacturing capacity growth. We set a correlation among those methods and take this correlation as the general method for capacity expansion for this paper, as follows:

General method:

1. establish organizational and production strategies;
2. analyze demand, product, materials and processes;
3. identify bottlenecks;
4. set changes to the processes;
5. if necessary, establish a new layout;
6. implement the changes; and
7. check the efficacy of the changes.

2.1.1. Details about the general method

Capacity planning is a managerial decision belonging to the organizational strategy. Several authors state that capacity must be planned for short, medium and long terms [8–11, 13, 16–19]. Nuclear fuel for research reactors is a product that does not change significantly in the short or medium terms and its market also varies little. Because of this, for the scope of this study we only plan capacity for the long term.

The so called “bottleneck” is the process with the highest cost or lead time among all processes, according to several authors [9–11, 13, 14, 16, 17, 19, 20]. According to the Theory of Constraints [21–23], we must investigate all possible details about the bottleneck itself and its relations to the production flow. The study of the bottleneck and its impacts on the production flow may indicate the need of changing other processes.

A logical layout is essential for the material’s flow to be efficient and safe throughout the factory [8–11, 13, 14, 16, 17, 19, 20]. After enhancing the bottleneck’s capacity, a larger flow of intermediate products will be established and requires balancing. The balance is achieved by means of the study of the new flow and its relation to the current layout [9–11, 13, 17, 19].

2.2. Nuclear Engineering

We assume that the plant produces only LEU U_3Si_2–Al fuel. The raw materials and intermediate products for the production of LEU U_3Si_2-Al fuel are well known and can be found in several references [24, 5, 25, 26]. In addition to the fuel itself, IPEN’s nuclear fuel plant also produces plate-type FE and loads them with LEU U_3Si_2–Al fuel. The design of that product is well established as are the production processes necessary for its fabrication. This FE is made by the assembly of several fuel plates (FP) and other mechanical components [3]. Its raw materials and productive processes are defined and set [7].

The objective of criticality safety is the prevention of a criticality accident. In order to achieve its goals, the area of safety against criticality recommends small quantities of nuclear fuel, reduced piping diameters, controlled flow of liquids and gases etc. These measures go against the raise in production capacity. Therefore the task of putting together capacity enlargement and safety against criticality is a delicate, complex and extensive task. These facts lead us to exclude that task from this paper.

2.3. Simulation Modeling

Several authors [27–35] stress the benefits of modeling manufacturing systems, explaining why we have included simulation in this paper. We used discrete event simulation (DES) due to the stochastic nature of the production processes of nuclear fuel and because DES is successfully employed in different areas of manufacturing like batch processes, continuous processes, capacity planning, job floor scheduling, and others [36–39].

There are sundry tools for DES simulation, such as Simul8, ProModel and AutoMod [40]. In this work we used the academic version of the software ARENA® from Rockwell Automation [41] because it allows the simulation of practically any scenario of material flow through sets of processes. The academic version of ARENA® is available to the University of São Paulo by means of its agreement with Rockwell Automation.

3. METHODOLOGY

3.1. Proposal of a Specific Method for Expansion of the Production Capacity

After studying the general concepts in the previous sections, we adapted them to the specific case of a LEU U_3Si_2–Al fuel plant, whose manufacturing path includes UF_6 hydrolysis. The proposed method is a conformation of the general procedure and it contains the following steps:

Proposed method
1. Establish organizational and production strategies;
2. Identify bottlenecks;
3. Increase the bottleneck's capacity;
4. Check for the risk of criticality in the new set up; and
5. Check if the demand is met.

Product, materials and processes are known and were discussed in Section 2.2. Items 6 and 7 of the general procedure could not be executed for this work and thus are not part of the specific procedure. On the other hand, only if the risk of criticality lies within its margins of safety in step 4 can we proceed to step 5. For the scope of this work, we assume that any change in material's flow or layout will only be made with due enforcement of IAEA and CNEN standards concerning criticality [42–44].

3.2. Testing and Evaluation of the Proposed Method

Testing of the proposed method was done by means of the following three activities:
- Application of the proposed specific procedure to the nuclear fuel plant at IPEN;
- Establishment of layout and production scenarios; and
- Running discrete event simulation of each scenario.

All three activities for testing the proposed procedure were done using real data from the nuclear fuel plant at IPEN. The evaluation of the proposed procedure was done by comparing the simulation's results.

3.2.1. Application of the proposed method to the nuclear fuel plant at IPEN

The organizational and production strategies corresponding to the nuclear fuel plant at IPEN are listed below.

- The institution produces and consumes its own nuclear fuel
- The institution does not supply any third party with its nuclear fuel
- The only fuel produced is U_3Si_2–Al enriched at 20% of ^{235}U
- The production route comprises UF_6 hydrolysis
- Only one type of FE is manufactured

The named strategies are part of the boundary conditions we used in this paper. In order to set the scope of this paper, we do not consider making any changes to the mentioned strategies.

One basic condition to identify bottlenecks is to thoroughly understand the processes. For that reason we started this work with the personal mapping of all processes of the fuel plant at IPEN.

We studied all departments of the plant and recorded several data, which are presented in the following sections.

The nuclear fuel plant at IPEN is divided into four work centers. Tables 1, 2, 3 and 4 present the production activities carried out in each of those centers, the process times of all activities, and the numbering of the activities in ascending order of execution. Details about all processes can be found in the literature [3, 7].

The production lot considered in this paper consists of 3.0 kg of UF_6, which is the main raw material of the fuel plant at IPEN. We based all analysis of this paper on that production lot and on its running through all processes of Tables 1 to 4, where it is chemically and physically transformed until a FE is finally produced.

Processes and times presented in Tables 1 through 4 reflect the actual materials' flow on the factory floor and they are suitable for simulation. The time units used in Tables 1 through 4 are working hours and we assume that one working day has eight working hours. The times presented in Tables 1 through 3 resulted from the direct measurement of process times in Work Centers 1, 2 and 3. The times presented in Table 4 have a different treatment, as explained below.

Table 1: Processes at Work Center 1

No.	Processes	Time (hours)
1	Reception of cylinders containing UF_6	0.80
2	Preparation for UF_6 transfer	2.45
3	UF_6 transfer from the cylinder to the ampoule	3.66
4	Preparation for UF_6 hydrolysis	2.54
5	UF_6 hydrolysis	3.74
6	Preparation for UF_4 precipitation	1.70
7	UF_4 precipitation	4.28
8	UF_4 washing and filtration	1.83
9	UF_4 drying	17.50
10	UF_4 dehydration	6.50

Table 2: Processes at Work Center 2

No.	Processes	Time (hours)
11	Crucible load with UF_4-Mg	2.35
12	UF_4 reduction to metallic uranium	7.28
13	Crucible disassembly and density measurement	0.84
14	Stripping of metallic uranium	0.56
15	Crucible load with metallic uranium and Si	1.18
16	Melting of the intermetallic alloy U_3Si_2	8.20
17	Density measurement of the U_3Si_2 ingot	0.34

In Table 4 the mentioned “set” is composed by the joining of a fuel core, a frame plate and two cladding plates. Still in Table 4, process number 32 is named as “Four processes on fuel plates (FP)” because it comprises the processes of the first radiography of FP, searching for defects on FP, FP’s tracing, and FP’s identification. These four processes happen at the same workstation, so they cannot be split.

Table 3: Processes at Work Center 3

No.	Processes	Time (hours)
18	Grinding of U_3Si_2 and classification of its powder	1.87
19	U_3Si_2 homogenization with Al^0	6.28
20	Pressing of the mix U_3Si_2 and Al^0, producing fuel cores	2.40
21	Fuel core dimensional control	2.76
22	Fuel core degassing	3.69

Table 4: Processes at Work Center 4

No.	Processes	Time (hours)
23	Reception of aluminum boards	1.67
24	Cladding and framing preparation	3.28
25	Cladding and framing stripping	4.55
26	Assembly of the set	1.12
27	Welding of the set	1.50
28	Hot rolling and annealing	8.83
29	Blister inspection	0.54
30	Cold rolling	1.08
31	Initial cut	3.43
32	Four processes on fuel plates (FP)	8.37
33	Final cut	2.86
34	Surface treatment	2.21
35	Dimensional inspection and second radiography of FP	3.89
36	Scratching test	1.67
37	Stripping of FP and FE components	6.33
38	FE assembly	6.82
39	Quality control	3.37
40	Nozzle fixation	1.06
41	Handling pin fixation	0.86
42	FE dimensional control	0.96
43	FE cleaning and packing	1.12
44	Delivery of the finished FE	0.48

The actual production lot uses 3 kilograms of UF_6 and all activities of IPEN’s fuel plant actually process this equivalent uranium quantity. That real production lot contains enough raw material to produce 24 FP. However, IEA-R1’s FE has only 18 FP. Thus at the end of the processing of one actual lot, one FE plus 6 FP are produced. Therefore, at the end of the entire processing of the third lot, 3 FE plus 18 FP are produced, and the extra 18 FP are converted into a fourth FE. In order to account for this difference, we decreased the times of processes of Work Center 4 by 28%. That percentage is the difference between the real yearly production and the production that would happen if Work Center 4 did not process the remaining 6 FP of each lot.

In order to find out the bottleneck, first we look for the work center with the longest lead time. After that, we look for the process within that work center that takes the longest to be executed. The next step is to increase the bottleneck's capacity. We did it by means of increasing the capacity of the single process of the bottleneck itself and can be found in numerous references [10, 17, 19–22, 45]. In this paper we assume that the bottleneck has its capacity doubled, what is usually done by means of acquiring new equipment. We do not enter in details on how that capacity is expanded, because that goes beyond the scope of this paper. Doubling the capacity of the bottleneck has two effects:

- The bottleneck`s process takes half the time, and
- the total processing time of the work center where the bottleneck is located is decreased.

The increase of the bottleneck's capacity established in the former step may impose changes in the production line and in its layout. Such changes alter the risk of criticality of the plant. The calculation of the risk of criticality is an extensive task. For this reason we do not attempt such calculations in this paper. Therefore, we consider that any increase in the production capacity mentioned in this paper generates sub-critical systems.

We did not set a goal for the demand, because we wanted to check how the proposed method would behave in different production schemes. This way the demand can be as high as the forecasted production.

3.2.2. Establishment of production and layout scenarios

We named each of the changes in the materials' flow or in layout as scenarios. Applying the proposed method to the fuel plant at IPEN reduces the time required by the bottleneck to its half. That new time is attributed to the process of the bottleneck, thus shaping the next scenario. Below we present the suppositions adopted for all scenarios.

1. Supply of UF_6 is continuous and sufficient;
2. The quality of UF_6 is good enough to run all processes of the plant;
3. There is no waste due to quality non-compliance in the whole factory;
4. Manpower is sufficient and trained to perform all scenarios;
5. Production time is 210 working days per year, corresponding to approximately ten production months per year; and
6. Daily operation time is eight hours per working day.

All scenarios are based on real data from the fuel plant at IPEN. DES is run for each scenario. It simulates one year of production under each scenario and its result is the yearly production achieved by each scenario in number of FE. We set the simulation period as one year with the aim of considering the several different situations that happen during one year. DES is replicated ten times for each scenario, therefore simulating ten years of production under each scenario. Replications of DES allow to obtain average values of the yearly production returned by the software ARENA®.

4. RESULTS

Scenario 1
As mentioned previously, the initial status of the fuel plant at IPEN is the source of data for our DES, therefore being the reference for the DES too. That status is represented by Tables 1 to 4, and we called it Scenario 1. The result of DES of Scenario 1 is 28 FE produced in one year. For the identification of the bottleneck of Scenario 1 we followed the procedures from previous sections. Thus we identified the bottleneck of Scenario 1 as hot rolling and annealing, which is process number 28 of Work Center 4.

Scenario 2
According to the previous sections, we doubled the capacity of the process of hot rolling and annealing. Thus, that process is now done in half the time, i.e., 4.415 hours. This new time shapes Scenario 2. At this point we ran DES for Scenario 2 and its result was 30 FE per year. In order to identify the bottleneck of Scenario 2, we followed the proceedings from previous sections and found that its bottleneck is the process number 32 of Table 4, four processes on FP, executed in Work Center 4.

Scenarios 3 to 8
We executed the same procedures of Scenario 2 and found respectively new times, yearly production and new bottlenecks for Scenarios 3 until 8, whose results and comparisons are presented in Table 7.

Table 7: Results of the proposed method

Scenario	Bottleneck			Production in FE per year	Percentage raise regarding	
	Name	Number	Table		Previous scenario	Scenario 1
1	Hot rolling and annealing	28	4	28	-	-
2	Four processes on FP	32	4	30	7%	7%
3	FE assembly	38	4	33	10%	18%
4	UF$_4$ drying	9	1	34	3%	21%
5	Stripping of FP and FE components	37	4	36	6%	29%
6	Hot rolling and annealing	28	4	38	6%	36%
7	Four processes on FP	32	4	40	5%	43%
8	Dimensional inspection and second radiography of FP	35	4	42	5%	50%

5. CONCLUSIONS

The objectives of this paper were met, because:

- We proposed a procedure for expansion of production capacity and
- We demonstrated that procedure expands production capacity.

The comparison of production between Scenarios 1 and 8 shows that an increase of 50% is possible.

As suggestions for future works, we mention the addition of data, creation of further cenarios and growth in the simulation detailing. Additional data may include costs and itemized layout. Further scenarios may encompass processing the critical uranium mass.

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